

Ioannis S. Arvanitoyannis



Irradiation of Food Commodities

Techniques, Applications, Detection,
Legislation, Safety and Consumer Opinion



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AMSTERDAM • BOSTON • HEIDELBERG • LONDON • NEW YORK
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Academic Press is an imprint of Elsevier



Academic Press is an imprint of Elsevier
32 Jamestown Road, London NW1 7BY, UK
30 Corporate Drive, Suite 400, Burlington, MA 01803, USA
525 B Street, Suite 1800, San Diego, CA 92101 4495, USA

First edition 2010

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British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data

A catalog record for this book is available from the Library of Congress

ISBN: 978 0 12 374718 1

For information on all Academic Press publications
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Typeset by TNQ Books and Journals

Printed and bound in United States of America

10 11 12 13 10 9 8 7 6 5 4 3 2 1

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This book is dedicated to

my beloved and precious wife for her unfailing support and encouragement throughout a too long time of continuous pressure and for waiting for my “lost spare time” and to my three children,

- *Iasson (the oldest and the most sentimental)*
- *Artemis-Eleni (the mindful)*
- *Nefeli-Kallisti (the youngest and the most sociable)*

who do not fail one single day to embellish our lives.

And to the memory of my grandparents, whose moral support in the early stages of my life was crucial for the rest of it.

—Ioannis S. Arvanitoyannis

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Preface

Since the early beginnings of their presence on Earth, humans have tried to prolong the shelf life of foods they collect or hunt. Among the first approaches to preservation of foods of animal origin was cooking, smoking, and freezing. However, the increase in population augmented the demands for shelf life prolongation, thereby requiring the introduction of novel techniques. Among the relatively recent techniques (high pressure, microwave heating, ohmic heating, UV irradiation, pulsed electric field pasteurization, etc.), irradiation in its many forms (γ -irradiation, microwave, UV, and electron beam) has gained ground at the expense of the already applied conventional techniques. Although reservations and doubts have been expressed both by scientists and by consumer movements/organizations regarding the usage of irradiation, the current opinion is that its employment has more advantages than disadvantages. On the other hand, the disadvantages can be substantially reduced if extra care is taken during the applied irradiation processes to ensure the usage of the appropriate irradiation dose and time and to minimize the possibility of irradiation leakage. There has been a “confrontation” between the European Union (EU) and the United States regarding legislation referring to labeling of irradiated foods. Similarly to genetically modified organisms and genetically modified foods, the EU adopted two directives—Directive 1999/2/EC concerning foods and food ingredients treated with ionizing radiation and Directive 1999/3/EC on the establishment of a community list of foods and food ingredients treated with ionizing radiation—in an attempt to eliminate or at least minimize the differences among the various EU member states. Labeling of the irradiated foodstuff is required for any food that has been subjected to irradiation either within the EU or outside the EU but that will be imported into it. In view of the continuously increasing interest in identifying irradiated foods, there has been strong emphasis on developing novel, rapid, reliable, and validated detection methods. In fact, 10 methods have been validated and approved as EN standards (EN 1784:1996, EN 1785:2003, EN 1786:1996, EN 1787:2000, EN 1788:2001, EN 13708:2001, EN 13751:2002, EN 13783:2001, EN 13784:2001, and EN 14569:2004). However, one should consider these standards as part of a dynamic process because in practice there has been a strong need for introducing modifications to improve their effectiveness and avoid potential interferences. A plethora of research articles have been published on applications

of irradiation detection methods covering a wide range of foods. Occasionally, two or more methods have been applied simultaneously for testing comparatively the effectiveness of methods. One important finding of the comparative studies is that methods such as electron spin resonance, thermoluminescence, and DNA comet assay are the most reliable, rapid, and promising methods.

This book comprehensively covers most of the aspects of food irradiation, such as irradiation equipment, food packaging materials for irradiation, applications of irradiation to all foods of plant and animal origin, irradiation detection methods, legislation issues, and consumer behavior with regard to irradiated foods. The book is divided into the following parts:

Part A: Legislation

Part B: Irradiation Techniques and Materials

Part C: Irradiated Food: Detection and Risk Assessment

Part D: Applications of Irradiation on Foods of Animal Origin

Part E: Applications of Irradiation on Foods of Plant Origin

Part F: Other Applications of Irradiation

Part G: Consumer Opinion

The aim of this book is to provide updated information on irradiation treatment, a technique that is gradually gaining ground, by thoroughly discussing all important issues, referring extensively to the literature. It is noteworthy that this book contains a large number of comprehensive tables, informative figures, and references.

This book is addressed to a wide audience, including food scientists and technologists, agriculturists, food chemists, microbiologists, veterinary doctors, academics (professors and researchers involved in food technology and food safety), industrialists, and, in general, anyone who would like to gain insight into the current situation/utilization of irradiation, either alone or in conjunction with other techniques, for food preservation.

—Ioannis S. Arvanitoyannis

Abbreviations

| Abbreviation | Full Name |
|--------------|--|
| %E | Percentage elongation at break |
| %UE | Ultimate percentage elongation |
| 2 ACBs | 2 Alkylcyclobutanones |
| 2 AF | 2 Aminofluorene |
| 2 DCB | 2 Dodecylcyclobutanone |
| 8 MOP | 8 Methoxy psoralen |
| 2 TCB | 2 Tetradecylcyclobutanone |
| 2 TDCB | 2 Tetradecenylcyclobutanone |
| 1,3 DTBB | 1,3 Di <i>tert</i> butylbenzene |
| 2,4 DTBP | 2,4 Di <i>tert</i> butylphenol |
| A | |
| AA | Ascorbic acid |
| AAC | Apparent amylose content |
| AAc | Acrylic acid |
| AAm | Acrylamide |
| ACBs | 2 Alkylcyclobutanones |
| ACC | 1 Aminocyclopropane 1 carboxylic acid |
| ACPY | 2 Acetyl 1 pyrroline |
| AD | Additive dose |
| AFM | Atomic force microscopy |
| AN | Acid number |
| AO | Acridine orange |
| APC | Aerobic plate count |
| AR | Aminoreductone |
| AU | Allylurea |
| AUDPC | Area under the disease progress curve |
| a_w | Water activity |
| B | |
| β LG | β Lactoglobulin |
| BAs | Biogenic amines |
| BEUC | Bureau Européen des Unions des Consommateurs |
| BF | Back fat |
| BHT | Butylated hydroxytoluene |
| BLG | Bovine β lactoglobulin |
| BMA | British Medical Association |
| BOPP | Biaxially oriented polypropylene |
| BP | Benzophenone |
| BSA | Bovine serum albumin |

(Continued)

| Abbreviation | Full Name |
|----------------------|---|
| C | |
| CA | Water contact angle |
| CaA | Calcium ascorbate |
| CAS | Calcium caseinate |
| CAS:WP | Caseinate whey protein |
| CC | Cotton cellulose |
| CCFAC | Codex Committee on Food Additives and Contaminants |
| CD | Circular dichroism |
| CEg | Consumers in Europe Group |
| CEN | European Committee for Standardisation |
| CEN/TC 275 | Technical Committee |
| CFPDC | Consolidated Forms and Publications Distribution Center |
| CFR | Code of Federal Regulations |
| CFU | Colony forming units |
| CGCD | Computerized glow curve deconvolution |
| CGP | Coated with pectin based materials containing 0.5% green tea powder |
| CH | Conventional heating |
| CHDM | 1,4 Cyclohexane dimethanol |
| CHO | Chinese hamster ovary |
| CIPC | Chlorophenyl isopropyl carbamate |
| <i>cis</i> 2dDeCB | <i>cis</i> 2 (dodec 5' enyl) cyclobutanones |
| <i>cis</i> 2 tDeCB | <i>cis</i> 2 (tetradec 5' enyl) cyclobutanones |
| CMC | Carboxymethyl cellulose |
| CM chitosan | Carboxymethylated chitosan |
| CMS | Carboxymethyl starch |
| CO | Corn oil |
| CON | Concentrate |
| CP | Coated with pectin based materials |
| CP | Crude protein |
| CPA | Cyclopiazonic acid |
| CPP | Cast polypropylene |
| CPV | Cool pasting viscosity |
| CR | Concentration ratio |
| CS | Cobalt stearate |
| CS | Canola seed |
| CSMA | Cobalt styrene maleate copolymer |
| CTA | Cellulose triacetate |
| CTS | Chitosan |
| C XANES | X ray absorption near edge spectroscopy |
| CZ | Corn zein |
| D | |
| d ₄ Furan | Deuterated furan |
| DAA | Dehydroascorbic acid |
| DAE | Dimethylacetamide acetone ethanol |
| DD | Deacetylation |
| DEFT | Direct epifluorescent filter technique |
| DEHP | Ethylhexyl phthalate |

(Continued)

| Abbreviation | Full Name |
|--------------|--|
| DEHP | Di(2 ethylhexyl)phthalate |
| DFD | Dark, firm, dry |
| DGC | Dry gluten content |
| DHP chitosan | Dihydroxypropyl chitosan |
| DM | Dry matter |
| DNA | Deoxyribonucleic acid |
| DON | Deoxynivalenol |
| DP | Degrees of polymerization |
| DPPH | 1,1 Diphenyl 2 picrylhydrazyl |
| DPPH | 2,2 Diphenyl 1 picrylhydrazyl |
| DS | Degree of substitution |
| DSC | Differential scanning calorimetry |
| DSE | Direct solvent extraction |
| E | |
| EA | Egg albumin |
| EB | Electron beam, e beam |
| ELISA | Enzyme linked immunosorbent assay |
| EO | Ethylene oxide |
| EPR | Electron paramagnetic resonance |
| ERA | Ecological risk assessment |
| ESD | Experimental sterilizing dose |
| ESR | Electron spin resonance |
| Euro Coop | European Community of Consumer Co operatives |
| EVOH | Ethylene vinyl alcohol |
| F | |
| FAO | Food and Agriculture Organization |
| FCC | Florisil column chromatography |
| FDA | U.S. Food and Drug Administration |
| FFA | Free fatty acid |
| FI | Fusarium infected |
| FO | Flaxseed oil |
| FRAP | Ferric reducing antioxidant power |
| FSA | Food Standards Agency |
| FSI | Food Safety Information Centre |
| FSIS | Food Safety and Inspection Service |
| FSO | Food Safety Objective |
| FT IR | Fourier transform infrared spectroscopy |
| FTR | Fourier transform Raman spectroscopy |
| G | |
| GAP | Good agricultural practices |
| GC | Gas chromatography |
| GM | Genetically modified |
| GMO | Genetically modified organism |
| GMP | Good manufacturing practice |
| GPC | Gel permeation chromatogram |
| GPC | Gel permeation chromatography |

(Continued)

xxii Abbreviations

| Abbreviation | Full Name |
|-----------------|---|
| GRAS | Generally recognized as safe |
| GS | Grape seed |
| GT | Green tea |
| H | |
| HACCP | Hazard analysis critical control point |
| HAV | Hepatitis A virus |
| HEMA | 2 Hydroxyethyl methacrylate |
| HESI | Health and Environmental Sciences Institute |
| HF | Hyperfine |
| HPLC | High performance liquid chromatography |
| HPMC | Hydroxypropyl methylcellulose |
| HPSEC MALLS RI | High performance size exclusion chromatography equipped with multiangle laser light scattering and refractive index |
| HPV | Hot pasting viscosity |
| HRGC | High resolution gas chromatography |
| HSP | Hydrochloride soluble pectin |
| I | |
| IAEA | International Atomic Energy Agency |
| ICGFI | International Consultative Group on Food Irradiation |
| IgE | Immunoglobulin E |
| ILSI | International Life Sciences Institute |
| IM | Intermediate moisture |
| IR | Infrared |
| IR H treatments | Irradiation followed by heat treatments |
| IV | Iodine value |
| IVPD | <i>In vitro</i> protein digestibility |
| J | |
| JECFA | Joint Food and Agriculture Organization/World Health Organization Expert Committees on Food Additives |
| L | |
| LBG | Locust bean gum |
| LD | Lethal dose |
| LDPE | Low density polyethylene |
| LDPEL | Low density polyethylene laminate |
| LET | Linear energy transfer |
| LEW | Liquid egg white |
| LEY | Liquid egg yolk |
| linac | Linear accelerator |
| LLDPE | Linear low density polyethylene |
| LOD | Limit of detection |
| LoDIF | Low dose rate irradiation facility |
| LODs | Limits of detection |
| LOOH | Lipid hydroperoxides |
| LPA | Low phytic acid |

(Continued)

| Abbreviation | Full Name |
|--------------|---|
| LPD | Lag phase duration |
| LWE | Liquid whole egg |
| M | |
| MAP | Modified atmosphere packaging |
| MCGC | Moisture of wet gluten content |
| MDCM | Mechanically deboned chicken meat |
| MeBr | Methyl bromide |
| MEHP | Mono(2 ethylhexyl)phthalate |
| MetMb | Metmyoglobin |
| MF | Mutant frequency |
| MG | Molds growth |
| MN | Micronucleus |
| MPD | Maximum population density |
| MRC | Mechanically recovered chicken |
| MRM | Mechanically recovered meat |
| MS | Mass spectrometry |
| MTG | Microbial transglutaminase |
| M_v | Viscosity average molecular weight |
| MW | Microwave |
| MW | Microwave cooking |
| M_w | Weight average molecular weight |
| MWI | Microwave irradiation |
| MYC | Mold and yeast counts |
| N | |
| NBD F | 4 Fluoro 7 nitro 2,1,3 benzoxadiazole |
| NDMA | Nitrosodimethylamine |
| NMR | Nuclear magnetic resonance |
| NPYR | Nitrosopyrrolidine |
| NSPs | Non starch polysaccharides |
| O | |
| OH Trp | Four hydroxytryptophan isomers |
| OP | Oxygen permeability |
| ORP | Oxidation reduction potential |
| OTA | Ochratoxin A |
| OTC | Over the counter |
| OVA | Ovalbumin |
| P | |
| P&T | Purge and trap |
| PA | Polyamide |
| PAM | Polyacrylamide |
| PB | Potassium benzoate |
| PB + SL | Potassium benzoate plus 2% sodium lactate |
| PC | Polycarbonate |
| PC scores | Principal component scores |
| PCL | Poly ϵ caprolactone |

(Continued)

xxiv Abbreviations

| Abbreviation | Full Name |
|---------------------|--|
| PCR | Polymerase chain reaction |
| PDA | Potato dextrose agar |
| PE | Polyethylene |
| PEG | Polyethylene glycol |
| PEPH | Pentafluorophenyl hydrazine |
| PET | Polyethylene terephthalate |
| PFP | Pulsed flame photometry |
| PG | Propylene glycol |
| PHB | Polyhydroxy butyrate |
| PIMF | Powdered infant milk formula |
| Pis | Photoinitiators |
| PKV | Peak viscosity |
| PL | Phospholipid |
| PLS | Partial least squares |
| PLST | Plasticized starch |
| PM | Postmortem |
| PMEs | Pectin methylesterases |
| PP | Polypropylene |
| PRA | Probabilistic risk assessment |
| PS | Polystyrene |
| PS | Potassium sorbate |
| PSB | Progressive saturation behavior |
| PSL | Photostimulated luminescence |
| PUFA/FSA | Polyunsaturated fatty acids/saturated fats |
| PV | Peroxide value |
| PVA | Polyvinyl alcohol |
| PVC | Polyvinyl chloride |
| PWL | Physiological weight loss |

Q

QRA Quantitative risk analysis

R

RDS Rapidly digestible starch
RF Radio frequency
ROK Republic of Korea
RP HPLC Reverse phase high performance liquid chromatography
RS Resistant starch
RTE Ready to eat
RT PCR Real time polymerase chain reaction
RVA Rapid Visco Analyzer
RY Red skin, yellow flesh
 R_z Gyration radius

S

SA Sodium alginate
SC Sodium carbonate
SCF Scientific Committee on Food
SDE Steam distillation solvent extraction

(Continued)

| Abbreviation | Full Name |
|--------------|---|
| SDS | Slowly digestible starch |
| SDS PAGE | Sodium dodecyl sulfate polyacrylamide gel electrophoresis |
| SEC | Size exclusion chromatography |
| SE HPLC | Size exclusion high performance liquid chromatography |
| SEM | Scanning electron microscopy |
| SFE | Supercritical fluid extraction |
| SGR | Specific growth rate |
| SL + SDA | Sodium lactate plus 0.1% sodium diacetate |
| SPC | Standard plate count |
| SPI | Soy protein isolate |
| SPME | Solid phase microextraction |
| SRD | Simulated retail display |
| SS | Sago starch |
| STPP | Sodium tripolyphosphate |
| T | |
| T_0 | Onset temperature |
| TAA | Triaxial angular accelerometer |
| TBA | Thiobarbituric acid |
| TBARS | Thiobarbituric acid reactive substances |
| TBC | Total bacterial count |
| T_c | Conclusion temperature |
| TCA | Trichloroacetic acid |
| TEG | Triethylene glycol |
| TGA | Thermogravimetric analysis |
| TI | Trypsin inhibitor |
| TIA | Trypsin inhibitor activities |
| Tinuvin P | 2,2 Hydroxy 5 tert octyl phenyl benzotriazole |
| TL | Thermoluminescence |
| T_m | Melting point |
| TMAH | Tetramethylammonium hydroxide |
| TMAN | Trimethylamine |
| T_p | Peak temperature |
| TPL | Total phospholipids |
| TRP | Tryptophan |
| TS | Tensile strength |
| TSP | Total aerobic plate count |
| TVBN | Total volatile base nitrogen |
| TVC | Total viable microbial counts |
| U | |
| UHMWPE | Ultra high molecular weight polyethylene |
| UHP | Ultra high hydrostatic pressure |
| USDA | U.S. Department of Agriculture |
| UTS | Ultimate tensile strength |
| UV | Ultraviolet |

(Continued)

Abbreviation

Full Name

V

VBN Volatile basic nitrogen

W

WAC Water absorption capacity

WAXS Wide angle X ray scattering

WG Wheat gluten

WGC Wet gluten content

WHO World Health Organization

WP White skin, purple flesh

WPC Whey protein concentrate

WPI Whey protein isolate

WS chitosan Water soluble chitosan

WTP Willingness to pay

WVP Water vapor permeability

WVTR Water vapor transmission rate

X

XPS X ray photoelectron spectroscopy

XRD X ray diffraction

Legislation on Food Irradiation

European Union, United States, Canada, and Australia

Ioannis S. Arvanitoyannis and Persephoni Tserkezou

1.1 Introduction

Irradiation is a physical treatment in which food is exposed to a defined dose of ionizing radiation and is used on more than 60 food types in more than 40 countries worldwide. Irradiation of food can control insect infestation, reduce the numbers of pathogenic or spoilage microorganisms, and delay or eliminate natural biological processes such as ripening, germination, or sprouting in fresh food. Like all preservation methods, irradiation should supplement rather than replace good food hygiene, handling, and preparation practices (Food Safety Authority of Ireland [FSAI], 2005).

In 1986, 1992, and 1998, the Scientific Committee on Food (SCF) expressed favorable opinions on irradiation of fruit, vegetables, cereals, starchy tubers, spices and condiments, fish, shellfish, fresh meats, poultry, camembert from raw milk, frog legs, gum arabic, casein/caseinates, egg white, cereal flakes, rice flour, and blood products. The SCF emphasized that food irradiation must not be used to cover negligence in handling foodstuffs or to mask their unsuitability for use as food (European Union [EU], 2007).

Food irradiation is the exposure of food to a form of energy called ionizing radiation. The technique is used to reduce the losses of spoilage and to control microbes and other organisms in food ([Confederation of British Industry, 2007](#)). Radiation is an energy form traveling through space (radiant energy) in a wave pattern and can either be naturally occurring (e.g., from the sun or rocks) or produced by man-made objects (e.g., microwaves and television sets). The frequency or wavelength of the energy waves produced by different sources distinguishes the different types and functionality of radiation, with high-frequency radiation of UV, X-rays, and gamma-rays posing the most significant risk to human health (FSAI, 2005). In specific cases, irradiation of food is permitted. In the EU, this is regulated by EU Directives 1999/2/EC and 1999/3/EC (EU, 2007).

Food irradiation in the United States is primarily regulated by the Food and Drug Administration (FDA, 1986) because it is considered a food additive. Other federal agencies that regulate aspects of food irradiation include the [U.S. Department of Agriculture/Food Safety and Inspection Service \(2006\)](#), which regulates meat and poultry products and fresh fruit; the Nuclear Regulatory Commission, which regulates safety of the processing facility; and the Department of Transportation, which regulates the safe transport of the radioactive sources. Each new food is approved separately with a guideline specifying a maximum dosage; in case of quarantine applications, the minimum dose is regulated. Packaging materials containing the food processed by irradiation must also undergo approval ([Wikipedia, 2008](#)).

1.2 EU Legislation

[Directive 1999/2/EC](#) (entry into force March 10, 1999) applies to the manufacture, marketing, and importation of foods and food ingredients, hereafter called “foodstuffs,” treated with ionizing radiation. It does not apply to: (i) foodstuffs exposed to ionizing radiation generated by measuring or inspection devices, provided that the dose absorbed is not greater than 0.01 Gy for inspection devices that utilize neutrons and 0.5 Gy in other cases, at a maximum radiation energy level of 10 MeV in the case of X-rays, 14 MeV in the case of neutrons, and 5 MeV in other cases; and (ii) the irradiation of foodstuffs that are prepared for patients requiring sterile diets under medical supervision. Member States may maintain existing authorizations concerning the treatment of foodstuffs with ionizing radiation provided that: (i) the treatment of the foodstuff concerned has been subject to a favorable opinion of the SCF; (ii) the overall average absorbed radiation dose does not exceed the limit values recommended by the SCF; and (iii) ionizing radiation and placing on the market are effected in accordance with this directive. Foodstuffs may be treated only by the following sources of ionizing radiation: (i) gamma rays from radionuclides cobalt-60 (^{60}Co) or cesium-137 (^{137}Cs); (ii) X-rays generated from machine sources operated at or below a nominal energy (maximum quantum energy) level of 5 MeV; and (iii) electrons generated from machine sources operated at or below a nominal energy (maximum quantum energy) level of 10 MeV. Food irradiation may be used only for the following purposes: (i) to reduce the incidence of foodborne disease by destroying pathogenic organisms; (ii) to reduce spoilage of foodstuffs by retarding or arresting decay processes and destroying spoilage organisms; (iii) to reduce loss of foodstuffs by premature ripening, germination, or sprouting; and (iv) to get rid of foodstuffs of organisms harmful to plant or plant products. Member States shall inform the commission of the competent authority or authorities responsible for: (i) prior approval of irradiation facilities; (ii) the allocation of an official reference number for approved irradiation facilities; (iii) official control and inspection; and (iv) withdrawal or modification of approval. The labeling of foodstuffs treated with ionizing radiation shall be governed by the specific provisions. Such a foodstuff may not be imported from a third country unless it complies with the conditions that

apply to those foodstuffs, is accompanied by documents showing the name and address of the facility that carried out the irradiation treatment, and was treated in an irradiation facility approved by the Community.

[Directive 1999/3/EC](#) (entry into force March 10, 1999) laid down the establishment of a Community initial positive list of food and food ingredients, which may be treated with ionizing radiation, together with the maximum doses authorized for the intended purpose. Treatment of the products in question with ionizing radiation may be carried out only in accordance with the provisions of the framework directive. The foodstuffs that may be treated with ionizing radiation are dried aromatic herbs, spices, and vegetable seasonings. The maximum overall average absorbed radiation dose should be 10 kilogray (kGy).

Regulation (EEC) No. 3954/87 (entry into force January 2, 1988) laid down the procedure for determining the maximum permitted levels of radioactive contamination of foodstuffs and of feeding stuffs that may be placed on the market following a nuclear accident or any other case of radiological emergency that is likely to lead to or has led to significant radioactive contamination of foodstuffs and feeding stuffs. For the purposes of this regulation, “foodstuffs” means products that are intended for human consumption either immediately or after processing, and “feeding stuffs” means products that are intended only for animal nutrition. In the event of the Commission receiving official information on accidents or on any other case of radiological emergency, substantiating that the maximum permissible levels are likely to be reached or have been reached, it will immediately adopt, if the circumstances so require, a regulation rendering applicable those maximum permissible levels. The period of validity of any regulation shall be as short as possible and shall not exceed 3 months. The regulation applies to baby foods, dairy products, liquid foodstuffs, and feedstuffs. There are maximum permitted levels for isotopes of strontium, notably ^{90}Sr ; isotopes of iodine, notably ^{131}I ; alpha-emitting isotopes of plutonium and transplutonium elements, notably ^{239}Pu and ^{241}Am ; and for all other nuclides with a half-life greater than 10 days, notably ^{134}Cs and ^{137}Cs .

In Regulation (EEC) No. 2219/89 (entry into force July 25, 1989) the conditions for exporting foodstuffs and feeding stuffs after a nuclear accident or any other radiological situation likely to lead to significant radioactive contamination of foodstuffs and feedstuffs are laid down. Foodstuffs and feed stuffs in which the level of radioactive contamination exceeds the relevant maximum permitted levels may not be exported. The Member States shall carry out checks to ensure that the maximum permitted levels are observed. Each Member State shall communicate to the Commission the fullest information on the application of this regulation, and in particular on any cases in which the maximum permitted levels have been exceeded. The Commission shall forward this information to the other Member States.

Regulation (EEC) No. 737/90 (entry into force April 1, 1990) applies to milk and dairy products. The accumulated maximum radioactive level in terms of ^{134}Cs and ^{137}Cs shall be: (i) 370 Bq/kg for milk and milk products and for foodstuffs intended for the special feeding of

infants during the first 4–6 months of life, which meet, in themselves, the nutritional requirements of this category of person and are put up for retail sale in packages that are clearly identified and labeled “food preparation for infants”; and (ii) 600 Bq/kg for all other products concerned. Member States shall check compliance with the maximum permitted levels set in this regulation, taking into account contamination levels in the country of origin. Checking may also include the presentation of export certificates. Depending on the results of the checks carried out, Member States shall take the measures required for regulation to apply, including the prohibition of release for free circulation, taking each case individually or generally for a given product. Each Member State shall provide the Commission with all information concerning the application of this regulation, notably cases of noncompliance with the maximum permitted levels. The Commission shall circulate such information to the other Member States. The Commission shall adopt measures that shall apply immediately. However, if these measures are not in accordance with the opinion of the committee, they shall be communicated by the Commission to the Council forthwith. In that event, (i) the Commission may defer application of the measures that it has decided for a period of not more than 1 month from the date of such communication and (ii) the Council, acting by a qualified majority, may take a different decision within the time limit referred to in the first indent.

Decision 87/600/EEC (entry into force March 21, 1988) shall apply to the notification and provision of information whenever a Member State decides to take measures of a widespread nature in order to protect the general public in case of a radiological emergency following: (a) an accident in its territory involving facilities or activities referred to in paragraph 2 from which a significant release of radioactive material occurs or is likely to occur; (b) the detection, within or outside its own territory, of abnormal levels of radioactivity that are likely to be detrimental to public health in that Member State; (c) accidents other than those specified in (a) involving facilities or activities from which a significant release of radioactive material occurs or is likely to occur; or (d) other accidents from which a significant release of radioactive material occurs or is likely to occur. The facilities or activities are the following: (a) any nuclear reactor, wherever located; (b) any other nuclear fuel cycle facility; (c) any radioactive waste management facility; (d) the transport and storage of nuclear fuels or radioactive wastes; (e) the manufacture, use, storage, disposal, and transport of radioisotopes for agricultural, industrial, medical, and related scientific and research purposes; and (f) the use of radioisotopes for power generation in space objects. The information shall include, as far as practicable and appropriate, the following: (a) the nature and time of the event, its exact location, and the facility or the activity involved; (b) the assumed or established cause and the foreseeable development of the accident relevant to the release of the radioactive materials; (c) the general characteristics of the radioactive release, including the nature, probable physical and chemical form, and the quantity, composition, and effective height of the radioactive release; (d) information on current and forecast meteorological and hydrological conditions, necessary for forecasting the dispersion of the radioactive release; (e) the results of environmental monitoring; (f) the results of

measurements of foodstuffs, feeding stuffs, and drinking water; (g) the protective measures taken or planned; (h) the measures taken, or planned, to inform the public; and (i) the predicted behavior over time of the radioactive release.

The titles, main points, and comments of the directives, regulations, and decision about food irradiation are summarized in [Table 1.1](#).

TABLE 1.1 EU Legislation Related to Food Irradiation

| Directive/Regulation | Title | Main Points | Comments |
|--|---|--|---|
| Directive 1999/2/EC (entry into force March 10, 1999) | The approximation of the laws of the Member States concerning foods and food ingredients treated with ionizing radiation | Application to the manufacture, marketing, and importation of foodstuffs treated with ionizing radiation. No application to food stuffs exposed to ionizing radiation generated by measuring or inspection devices under conditions. No application for the irradiation of foodstuffs that are prepared for patients. Specific limits of maximum dose of irradiation. | |
| Directive 1999/3/EC (entry into force March 10, 1999) | On the establishment of a Community list of foods and food ingredients treated with ionizing radiation | Establishment of a Community initial positive list of food and food ingredients that may be treated with ionizing radiation, together with the maximum doses authorized for the intended purpose. | |
| Regulation (EEC) No. 3954/87 (entry into force January 2, 1988) | Determination of maximum permitted levels of radioactive contamination of foodstuffs and of feedstuffs following a nuclear accident or any other case of radiological emergency | Maximum permitted levels of radioactive contamination of foodstuffs and of feedstuffs in case of nuclear accident. Any foodstuff or feedstuff that exceeds the maximum permitted levels is banned from the market disposal. | This regulation was amended by Regulation (EEC) No. 2218/89 (entry into force July 25, 1989). |

(Continued)

Table 1.1 EU Legislation Related to Food Irradiation—cont'd

| Directive/Regulation | Title | Main Points | Comments |
|---|--|--|--|
| Regulation (EEC) No. 2219/89 (entry into force July 25, 1989) | Special conditions for exporting foodstuffs and feedstuffs following a nuclear accident or any other case of radiological emergency | Conditions for exporting foodstuffs and feedstuffs after a nuclear accident. Any foodstuff or feedstuff that exceeds the maximum permitted levels is banned from exportation. | |
| Regulation (EEC) No. 737/90 (entry into force April 1, 1990) | Conditions governing imports of agricultural products originating in third countries following the accident at the Chernobyl nuclear power station | Application for products originating from third countries. Determination of maximum accumulated radioactivity of ^{134}Cs and ^{137}Cs . Control measures in case of noncompliance. | There are three regulations that amended this one. The last one is Regulation (EC) No. 806/2003 (entry into force June 5, 2003). |
| Decision 87/600/EC (entry into force March 21, 1988) | Community arrangements for the early exchange of information in the event of a radiological emergency | The Decision introduced the “Ecurie” system. Member States could provide information to the commission. The point of contact and the commission service designated to forward this information shall be available on a 24 h basis. | |

Adapted from Arvanitoyannis et al. (2005) and Arvanitoyannis (2008).

1.3 U.S. Legislation

The use of ionizing radiation for food preservation began in the early 1920s. During the 1950s and 1960s, the U.S. Army conducted research on low-dose and high-dose irradiation of military rations. These experiments prompted similar studies in other countries, and the interest in food irradiation has grown ever since. With proper application, irradiation can be an effective means of eliminating and/or reducing microbial and insect infestations along with the foodborne diseases they induce, thereby improving the safety of many foods as well as extending shelf life (Diehl, 1995).

Another technological aspect is food irradiation. Food irradiation is one means of food preservation that may not be familiar to many, but it has been in development since the early 20th century. If properly applied, irradiation can be an effective way to treat a variety of problems in our food supply, such as insect infestation of grains, sprouting of potatoes, rapid ripening of fruits, and

bacterial growth. However, it has not yet obtained a significant place in the U.S. food industry (Andress et al., 2005). On December 2, 1997, the FDA approved irradiation of meat products for controlling disease-causing microorganisms. The approval applies to fresh and frozen meats such as beef, lamb, and pork. The FDA concluded that irradiation is safe in reducing disease-causing microbes in or on meats, and that it does not compromise the nutritional quality of treated products. Disease-causing microorganisms that can be controlled by irradiation include the *Escherichia coli* O157:H7 and *Salmonella* species (Whitmore, 1997).

In U.S. Regulatory Requirements for Irradiating Foods (1986), Congress explicitly defined a source of radiation as a food additive. In a report accompanying the legislation, Congress explicitly stated, “Sources of radiation (including radioactive isotopes, particle accelerators, and X-ray machines) intended for use in processing food are included in the term ‘food additive’ as defined in this legislation.” In early work on food irradiation, sources of sufficiently high energies to induce radioactivity in foods were sometimes used. As research continued, sources whose energies are too low to induce detectable radioactivity were adopted by the international community. Therefore, this issue is of no concern when currently approved sources of radiation are used, but it must be addressed if other sources are being considered. Toxicological safety of typical food additives has traditionally been assessed by feeding large amounts of purified substances to laboratory animals and applying a safety factor to the highest dose of a tested substance that causes no toxic effects in any species. Moreover, standards for the conduct of such studies have evolved over time. For substances such as irradiated whole foods, which may become a large proportion of the diet, application of a 100-fold safety factor is impossible; attempts to exaggerate the amount of irradiated food in the diet have produced adverse nutritional effects that have confounded the results of many feeding studies. It is recommended that foods irradiated at doses of less than 1 kGy, or foods representing a very small fraction of the diet, should be exempt from requirements for toxicological testing because the types and amounts of radiolytic products would not show any toxic effects in well-conducted tests and their presence in the diet did not justify such testing. For foods irradiated at higher doses that were consumed in significant amounts, the Committee recommended a testing regime. Under the general labeling requirements, the FDA has found it necessary to inform the consumer that an irradiated food has been processed because irradiation, like other forms of processing, can affect the characteristics of food. For situations in which the processing is not obvious, such as whole foods that have been irradiated, the FDA requires that the label bear the radura symbol and the phrase “treated with radiation” or “treated by irradiation.” If irradiated ingredients are added to foods that have not been irradiated, no special labeling is required on retail packages because it is obvious that such foods have been processed. Special labeling is required for foods not yet in the retail market that may undergo further processing, however, to ensure that foods are not irradiated multiple times. In promulgating this regulation, the FDA advised that other truthful statements, such as the reason for irradiating the food, could be added to the label and encouraged food manufacturers to do so. Irradiation can cause chemical change in packaging,

as well as in food, and this can affect migration of the package components (or degradation products of those components) to food. Irradiation can cause cross-linking, which would likely reduce migration, but it can also cause decomposition to lower molecular weight entities with increased migration characteristics. Sometimes, irradiation has been used in the manufacture (or sterilization) of packaging before food is added. The FDA considers this use the same as any other manufacturing process, namely the final irradiated packaging must comply with the appropriate regulations and must not otherwise adulterate food.

In *Poultry Irradiation to Control Foodborne Illness* (USDA, 1990), the FDA approved as safe and effective the use of irradiation to control a major source of foodborne illness, the *Salmonella* and other illness-causing bacteria in chicken, turkey, and other fresh or frozen, uncooked poultry. Agency scientists described the process as the first approved process to “pasteurize” solid foods. As in the heat pasteurization of milk, the irradiation process greatly reduces but does not eliminate all bacteria. Thus, the processed poultry would be safe longer than unprocessed poultry but would still require refrigeration, just as pasteurized milk does. The agency emphasized that the process does not make the food radioactive and, as a result, does not expose consumers to radiation. In a notice published in the *Federal Register* (USDA, 1990), the FDA stated that it had determined that the use of gamma radiation, electron radiation, and X-ray to treat poultry or its parts, including mechanically deboned poultry, is safe at the levels being approved. The process could be used to control such foodborne pathogens as *Salmonella*, *Yersinia*, and *Campylobacter*, which are common in poultry and can cause human gastrointestinal illnesses through cross-contamination of other foods and via poultry when it is not thoroughly cooked. Approval limits the amount of radiation to be used to 3 kGy.

In *Irradiation in the Production, Processing, and Handling of Food* (1997), the FDA amended the food additive regulations to provide for the safe use of a source of radiation to treat refrigerated or frozen uncooked meat, meat byproducts, and certain meat food products to control foodborne pathogens and extend product shelf-life. Although proper handling practices and cooking to recommended internal temperatures are effective interventions in preventing foodborne illness associated with meat products, much effort has gone into the development of other interventions aimed at reducing microbial pathogens. Irradiation has been proposed as one such additional tool. The subject petition requests that the FDA amend the food additive regulations to authorize the use of ionizing radiation to “control microbial pathogens in raw, fresh-chilled, and frozen intact and comminuted edible tissue of the skeletal muscle and organ meat of domesticated mammalian food sources; with concomitant control of infectious parasites, and extension of acceptable edible/marketable life of chilled/refrigerated and defrosted meat through the reduction in levels of spoilage microorganisms.” The petition also specifies that the proposed foods are to be “primarily from bovine, ovine, porcine, and equine sources.” The petition requests that a maximum dose of 4.5 kGy be established for the irradiation of fresh (chilled, not frozen) meat, and that a maximum dose of 7.0 kGy be established for the irradiation of frozen meat. In addition, the FDA is establishing 4.5 kGy as the maximum permitted

dose for irradiation of refrigerated meat, meat by-products, and certain meat food products and 7.0 kGy as the maximum permitted dose for irradiation of frozen meat, meat byproducts, and certain meat food products.

Food irradiation is a technology for controlling spoilage and eliminating foodborne pathogens, such as *Salmonella* (Food Irradiation, 1999). The result is similar to conventional pasteurization and is often called “cold pasteurization” or “irradiation pasteurization.” Like pasteurization, irradiation kills bacteria and other pathogens that could otherwise result in spoilage or food poisoning. The fundamental difference between the two methods is the source of the energy they rely on to destroy the microbes. Whereas conventional pasteurization relies on heat, irradiation relies on the energy of ionizing radiation. The FDA emphasizes that no preservation method is a substitute for safe food handling procedures. The food irradiation process uses three types of ionizing radiation sources: ^{60}Co gamma sources, electron beam generators, and X-ray generators. ^{60}Co emits ionizing radiation in the form of intense gamma rays. “Gamma facilities” store it in stainless-steel capsules in underwater tanks. ^{60}Co has several advantages: (i) up to 95% of its emitted energy is available for use; (ii) it penetrates deeply; (iii) it yields substantial uniformity of the dose in the food product; (iv) it decays to nonradioactive nickel; and (v) it is considered to pose a low risk to the environment. However, its 5.3-year half-life offers disadvantages: ^{60}Co “pencils” require frequent replenishment, and treatment of the food is relatively slow. ^{137}Cs is a gamma source that is also used for irradiation. ^{137}Cs has a less penetrating gamma beam and a longer half-life, making it more suitable in certain circumstances. Electron beam facilities generate electron beams with an electron beam linear accelerator. (It works on the same principle as a television tube.) The electrons are concentrated and accelerated to 99% of the speed of light and energies of up to 10 MeV. Because electron beams are generated electrically, they offer certain advantages: (i) they can be turned on only as needed; (ii) they do not require replenishment of the source as does ^{60}Co ; and (iii) there is no radioactive waste.

In *Irradiation in the Production, Processing and Handling of Food* (2000), the FDA amended the food additive regulations to provide for the safe use of ionizing radiation for the reduction of *Salmonella* in fresh shell eggs. The FDA reviewed the relevant data and information submitted in the petition regarding the radiation chemistry of fresh shell eggs and data available in the agency’s files. Fresh whole eggs are composed mainly of water (75.3%), protein (12.5%), and lipid (10.0%). The radiation chemistry associated with these types of compounds is well-known. The FDA concluded that the concentrations and types of radiolysis products formed by the irradiation of eggs will be comparable to those products produced by the irradiation of other foods of similar composition, such as meat. In addition, the petitioner’s data support the conclusion that there is little change in the levels of individual fatty acids, or in the structure, digestibility, or biological value of protein, when shell eggs are treated with ionizing radiation up to 3 kGy. Most of the radiolysis products are either the same as or structurally similar to compounds found in foods that have not been irradiated, and they are formed in very small

amounts. In summary, an absorbed dose of 3 kGy for the irradiation of fresh shell eggs will result in only minimal changes in the macronutrients (protein, lipid, or carbohydrate), and the chemical composition of eggs will not differ in any significant manner from that of eggs that have not been irradiated. Included in the information considered by the FDA in the review of this petition are three studies conducted specifically on irradiated eggs. In the first such study, rats were fed a biscuit diet containing whole eggs irradiated at 5 kGy at a dietary level of 25% on a dry weight basis for 3 years (two generations). No adverse effects were observed compared to the control group fed a diet containing non-irradiated eggs. In the second study, mice and rats were fed a diet containing dried eggs irradiated at 93 kGy and irradiated pork brain. No effects were observed that were attributed to the irradiated food. In the third study, rats were fed canned eggs irradiated at 5 kGy in their diet for two generations. No effects were observed that were attributed to the irradiated diet. Based on the totality of evidence from all evaluated data and studies, the FDA concluded that the petitioned use of irradiation on fresh shell eggs raises no toxicity concerns.

The Federal Food, Drug and Cosmetic Act (2005) claims that the Director of the Center shall: (a) conduct postmarket risk assessment of drugs approved under this Act and of biological products licensed under the Public Health Service Act; (b) conduct and improve postmarket surveillance of approved drugs and licensed biological products using postmarket surveillance programs and activities, risk–benefit analyses, adverse event reports, the scientific literature, any clinical or observational studies, and any other resources that the Director of the Center determines appropriate; (c) determine whether a study is required under this subsection and consult with the sponsors of drugs and biological products to ensure that such studies are completed by the date, and according to the terms, specified by the Director of the Center; (d) contract, or require the sponsor of an application or the holder of an approved application or license to contract, with the holders of domestic and international surveillance databases to conduct epidemiologic and other observational studies; (e) determine, based on postmarket surveillance programs and activities, risk–benefit analyses, adverse event reports, the scientific literature, and any clinical or observational studies and any other resources that the Director of the Center determines appropriate, whether a drug or biological product may present an unreasonable risk to the health of patients or the general public, and take corrective action if such an unreasonable risk may exist; (f) make information about the safety and effectiveness of approved drugs and licensed biological products available to the public and health care providers in a timely manner; and (g) conduct other activities as the Director of the Center determines appropriate to ensure the safety and effectiveness of all drugs approved under this section and all biological products licensed under the Public Health Service Act. No later than 90 days after the date of enactment of the Food and Drug Administration Safety Act of 2005, the Director of the Center shall (I) review and publish a list in the *Federal Register* of any postmarketing studies outstanding on the date of enactment of the Food and Drug Administration Safety Act of 2005, and (II) as the Director determines appropriate,

require the sponsor of a study described in subparagraph (I) to conduct such study under this subsection.

Governmental regulation of irradiation of food varies considerably from country to country. Where irradiation is permitted, regulations are needed to license the plant, radioactive materials, or process; to ensure radiation safety, environmental security, and general health and safety during plant operation; and to provide for safe disposal of any hazardous materials at the end of the operation. Each country has adopted its own unique approach to the introduction, approval, and regulation of the technology for food production. Although there is an agreement among international committee experts that food is safe and wholesome for consumption after irradiation up to a dose of 10 kGy, there is no approval for irradiation of all foods up to this limit in any country. Most countries approve food irradiation on a case-by-case basis ([Morehouse and Komolprasert, 2004](#)).

The main points of U.S. legislation focused on food irradiation are summarized in [Table 1.2](#).

1.4 Canadian Legislation

The Canadian Food Inspection Agency (CFIA) is responsible for the enforcement of the regulations relating to the labeling of irradiated food products under the Food and Drug Act. The CFIA establishes inspection and testing programs to verify compliance by both domestic producers and importers. Irradiated foods that have not been approved for sale in Canada are not permitted entry, and the CFIA takes appropriate action if such products are illegally imported. Prepackaged foods that have been wholly irradiated display the international radiation symbol, along with a statement that the product has been irradiated. Food that is not prepackaged must have a sign with this information displayed beside the food (CFIA, 2002).

In the Food and Drug Act (2008), the symbol of the label of irradiated food required shall appear in close proximity on the principal display panel or on the sign to one of the following statements or a written statement that has the same meaning: “treated with radiation,” “treated by irradiation,” or “irradiated.” The symbol that indicates irradiated food shall: (i) have an outer diameter equal to or greater than the height of the numerical quantity and the declaration of net quantity of the package; and (ii) be not less than 5 cm. If an ingredient or component of a prepackaged product has been irradiated it shall, if the food constitutes 10% or more of the prepackaged product, be included in the list of ingredients and preceded by the statement “irradiated.” The label attached to a shipping container that contains any food referred to in the Act that has been subjected to the maximum permitted absorbed dose shall have the statement “Do not irradiate again.” Any advertising of an irradiated food referred to this Act shall identify the food as having been irradiated. No person shall sell milk, skim milk, partly skimmed milk, (naming the flavor) milk, (naming the flavor) skim milk, (naming the flavor) partly skimmed milk, skim milk with added milk solids, partly skimmed milk with

TABLE 1.2 U.S. Legislation Related to Food Irradiation

| Act | Entry into Force | Main Points | Comments |
|--|------------------|---|---|
| U.S. Regulatory Requirements for Irradiating Foods | 1986 | Legal requirements Safety issues (radiological, toxicological, microbiological, nutritional adequacy) Labeling of irradiating foods Packaging of irradiating foods. | There are two amendments (Federal Register 62(1997) and 64(1999)) for these requirements. |
| Poultry Irradiation to Control Food Borne Illness | 1990 | The FDA approved as safe and effective the use of irradiation to control a major source of foodborne illness, the <i>Salmonella</i> and other illness causing bacteria in chicken, turkey and other fresh or frozen, uncooked poultry. | |
| Irradiation in the Production, Processing and Handling of Food | 1997 | The petition requests that a maximum dose of 4.5 kGy be established for the irradiation of fresh (chilled, not frozen) meat. A maximum dose of 7.0 kGy can be established for the irradiation of frozen meat. | |
| Food Irradiation | 1999 | Food irradiation is the process of exposing food to ionizing radiation. Food irradiation is a technology for controlling spoilage and eliminating foodborne pathogens, such as <i>Salmonella</i> . FDA approved irradiation for the control of pathogenic microorganisms in red meats. | |
| Irradiation in the Production, Processing and Handling of Food | 2000 | The safe use of ionizing radiation for the reduction of <i>Salmonella</i> in fresh shell eggs An absorbed dose of 3 kGy for the irradiation of fresh shell eggs will result in only minimal changes in the macronutrients. | |
| Federal Food, Drug and Cosmetic Act | 2005 | Duties of the center for postmarket drug evaluation and research Publication of progress reports and completed studies Amount of penalties. | |

Adapted from Arvanitoyannis et al. (2006).

added milk solids, (naming the flavor) skim milk with added milk solids, (naming the flavor) partly skimmed milk with added milk solids, condensed milk, evaporated milk, evaporated skim milk, evaporated partly skimmed milk, milk powder, or skim milk powder in which the vitamin content has been increased by either irradiation or addition unless: (i) in the case of the addition of vitamin D, the menstrem containing the vitamin D contributes not more than 0.01% fat foreign to milk; and (ii) in cases in which the vitamin D content is increased by irradiation, the principal display panel of the label carries the statement “Vitamin D Increased” immediately preceding or following the name of the food, without intervening written, printed, or graphic matter. A manufacturer who sells a food that has been irradiated shall keep on his or her premises, for at least 2 years after the date of the irradiation, a record containing the following information: (i) the food irradiated and the quantity and lot numbers of the food; (ii) the purpose of the irradiation; (iii) the date of the irradiation; (iv) the dose of ionizing radiation absorbed by the food; (v) the source of the ionizing radiation; and (vi) a statement indicating whether the food was irradiated prior to the irradiation by the manufacturer and, if so, the information referred to in paragraphs (i)–(v) in respect of that prior irradiation. Every person who imports a food that is intended for sale in Canada that has been irradiated shall keep on his or her premises a record of the information referred to this Act for at least 2 years after the date of importation. A request that a food be added or a change made to the table to this Division shall be accompanied by a submission to the Director containing the following information: (i) the purpose and details of the proposed irradiation, including the source of ionizing radiation and the proposed frequency of and minimum and maximum dose of ionizing radiation; (ii) data indicating that the minimum dose of ionizing radiation proposed to be used accomplishes the intended purpose of the irradiation and the maximum dose of ionizing radiation proposed does not exceed the amount required to accomplish the purpose of the irradiation; (iii) information on the nature of the dosimeter used, the frequency of the dosimetry on the food, and data pertaining to the dosimetry and phantoms used to ensure that the dosimetry readings reflect the dose absorbed by the food during irradiation; (iv) data indicating the effects, if any, on the nutritional quality of the food, raw and ready-to-serve, under the proposed conditions of irradiation and any other processes that are combined with the irradiation; (v) data establishing that the irradiated food has not been significantly altered in chemical, physical, or microbiological characteristics to render the food unfit for human consumption; (vi) where the Director so requests, data establishing that the proposed irradiation is safe under the conditions proposed for the irradiation; (vii) the recommended conditions of storage and shipment of the irradiated food, including the time, temperature, and packaging, and a comparison of the recommended conditions for the same food that has not been irradiated; (viii) details of any other processes to be applied to the food prior to or after the proposed irradiation; and (ix) such other data as the Director may require to establish that consumers and purchasers of the irradiated food will not be deceived or misled as to the character, value, composition, merit, or safety of the irradiated food. The main points of this Act are given in [Table 1.3](#).

TABLE 1.3 Canadian Legislation Related to Food Irradiation

| Act | Entry into Force | Main Points |
|-------------------|------------------|---|
| Food and Drug Act | 2008 | Labeling of irradiating foods. No person shall sell a number of products in which the vitamin content has been increased by either irradiation or addition. Every person who imports a food that is intended for sale in Canada that has been irradiated shall keep on his or her premises a record of the information. |

1.5 Australian Legislation

Food irradiation is a food preservation process and a quarantine measure (Food Irradiation, 2003). Food processors use it to kill bacteria that cause food decomposition and food poisoning. Those bacteria include the parasites, moulds, and yeasts that spoil food and also salmonella and campylobacter that cause illness. Food can only be irradiated if there is no other safe method available. Any irradiated food must go through a strict safety assessment by Food Standards Australia New Zealand (FSANZ) and, if approved, must be labeled as having been treated by radiation. To date, in Australia and New Zealand, only herbs and spices, herbal teas, and some tropical fruits have been approved to be irradiated. Under the Food Standard covering the irradiation of food in Australia and New Zealand, this energy can be in the form of gamma rays from ^{60}Co , machine-generated X-rays, or an electrically generated electron beam. All food preservation methods, such as canning and freezing, change the composition of the food in some way. Some change the taste, appearance, texture, and nutritional value of the food more than others do. When food is cooked or preserved in any way, its composition changes and new compounds form. Irradiation causes minimal changes to the chemical composition of the food, although many of the composition changes that do occur are similar to those formed when food is cooked or preserved in more traditional ways. However, with irradiation, different doses have different effects. At low doses, irradiation lengthens the shelf life of fruits such as strawberries by destroying moulds, and it inhibits sprouting in vegetables such as potatoes. At higher doses, irradiation helps to kill the bacteria and pathogens that cause food poisoning. More than 40 countries allow the use of irradiation for food safety reasons. Most of the frogs legs sold in France, for example, are irradiated. Most of the herbs and spices sold in South Africa have been irradiated, whereas in Thailand there is growing demand for irradiated Nham, a fermented pork sausage that is usually eaten raw.

According to Irradiation of Tropical Fruit (2003), FSANZ has approved an application seeking permissions to irradiate a range of tropical fruits (breadfruit, carambola, custard apple, litchi, longan, mango, mangosteen, papaya, and rambutan) as a phytosanitary measure. The safety of irradiating tropical fruits has been examined by FSANZ. The available studies

on fruits indicate that there are no safety concerns. There are no changes to the composition of the fruits following irradiation that are likely to cause public health and safety concerns. Irradiation of tropical fruits up to a maximum of 1 kGy employing good manufacturing/irradiation practices is considered safe for Australian and New Zealand consumers. When the nutritional changes induced by irradiation are considered in conjunction with the FSANZ analysis of dietary intake of nutrients, the irradiation of tropical fruits is found not to have a significant nutritional effect on the diet of the Australian and New Zealand populations. The tropical fruits being considered for irradiation are not significant sources of certain vitamins, including beta-carotene, folate, vitamin C, and vitamin B₁, within the context of the total dietary intake.

The Food Additives Guide (2005) makes clear that food additives are an important component of our food supply. By using food additives, we can enjoy a wide variety of foods throughout the year. They also have an important role in ensuring that our food lasts longer and is easier to use. There are good reasons for the use of food additives. They can be used to improve the keeping quality or stability of a food. For example, sorbitol, humectant (E420), may be added to mix dried fruit to maintain the moisture level and softness of the fruit preserve food when this is the most practical way of extending its storage life. Sulfur dioxide, preservative (E220), is added to some meat products such as sausage meat to prevent the bugs that cause food poisoning from growing and to improve the taste or appearance of a processed food. Lecithin, emulsifier (E322), may be added to margarine to help maintain texture. Additives are used in processed foods in relatively small quantities. Many substances used as additives also occur naturally, such as vitamin C or ascorbic acid (E300) in fruit and lecithin (E322) in eggs or soybeans. Some food additives have more than one use. Food additives are listed according to their functional or class names: (i) colorings add or restore color to foods; (ii) color retention agents retain or intensify the color of a food; (iii) preservatives help protect against deterioration caused by microorganisms; (iv) artificial sweetening substances impart a sweet taste for fewer kilojoules/calories than sugar; (v) flavor enhancers improve the flavor and/or aroma of food; (vi) flavorings restore taste losses due to processing, maintain uniformity, and make food more palatable; (vii) anti-caking agents keep powdered products such as salt flowing freely when poured; (viii) emulsifiers help to prevent oil and water mixtures separating into layers; (ix) food acids help maintain a constant level of sourness in food; (x) humectants prevent foods such as dried fruits from drying out; (xi) mineral salts improve the texture of foods, such as processed meats; (xii) thickeners and vegetable gums improve texture and maintain uniform consistency; (xiii) stabilizers maintain the uniform dispersion of substances in a food; (xiv) flour treatment agents are substances added to flour to improve baking quality or appearance; (xv) glazing agents impart a shiny appearance or provide a protective coating to a food; and (xvi) propellants are gases that help propel food from a container. The main points of Australian legislation are shown in [Table 1.4](#).

TABLE 1.4 Australian Legislation Related to Food Irradiation

| Act | Entry into Force | Main Points |
|-------------------------------|------------------|---|
| Food Irradiation | 2003 | Irradiation of food in Australia and New Zealand, this energy can be in the form of gamma rays from ^{60}Co , machine generated X rays, or an electrically generated electron beam. At low doses, irradiation lengthens the shelf life of fruits such as strawberries by destroying moulds and inhibits sprouting in vegetables such as potatoes. At higher doses, irradiation helps to kill the bacteria and pathogens that cause food poisoning. |
| Irradiation of Tropical Fruit | 2003 | The tropical fruits that are irradiated are breadfruit, carambola, custard apple, litchi, longan, mango, mangosteen, papaya, and rambutan. Irradiation of tropical fruits up to a maximum of 1 kGy employing good manufacturing/irradiation practices is considered safe for Australian and New Zealand consumers. |
| Food Additives Guide | 2005 | Use of food additives. Food additives are listed according to their functional or class names. Intolerance and food additives. Food additive safety. |

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Food Irradiation Techniques

Kyriakos A. Riganakos

2.1 Introduction

Three types of ionizing radiation are used in commercial radiation to process products such as foods and medical and pharmaceutical devices (International Atomic Energy Agency [IAEA], 1982): radiation from high-energy gamma rays, X-rays, and accelerated electrons. In accordance with the Codex General Standard for Irradiated Foods (Codex Alimentarius Commission, 2003), only these ionizing rays are authorized to be used in food irradiation applications. These types of radiation are called “ionizing” because their energy is high enough to dislodge electrons from atoms and molecules and to convert them to electrically charged particles called ions. Ionizing radiation may originate from different sources:

- Gamma rays, which are produced by radioactive substances (called radioisotopes). The approved sources of gamma rays for food irradiation are the radionuclides cobalt-60 (^{60}Co ; the most common) and cesium-137 (^{137}Cs). They contain energy levels of 1.17 and 1.33 MeV (^{60}Co) and 0.662 MeV (^{137}Cs).
- Electron beams, which are produced in accelerators, such as in a linear accelerator (linac) or a Van de Graaff generator at nearly the speed of light. Maximum quantum energy is not to exceed 10 MeV.
- X-rays or decelerating rays, which can be likewise produced in accelerators. Maximum quantum energy of the electrons is not to exceed 5 MeV.

Gamma rays and X-rays form part of the electromagnetic spectrum, like radio waves, microwaves, ultraviolet, and visible light rays. Gamma rays and X-rays are in the short-wavelength, high-energy region of the spectrum. Both gamma and X-rays can penetrate foods to a depth of several decade centimeters.

Energies from the previously mentioned radiation sources are too low to induce radioactivity in any material, including food.

There is wide expertise in the design, building, and operation of both radionuclide and electrical machine irradiation facilities (Leemhorst and Miller, 1990).

Radionuclide facilities are currently used for the treatment of food and for nonfood applications, such as sterilization of medical supplies and for pharmaceutical, cosmetic, and veterinary products.

Electron accelerators are used in the manufacture of certain packaging materials (e.g., cling film) and in the treatment of plastic wire insulation to improve its properties.

Commercial irradiation facilities for food are available in approximately 50 countries.

Food irradiation plants may be operated in batch or continuous mode. Batch facilities are considered to be more flexible and able to accommodate a wide range of doses (World Health Organization, 1988). Continuous facilities are better able to accommodate large volumes of food products, especially when treating a single food at a specific dose.

Mobile irradiators have been used in research for the treatment of seasonal food, such as fruits and vegetables, and for fish irradiation onboard ships. A comparison of radionuclide irradiators and electron accelerators is shown in Table 2.1.

A food irradiation facility is composed of the following elements:

- A source of radiation (i.e., radionuclide or electron beam).
- Biological shielding to protect personnel operating the facility from radiation exposure.
- A carrier or conveyor system to take the food product into the vicinity of the source for processing.
- An air evacuation system.

TABLE 2.1 Comparison of Radionuclide Irradiators and Electron Accelerators

| Radionuclide Irradiators | Electron Accelerators |
|--|---|
| Good penetration power of gamma rays; can be used to treat food in large packaging units | Relatively limited penetration power (5–8 cm). |
| Low dose rate | High, variable dose rate; allows high throughput (e.g., grain). |
| High reliability | More sensitive to breakdown; need for specialized personnel for regular maintenance. |
| Need to replenish radionuclide source | High requirements for power and cooling Machine can be switched off. Small units of equipment could be integrated into a production line. |

From Fink and Rehmann (1994).

- A safety interlock/control console system, which ensures that conveyor movement occurs when the source is exposed or the machine is switched on (no conveyor movement when the source is in a “safe” position or the machine is turned off) (Farkas, 1988).

The food irradiation facilities do not become radioactive and do not create radioactive waste. ^{60}Co is manufactured in a commercial nuclear reactor by exposing nonradioactive cobalt to intense radiation in the reactor core. The cobalt sources used in irradiation facilities decay by 50% in 5 years and therefore require periodic replacement. The sources are removed from the irradiator when the radioactivity falls to a low level, usually between 6 and 12% of the initial level (this takes 16–21 years for ^{60}Co). The small radioactive cobalt “pencils” are shipped back to the original nuclear reactor. The shipment occurs in special hardened steel canisters that have been designed and tested to survive crashes without breaking. Cobalt is a solid metal, and even if something should break, it will not spread through the environment. ^{60}Co may also be disposed of as a radioactive waste. Given its relatively short half-life (5 years) and its stable metallic form, the material is not considered to be a problematic waste. Electron beam and X-ray facilities do not use or create radioactive substances (IAEA, 1992).

2.2 Comparison of Sources

Gamma ray, electron beam, and X-ray sources are used for a variety of industrial processes. Gamma radiation is preferred because it can penetrate deeply, whereas “e-beams” penetrate food to a depth of only $1\frac{1}{2}$ in (3.80 cm). X-rays are capable of irradiating thicker items, but the process is extremely expensive and energy intensive. Large amounts of food would have to be irradiated to make it affordable.

2.2.1 Comparison between Gamma and Electron Beam Facilities

Both types of facilities have many common characteristics because they result in ionizing radiation. They also have some differences regarding the operation of the facilities. There are differences in safety, the procedures of malfunction and maintenance, product configuration, and operations.

A characteristic difference is that a ^{60}Co source can never be turned off. This source must be transported, loaded into the facility, and always handled with a biological shield to protect the workers from exposure.

There is the possibility that a ^{60}Co pencil could become defective and some of the ^{60}Co could escape from the pencil. Because ^{60}Co is not soluble in water, the released material can be isolated and vacuumed out of the water pool. An immovable source rack or a leaking pencil are rare events, but they are possibilities that can be remedied, although with some difficulty.

In an electron beam facility, electricity is the source generating electrons. Therefore, there is no inherent radioactivity in the facility, and the machine can be transported and installed without a biological shield. Malfunctions trip electrical relays to the high-voltage source, causing electron generation to stop immediately.

Considerably more maintenance is required in the various systems of a linear accelerator facility than is needed for a gamma facility (Olson, 1995).

Compared to gamma sources, electron beam sources are more efficient in the utilization of electrons because they are directed at the product rather than emitted in all directions.

2.3 Gamma Ray Sources

Gamma rays with specific energies normally come from the spontaneous disintegration of radionuclides. Naturally occurring and man-made radionuclides, also called radioactive isotopes or radioisotopes, are unstable and emit radiation as they spontaneously disintegrate, or decay, to a stable state. The radionuclide almost always used for the irradiation of food by gamma rays is ^{60}Co . It is produced by neutron bombardment in a nuclear reactor of the metal cobalt-59 and then doubly encapsulated in stainless-steel “pencils” to prevent any leakage during its use in a radiation plant. This technology has been used routinely for more than 30 years to sterilize medical, dental, and household products. It is also used for radiation treatment of cancer. Radioactive substances emit gamma rays all the time. When not in use, the gamma ray source is stored in a pool of water that absorbs the radiation harmlessly and completely. To irradiate food or some other product, the source is pulled out of the water into a chamber with massive concrete walls that keep any rays from escaping. Medical products or foods to be irradiated are brought into the chamber and are exposed to the rays for a defined period of time. After it has been used, the source is returned to the water tank.

Gamma rays are ionizing rays. When ionizing rays have an impact on the material, they can pick electrons from the atoms. Free electrons can take part in chemical reactions or destroy DNA molecules from the living organisms. This process is the basis for killing the microorganisms by irradiation.

^{60}Co has the following advantages (from http://www.epa.gov/rpdweb00/sources/food_irrad.html#cobalt60):

- Up to 95% of its emitted energy is available for use.
- It penetrates deeply.
- It yields substantial uniformity of the dose in the food product.
- It decays to nonradioactive nickel.
- It is considered to pose a low risk to the environment.

However, because of its 5.3-year half-life, it has the following disadvantages:

- ^{60}Co pencils require frequent replenishment.
- Treatment of the food is relatively slow.

In the ^{60}Co process, there are four different categories of irradiators with regard to the way the isotope source is stored and shielded:

- Category I—Small sources used for various research activities.
- Category II—Air storage and air irradiation; not used for food.
- Category III—Water shielding and irradiation under water.
- Category IV—Water storage but moves into air to irradiate.

For category IV irradiators (most gamma ray facilities are of this type), trays of food are placed inside tall towers mounted on remote-controlled tracks. An operator in a control room moves the food-carrying towers into a chamber protected by 6 m thick concrete walls, where a rack of radioactive ^{60}Co pencils is immersed in a pool of water 6 m deep. This rack of cobalt rises out of the water, and the aluminum towers containing the food rotate around it (see <http://www.foodandwaterwatch.org/food/foodirradiation/irradiation-facts/irradiation-facilities-1>).

The commercial use of gamma radiation to sterilize health care products began in the late 1950s, and the technology of processing products with gamma radiation is now well entrenched. With increasing experience and confidence in the technology, more applications are being investigated and more facilities being built. This expansion in the industrial processing calls for not only larger irradiators but also novel designs to optimize each new application. Manufacturers of irradiators have taken up the challenge to keep pace with the expansion of the industry. Currently, several manufacturers offer a variety of designs that are optimized specifically for different applications, whether in the field of food irradiation or for environmental applications. This in turn has given impetus to the radiation processing industry regarding the types of applications and the size of irradiators.

There is an important difference among food irradiation facilities and medical facilities. Food irradiation facilities usually use approximately 100 PBq (3 MCi) of cobalt. Nuclear medicine facilities use various materials with only a few terabecquerel to a few hundred terabecquerel.

The current inventory of ^{60}Co in all the irradiation facilities throughout the world amounts to more than 250 million Ci. Thus, it is important to realize the vital role that nuclear power reactors play in providing countless benefits through the use of cobalt in medical as well as industrial radiation applications (Masefield, 2004). Also, more than 3 million cubic meters of

single-use medical devices are sterilized by gamma radiation each year. The wide use of this method of sterilization is a result of the lethal effects of ionizing radiation on microbial populations and the penetrative powers of ^{60}Co .

More than 200 gamma ray facilities are used for various industrial applications, mainly for sterilizing medical devices and for food irradiation. Gamma rays from ^{60}Co and ^{137}Cs are allowed by the U.S. Food and Drug Administration and by international standards for food irradiation (CFR, 1986; *Codex Alimentarius Commission*, 2003). However, ^{137}Cs is seldom used. The large ^{137}Cs sources are not readily available due to practical difficulties in handling this isotope. Cesium chloride is highly soluble in water and the use of ^{137}Cs in this form is not recommended. ^{137}Cs is produced as a result of uranium fission and may remain as a by-product of nuclear fuel reprocessing. The use of ^{137}Cs has been limited to small self-contained, dry-storage irradiators, used primarily for the irradiation of blood and for insect sterilization. Currently, all industrial radiation processing facilities employ ^{60}Co as the gamma radiation source.

The main commercial suppliers of encapsulated ^{60}Co sources are located in Canada (MDS Nordion) and the United Kingdom (REVISS).

According to data from IAEA, on the total cumulative sale of ^{60}Co by all suppliers during the past 25 years, it can be estimated that the installed capacity of cobalt is increasing at the rate of approximately 6% per year. It is interesting to note that the worldwide use of disposable medical devices is increasing at approximately the same rate (5 or 6%), which seems to be driving the growth in the sale of cobalt. The kinds of applications that use gamma radiation have also steadily increased, from cross-linking/polymerization and sterilization of health care products to food irradiation and environmental applications such as flue gases, wastewater, and sludge treatment. Emerging applications could be in the fields of nanomaterials, structure engineered materials (sorbents, composites, ordered polymers, etc.), and natural polymers. Some of the irradiators are operated for a single product/process, whereas others are multi-purpose. An IAEA survey showed that 85% of the gamma irradiators treat health care products for the purpose of sterilization. A similar percentage of irradiators treat food and agricultural products for various end objectives. Approximately 50% of the units process pharmaceutical products, including raw materials, for the purpose of sterilization or microbial load reduction, whereas approximately 30% treat polymers, including cables and tubings for property modification (IAEA, 2004).

2.3.1 Gamma Irradiation Processes

All irradiation facilities have some common characteristics. A gamma irradiation facility consists of an irradiation source, irradiation cell (biological shield), source panel, source storage water pool, product carriage and source transition system, warehouse, and automatic

control system. Product transport systems are classified into four categories: tote box, carrier, pallet carrier, and pallet conveyor systems (Farkas, 1988).

The irradiation process occurs in the irradiation cell protected by a biologic shield made of 2 m thick concrete walls. When the irradiator is off, the source panel is kept in a 6 m deep water pool. To switch on the device to the radiation position, the source is pulled by means of a pneumatic piston and placed between the tote boxes filled with products. The products to be exposed to irradiation are put inside the boxes in their own packages and taken to the irradiation cell by a conveyor system. The boxes filled with products are moved around the source in a stop-and-go manner and radiated in different positions, and then removed from the radiation room automatically by the conveyor system. The radiation device and conveyor system are completely controlled by a computer. A pallet-type ^{60}Co irradiator is shown in Figure 2.1.

2.3.1.1 Process control

The irradiation process is realized by means of a powerful and reliable computer system (programmable logic control). Each stage of the irradiation process is controlled in a very sensitive manner, and if an abnormal situation occurs, the irradiator turns off automatically and gives audio and visual alarms. Furthermore, each stage is recorded automatically.

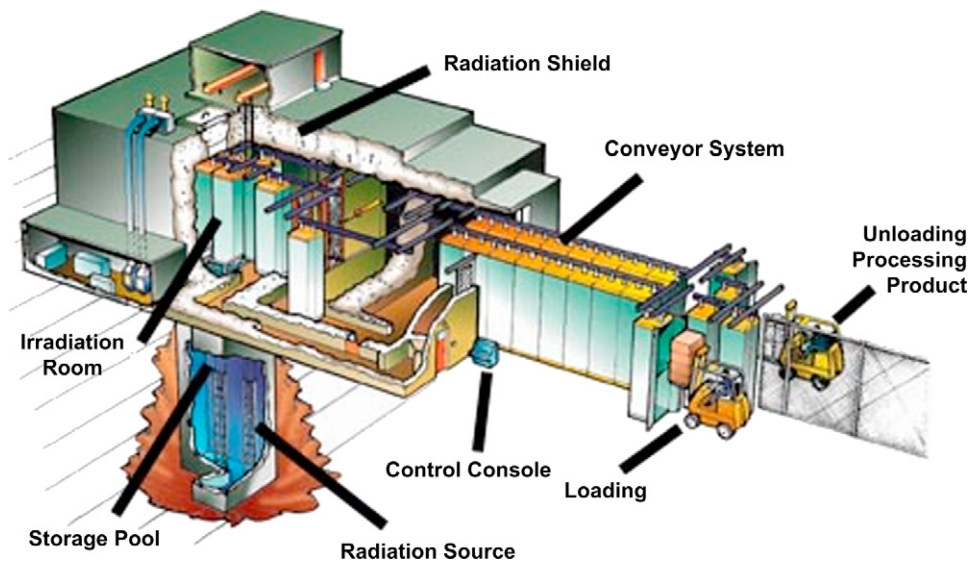


Figure 2.1: Pallet-type commercial ^{60}Co irradiator facility (courtesy of Nordion International Inc., Ontario, Canada).

2.3.1.2 Product transportation system (conveyor and source transition system)

The products to be processed are placed inside the tote boxes on the conveyor in their own packages and are sent to the irradiation room by means of the conveyor. The boxes full of products are moved around the source by means of pneumatic pistons and exposed to gamma irradiation (see <http://www.gammapak.com/english/index.html>).

Movement of the carriers on the conveyor system in the irradiation chamber is typically by a “shuffle and dwell” method. With this method, a carrier is moved to a position, held there for a specified period of time, and then moved to the next position, where it is held for the same period of time. This process continues until a carrier has occupied each position around the source rack. The speed at which the carriers are moved from one position to the next and the time each carrier dwells in each position depend on the receiving dose and the number of carriers on the source rack. Over time, the speed and dwell times are changed due to decay of the source or replenishment of the source (Olson, 1995; Woods and Pikaev, 1994).

After the irradiation process, the tote boxes full of products are automatically taken out by conveyor and stored in the irradiated product area. The volume of the tote boxes made of proper material is several hundred liters, and each can carry loads up to 125 kg.

2.3.1.3 Radiation source and source rack

The radiation source is either in the irradiation room (during irradiation of the product) or in its shielded storage room (generally located under the irradiation room), which could be dry or wet. Enough shielding is provided by solid wall (dry) storage or water (wet) storage so that personnel can work in the irradiation room (e.g., for maintenance) when the source is in the storage room. Water has several desirable characteristics as a shielding material. It is an easily available liquid that is convenient to circulate for heat transfer, and it is transparent. For a wet storage facility, nearly all materials used to construct the source rack, guide system, and source containers are stainless steel to eliminate galvanic corrosion. Most ^{60}Co sources are in the form of pencils with a length of 452 mm (17.8 in) and a diameter of 11.1 mm (0.44 in). The nickel-plated cobalt slugs are doubly encapsulated in zircaloy tubes (MDS Nordion). The activity in one pencil can be 14.25 kCi or 527 TBq. Each pencil has a different amount of gamma-producing power, depending on its age. Commercial facilities generally have more than 1 million Ci of ^{60}Co . After the ^{60}Co pencils are produced, they are transported to the irradiation facility in a large cask from depleted uranium. A cask can carry up to 200,000 Ci of ^{60}Co . The pencils are loaded into flat, vertical racks (Figure 2.2). These racks are lowered into deep water-filled pools when personnel need to enter the treatment room. They are raised above the pool water to irradiate product containers passing by the source rack on a conveyor. The treatment room is

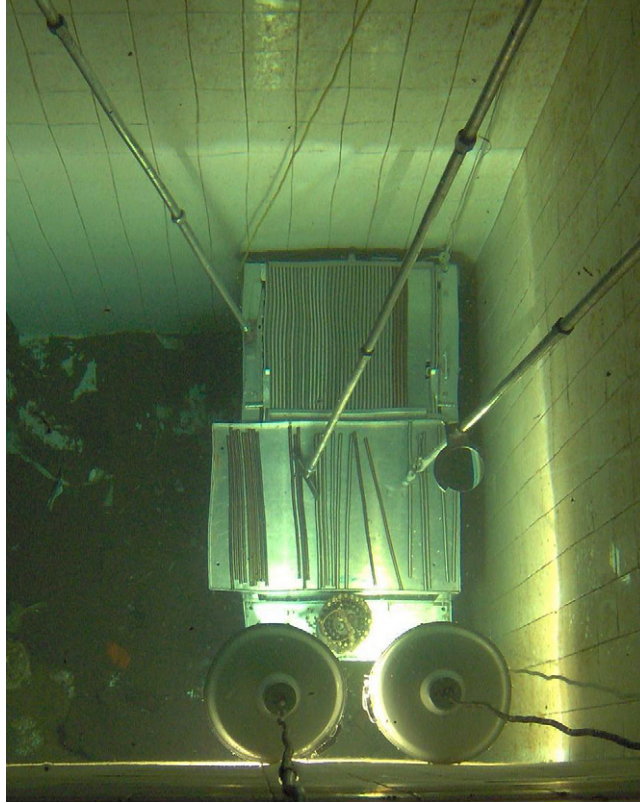


Figure 2.2: The source rack of a ^{60}Co .

surrounded by a thick concrete shield, which protects operating personnel from the gamma radiation when the source rack is in the raised position (Cleland, 2006).

The source rack consists of a stainless-steel frame with dimensions of 250×300 cm and 20 rectangular intermediate modules. Forty source pencils measuring 45 cm long and with a diameter of 0.81 cm can be placed on each module. Metallic formed ^{60}Co slugs used as gamma sources are placed in these source pencils. Source pencils are double encapsulated in stainless-steel tubes, and both ends are welded in a leakage-proof manner.

Unstable ^{60}Co isotope can be activated by placing metallic slugs of stable ^{59}Co in a nuclear power reactor. The absorption of a neutron, released by the fission of ^{235}U , changes ^{59}Co to ^{60}Co . The ^{60}Co isotope emits two gamma rays simultaneously with energy levels of 1.17 and 1.33 MeV, respectively, and is transformed to a stable ^{60}Ni atom. It also emits one low-energy beta ray (electrons) with a maximum energy of 0.32 MeV. ^{60}Co has a half-life of 5.3 years, so the activity decays by 12.35% per year. The total activity in the irradiation

facility is replenished by adding new sources when needed. Older sources are usually kept in the facility for up to four half-lives or approximately 20 years before being replaced. Because beta particles cannot pass through stainless steel, the irradiation process is realized only by the gamma rays. The irradiated products never become radioactive, no matter how long the irradiation period. The energy level of the gamma rays emitted by ^{60}Co isotopes is not enough to make any material radioactive. Therefore, no treated product by gamma irradiation process will be radioactive.

2.3.1.4 Gamma radiation

Gamma rays are electromagnetic energy, as are radio waves, TV waves, microwaves, visible light, and X-rays. On the other hand, the wavelength and energy of all these ray types are different. Microwaves have enough energy to cause the molecules to move, resulting in heat energy. Gamma rays have more energy compared to the other types of rays; they can diffuse inside the materials easily. They might knock off electrons from the atoms or molecules while they are passing through the materials. As a result, electrically charged particles (i.e., ions) are formed. The energy stored within the material is called “absorbed energy.” A 1-kGy ray dose equals 1 kJ/kg of energy. If this energy is represented as heat energy, 10-kGy absorbed doses can increase the temperature of 1 kg of water by 2.5°C.

2.3.1.5 Irradiation cell (biological shield)

This is the shielded room in which the irradiation process is realized. When the irradiation facility is operating, the ^{60}Co source rack is taken out of the water pool and placed among the boxes full of products. To avoid any radiation leakage out of the irradiation cell, the walls, ceiling, and floor of the irradiation cell are made of 2 m thick concrete. These concrete barriers eliminate the gamma radiation formed by 4.0 MCi ^{60}Co sources and decrease the dose to an acceptable level for the employees and the environment. These protective concrete barriers are called biological shields. The thickness of the biological shield depends on the activity of the employed cobalt source, and it is designed to meet the requirements of the International Radiation Protection Regulations. The personnel and product entry doors of the irradiation cell can be accessed after a maze (labyrinth) for protection purposes.

2.3.1.6 Source storage pool

To turn the irradiation process off in the irradiator, the ^{60}Co source panel is submerged into a water pool. The water pool is approximately 6 m deep. The large depth of the pool is needed because the pencils are removed from the cask inside the pool by the facility personnel standing above the pool. The ^{60}Co source continues emitting gamma radiation within the water. On the other hand, the 3.2 m thick water mass from the upper part of the source rack

does not allow the gamma lights to reach into the irradiation cell. In this way, personnel can enter the irradiation cell without being exposed to the gamma rays and carry out maintenance and repair work safely.

Auxiliary systems are used, including equipment to deionize the water in the pool and remove excess heat and air handling systems to vent the ozone produced from the irradiation of oxygen in the air (Farkas, 1988).

2.3.1.7 Product storage area

The product storage area in the gamma irradiation facility consists of two parts: an unprocessed products storage area and a processed products storage area. The products to be irradiated are taken to the unprocessed products storage area, and after they are prepared for the irradiation process they are loaded on the conveyor. After the irradiation process, the treated products are taken to the processed products storage area for loading into vehicles. Also, all facilities have laboratories suitable for carrying out dosimetry measurements. Some facilities also have a microbiology laboratory or a materials testing laboratory.

2.4 Electron Beam Sources

The e-beam is a stream of high-energy electrons, propelled out of an electron gun. This electron gun apparatus is a larger version of a standard television tube. The e-beam generator can be switched on or off simply by “pushing a button.” A treatment of food with ionizing electrons is often more easily accepted because there are no radioactive substances in the process. The electrons can penetrate food only to a depth of 3 cm, or slightly more than 1 in, so the food to be treated must be no thicker than this for it to be treated all the way through. This is a disadvantage of electron radiation compared with gamma rays produced by radionuclides. Two opposing beams can treat food that is twice as thick. E-beam medical sterilizers have been in use for at least 15 years.

Because e-beams are generated electrically, they offer the following advantages (from http://www.epa.gov/rpdweb00/sources/food_irrad.html#cobalt60):

- They can be turned on only as needed.
- They do not require replenishment of the source as does ^{60}Co .
- There is no radioactive waste.

E-beam technology also has the following disadvantages:

- The depth of penetration is shallow.
- E-beams must be converted to X-rays to penetrate large items such as carcasses.

- There is high electric power consumption.
- The technology is complex and there is potentially high maintenance.

2.4.1 Electron Accelerators

The irradiation source is an electron beam accelerator, which is not a radioactive source. An electron accelerator consists of three parts: (i) a high-voltage generator connected to an electron source or gun; (ii) an evacuated acceleration tube; and (iii) a target or scanning/focusing system (Figure 2.3). The electron stream emitted from the electron gun is injected into the accelerating tube (Wilkinson and Gould, 1996). The machine generates and accelerates electrons under vacuum. Due to the small mass of electrons, they cannot penetrate very deeply into a product. In addition, product densities can affect electron penetration. To be useful for food irradiation, electrons should be accelerated to energies of at least 5 MeV. The maximum energy approved for use in food is 10 MeV. Higher energy electrons have greater

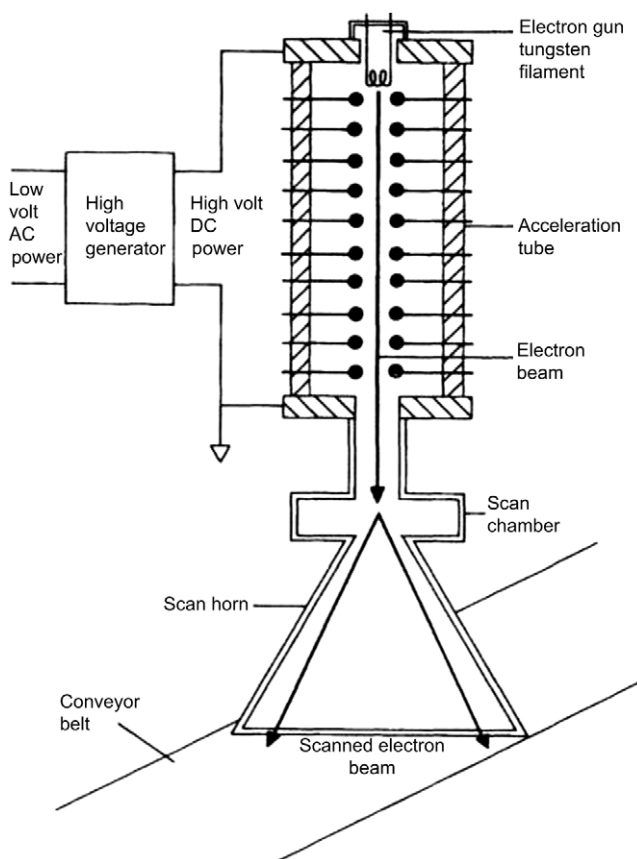


Figure 2.3: Simplified construction of an electron beam machine (L Leatherhead Food RA, UK).

penetration into the product. However, at 5 MeV and irradiating the product from both sides, the maximum thickness that can be penetrated is approximately 3.8 cm (1.5 in). At 10 MeV and with two-sided irradiation, the maximum thickness that can be penetrated is approximately 8.9 cm (3.5 in) (Olson, 1995; Woods and Pikaev, 1994).

High-energy and high-power electron beam accelerators generate heat during operation, which can cause instability in the accelerator and a loss of power. To maintain the stability and power output of the accelerator, the temperature must be maintained within a narrow range, requiring a large volume of circulating water that must be cooled and whose temperature must be tightly controlled to have less than 0.5°C variation. Water cooling of some vacuum pumps is also usually connected to the same system (Olson, 1995).

There are many commercial manufacturers of electron accelerators for a wide variety of applications, including radiography, materials processing and diagnostics, and medical diagnostics and treatment. There are also several different types of electron beam accelerators that are used for many different industrial applications. In 2002, it was estimated that there were more than 17,000 accelerators in use in industrial, research, and medical applications throughout the world (Maciszewski and Scharf, 2004). More than 1000 industrial electron beam accelerators are used for a variety of irradiation processes mainly for treated plastic and rubber products to improve their quality and for sterilizing single-use medical devices and foodstuffs. Only a few of these machines are used for food irradiation applications. For food irradiation, radio frequency (RF) linear accelerators can produce energies from 5 to 10 MeV and power from 10 to 50 kW. Food products are treated as they pass through a curtain of electrons on a suitable conveyor. The choice of product conveyor depends on the type of product to be handled. Packaged products can be transported on monorail carriers or horizontal conveyors or cart systems. Food products in granule or powder form may be handled on belt or vibratory conveyors.

2.4.2 Typical Electron Beam Plant

In a typical sterilization plant designed for high-volume processing, products enter on a conveyor through a labyrinth that permits access but stops radiation from escaping (Figure 2.4). The treatment room houses the accelerator and, like the entire installation, is constructed of thick concrete to protect workers from radiation. In the treatment room, the materials pass under the accelerator for processing. Once the materials have been “sprayed” with electrons, they continue on the belt until they exit the installation. The equipment area contains the electrical, electronic, and cooling equipment required to run the accelerator.

2.4.3 Acceleration Methods

Several different methods are used to produce high-energy and high-power electron beams. These can generally be grouped into three categories: (i) direct methods, in which the

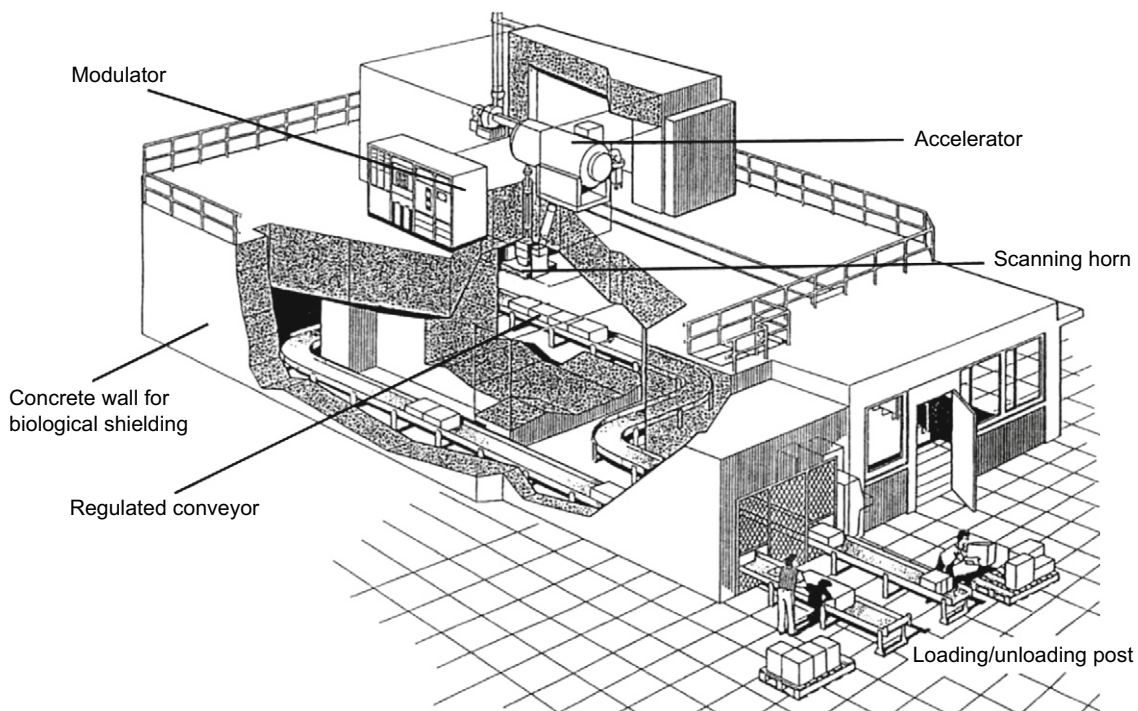


Figure 2.4: Commercial electron beam machine facility (MeV Industrie SA, France).

accelerating field results from the direct application of a high potential difference across an insulating column; (ii) induction methods, in which the accelerating field results from a time-changing magnetic field; and (iii) microwave or radio-frequency (RF) acceleration methods, in which acceleration results from oscillating electromagnetic fields established in a resonant microwave cavity structure (Miller, 2005). The choice of accelerator type for a particular application is usually based on the process requirements for electron energy and average beam power.

2.4.3.1 Direct acceleration methods

Examples of systems using direct acceleration methods include transformer-rectifier units, resonant transformers, Dynamitrons, and various electrostatic approaches including the Van de Graaff accelerator and the Pelletron. The common feature of these approaches is the generation of a high potential difference across a graded insulating column, which also serves as the vacuum interface (Miller, 2005).

2.4.3.2 Induction acceleration methods

The primary drawback of the direct acceleration methods for generating electron beams with kinetic energies in excess of a few million electron volts is the development of the total potential difference across a single long insulating column. An alternative approach is

to pass a beam many times through relatively smaller accelerating sections. For the exterior of the accelerator to remain at ground potential, these smaller accelerating increments should be induced by time-changing magnetic fields. Two practical embodiments of the induction acceleration principle are the linear induction accelerator and the betatron (Miller, 2005).

Betatrons are inexpensive and reliable electron accelerators that are simple in operation. Their main advantage over accelerators of other types is the absence of high-frequency accelerating systems. The induction acceleration method used in betatrons is low impedance and is better suited for acceleration of high currents rather than the high-frequency resonant method. A disadvantage of betatrons is the necessity of creating a magnetic field in the region encompassing orbits of particles being accelerated, and this field is doubled, on average, compared to the field in the equilibrium orbit. This leads to a fast increase in the accelerator mass as the energy of particles increase. Therefore, betatrons are used to accelerate electrons to low energies, when the dimensions of the facility are not very large (Moskalev and Sergeev, 2003).

2.4.3.3 Microwave acceleration approaches

The common feature of the several microwave or RF accelerator approach is electron acceleration by the oscillating electric fields established in an electromagnetic cavity structure that is driven at resonance by a suitable microwave or RF power source. The accelerating structure can consist of either a single cavity or multiple coupled cavities, and the beam can make either a single pass or multiple passes through the accelerating structure. The simplest microwave accelerator concept consists of a single accelerating cavity through which the beam passes only once. The most common microwave accelerator approach is to pass the beam through a linear series of such accelerating cavities that are electromagnetically coupled (i.e., a microwave or RF linac). Other approaches recirculate the beam through a single cavity or multiple cavities several times (Miller, 2005).

2.4.4 Types of Accelerators

Major accelerator facilities use several types of devices to build up the energy of the particles, including the following (from <http://hyperphysics.phy-astr.gsu.edu/hbase/particles/accel2.html#c1>):

- Cockroft–Walton accelerators: high DC voltage devices that accelerate ions through steps of voltage created by a voltage divider.
- Van de Graaff accelerators: charge is transported by an insulating belt to a conductor that builds in voltage as a result of charge collection.
- Cyclotrons: oscillating electric field repetitively accelerates charged particles across the gap between semicircular magnetic field regions.

- Synchrocyclotrons: cyclotrons with variable-frequency accelerating voltages to track relativistic effects.
- Betatrons: electron accelerators in a circular geometry with acceleration achieved by magnetic flux increase.
- Synchrotrons: large ring accelerators in which the particles move in an evacuated tube at constant radius accelerated by RF applications with synchronous magnetic field increases to maintain the constant radius.
- Linear accelerators: linear arrays of RF acceleration cells.

2.4.4.1 Radio frequency electron accelerators

For most applications involving particle energies of 1 MeV or higher, RF linacs are employed. In these accelerators, the electric and magnetic fields oscillate at high frequencies, commonly known as “radio frequencies,” in the range of millions to billions of cycles per second. RF linacs are one of the best ways to accelerate charged particles to MeV and GeV energies (see <http://www.linac.com/index.html>).

RF linacs were developed in the 1940s and are used for many applications, ranging from the generation of X-rays in a hospital environment to injectors into higher energy synchrotrons at particle physics laboratories.

RF linacs are constructed from four main elements: (i) a high-voltage power supply (modulator); (ii) an RF power source; (iii) a microwave cavity; and (iv) a charged particle source. The microwave cavity is the “heart” of the accelerator. It is constructed from a series of cavities with an aperture along the axis for the beam. The size of the cavities is selected on the basis of wavelength (and therefore the RF frequency) of the linac and is independent of the overall size of the accelerator (Committee on Radiation Source Use and Replacement, 2008).

RF accelerators produce beams with RF cavities that typically operate at low microwave frequencies (on the order of 1 GHz), although there are accelerators based on lasers (approximately 100 THz) and relatively low-frequency RF accelerators, which operate in the 100 MHz regime. There are many different variants of RF accelerators; examples include linear accelerators for medical applications (on the order of 1–10 MeV), synchrotron storage rings for synchrotron radiation generation (on the order of 1 GeV), and high-energy synchrotrons or linacs for high-energy physics (on the order of 1 TeV). RF accelerators may be single-pass linacs or multiple-pass accelerators, such as microtrons or the Rhodotron, or circular accelerators such as cyclotrons or synchrotrons. The largest linac in the world, at Stanford University’s SLAC National Accelerator Laboratory, is 3.2 km (2 miles) long. It is capable of accelerating electrons to an energy of 50 GeV. Stanford’s linac is designed to collide two beams of particles accelerated on different tracks of the accelerator.

Usually, the RF cavities are limited to accelerating fields of a few tens of megavolts per meter (MV/m). Laser-based accelerators have achieved fields as high as 100 GeV/m, but these are far from being commercial devices. RF accelerators do not have to prevent discharge across the full acceleration voltage along their length, which allows them to operate over a large energy range and to be relatively compact.

2.4.5 Comparison of Accelerator Approaches for Food Irradiation Applications

The direct acceleration methods are generally deemed less favorable for food processing applications for two primary reasons: (i) the large size of the equipment for generating electron kinetic energies up to 10 MeV; and (ii) the significant downtime required for repair or replacement of a high-voltage insulating column. For foodstuffs that are nonperishable, and that can be treated in a thin stream, these unfavorable aspects become much less important. For example, direct acceleration methods could process huge quantities of grain streams quite successfully.

Of the induction methods, the average power of the betatron appears to be too low to be of use, whereas the induction linac approach is quite expensive (Miller, 2005). However, several microwave (RF) accelerator approaches appear to have the flexibility to process almost every type of food product in an efficient, effective manner in facilities of reasonable size and at reasonable cost.

2.5 X-Ray Sources

X-rays are a form of electromagnetic radiation with a wide range of short wavelengths. They are caused by atomic transitions, and they are usually less energetic than gamma rays. They have the same properties and effects on materials, whereas their origin is the main difference between them. X-rays with varying energies are generated by machines. They use the same technology that produces electron beams, but they have more flexibility in food processing applications because of their greater penetrating power. However, the X-ray generation efficiency is quite low. Like gamma rays, X-rays can pass through thick foods and require heavy shielding for safety. However, like E-beams, the machine can be switched on and off, and no radioactive substances are involved. The X-ray machine is a more powerful version of the machines used in many hospitals and dental offices to take X-ray pictures.

2.5.1 X-Ray Interaction Processes

The most important method of producing X-rays depends on a process known as bremsstrahlung (German meaning “braking radiation”). X-rays are produced when charged particles, moving with a very high velocity, are slowed rapidly by striking a target. A beam

of high-velocity electrons is directed at a thin plate of heavy metal (usually tungsten or tantalum), producing a stream of X-rays. The fraction of kinetic energy of the electrons that is converted into X-rays (conversion efficiency) is higher for absorbers with a higher atomic number; therefore, materials such as tungsten and tantalum are used as X-ray converters. The conversion efficiency also increases with increasing electron energy. At 5 MeV, it is approximately 5% in tungsten, increasing to approximately 12.5% at 10 MeV (Seltzer et al., 1983). In contrast to radionuclide sources, which emit nearly monoenergetic photons, X-ray sources emit a broad spectrum of photons from the maximum energy of the electrons to zero energy. For example, an X-ray beam generated by 5 MeV electrons has approximately the same penetration characteristics as ^{60}Co radiation. Although penetration into products is nearly the same for both gamma rays and X-rays, production of X-rays is not currently economical (Morrison, 1989). Other characteristics of the X-ray beam, such as scanning and pulsing of the beam, are derived from the characteristics of the electron beam that generated the X-rays (Stichelbaut et al., 2004).

For food treatment, X-ray machines must be operated at an energy level of 5 MeV or lower. This restriction is based on the need to prevent induced radioactivity. X-ray production is relatively inefficient, but it can be competitive with gamma radiation for high-capacity plants. The possibility of using electron beams and X-rays in the same irradiation facility is attractive (Farkas, 1988; Wilkinson and Gould, 1996). Four commercial X-ray irradiation units have been built since 1996. A number of X-ray irradiators have been built by converting electrons into X-rays to gain the deep penetration necessary for pallets of foods (Moy, 2005).

2.6 Conclusions

Although several techniques are available for food irradiation (gamma rays, e-beam, and X-rays), the most widely used is the gamma ray followed by the e-beam. However, e-beams must be converted to X-rays to penetrate large items such as carcasses. While there has been increasing demand for X-rays at the time of writing the majority of food is still irradiated with gamma rays (^{60}Co). The choice of product conveyor depends greatly on the product to be handled. Packaged products can be transported on monorail carriers or horizontal conveyors or cart systems. Food products in granule or powder form may be handled on belt or vibratory conveyors.

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Food Packaging Materials for Irradiation

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3.1 Introduction

Irradiation of packaging materials—in most cases, plastics—generally leads to the formation of free radicals and ions, which eventually result either in cross-linking or in chain scission. The latter leads to the release of volatile radiolysis products that may induce off-odors in the polymers, thereby altering the migration characteristics of packaging materials. Irradiation also affects polymer additives, which change the specific migration behavior of polymer additives and additive-related decomposition products. Both migration and sensory changes of presterilized packaging materials strongly affect the quality of packaged goods and consumer safety (Welle et al., 2002).

Radiation processing is widely used for medical product sterilization and food irradiation. Moreover, the use of irradiation has become a standard treatment to sterilize packages in aseptic processing of foods and pharmaceuticals. Nowadays, packaging consists of natural or synthetic plastics; therefore, the effect of irradiation on these materials is crucial for packaging engineering (Hadi-Saeid et al., 2007).

The effect of ionizing radiation on polymeric materials has been found to manifest itself in two ways: (i) as a molecular weight increase (cross-linking); and (ii) as a molecular weight decrease (chain scission degradation). The ability of radiation to process the packaged material, compared to the ineffectiveness of chemical treatments, is a critical advantage over the others. The most important applications of polymer irradiation are: (i) sterilization of medical disposables, syringes, and tubing; and (ii) food and food packaging irradiation.

Cross-linking is the most important reaction during irradiation in most plastics [polyethylene (PE), polypropylene (PP), and polystyrene (PS)] used for food packaging. Cross-linking has the following effects on polymeric structure: decreases in percentage elongation (%E), crystallinity, and solubility and an increase in the tensile strength (TS) of polymers. However, when chain scission occurs, the chain length of polymers decreases and release of hydrogen, methane, and hydrogen chloride for chlorine may take place.

Companies in the dairy (cream, butter, and eggnog), processed food (sauces, salad dressings, processed meats, and fruit gels), beverage (juice and wine), over-the-counter pharmaceuticals, and medical device industries irradiate packaging materials before filling them (see www.cbesa.com.br).

Some of the major polymeric materials, such as PE, PP, polyethylene terephthalate (PET), polyamide (PA), PS, and polyvinyl chloride (PVC), were investigated after having been treated with an irradiation dose of 44 kGy. In most cases, the radiolysis products formed could be identified using gas chromatography–mass spectrometry (GC/MS). The polyolefin materials (PE and PP) displayed an increase in volatile compounds after irradiation due to an oxidative decomposition of the polymer and typical polymer substances such as oligomers and additives. Other packaging materials, such as PET, PA, and PS, did not display significant changes in the amount of solvent extractable compounds after irradiation with 44 kGy (Demertzis et al., 1999).

3.2 Synthetic Packaging Materials

3.2.1 Polyethylene

The effect of electron beam irradiation, storage conditions (4, 21, and 35°C), and model food pH (4, 7, and 10) on the release characteristics of *trans*-cinnamaldehyde incorporated into PA-coated low-density polyethylene (LDPE) films was studied by Han et al. (2008). In aqueous solution, *trans*-cinnamaldehyde was highly unstable to ionizing radiation, with loss in concentration from 24.50 to 1.36 µg/ml after exposure to 2.0 kGy. Fourier transform infrared (FTIR) analysis revealed that exposure to ionizing radiation up to 10.0 kGy did not affect the structural conformation of LDPE/PA films and the *trans*-cinnamaldehyde in the films, although it induced changes in the functional group of *trans*-cinnamaldehyde when the dose was increased up to 20.0 kGy. Studies with naphthalene revealed that ionizing radiation induced the cross-linking in polymer networks of LDPE/PA film, thereby leading to the slow and gradual release of the compound. Therefore, irradiation can potentially act as a controlling factor for release of active antimicrobial compounds. The effects of e-beam irradiation/dose in conjunction with antimicrobial coating on mechanical properties (TS and %E at break) of PA/LDPE films (in the presence of plasticizer or not) are shown in Figure 3.1 (Han et al., 2007).

Duarte and co-workers (2009) evaluated the pesticide degradation of ametryne, whose residues are detectable in water and soil for years after its application. Commercially available high-density polyethylene (HDPE) was irradiated in the presence of water, in various absorbed doses, with 1.5 MeV energy and 37 kW, in a batch system. The radiation processing yield was evaluated by the destruction G value. The e-beam irradiation processing displayed higher efficiency in decomposing ametryne in the HDPE packaging when the samples were irradiated in the presence of small quantities of water.

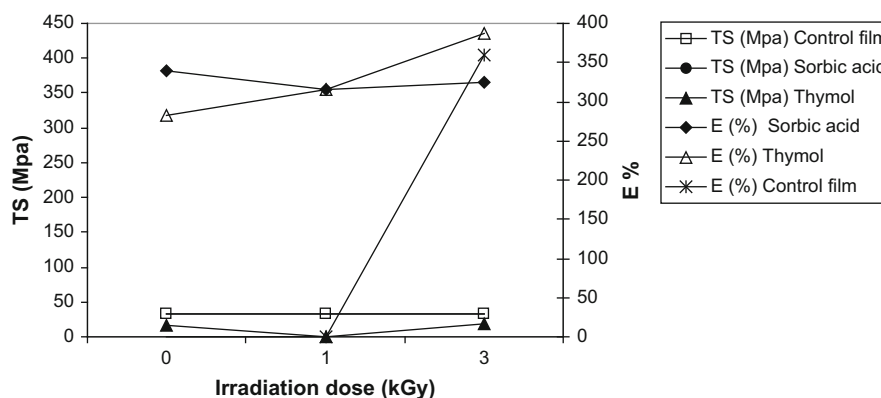


Figure 3.1: The impact of E-beam irradiation/dose on mechanical (TS and %E at break) of PA/LDPE films (adapted from Han et al., 2007).

Riganakos et al. (1999) investigated the volatile compounds (VCs) produced in LDPE packaging during E-beam irradiation, isolated with the purge and trap technique, and identified with GC/MS after thermal desorption. The authors managed to isolate and identify the VCs in non-irradiated LDPE at 100 kGy. Out of 53 VCs recorded in non-irradiated LDPE, 35 saturated hydrocarbons, aldehydes, carboxylic acids ketones, and phenols were identified with GC/MS. Similarly, out of 74 VCs reported in irradiated LDPE, 49 were identified with GC/MS. In the case of irradiated LDPE samples, apart from the previously mentioned VCs, other identified compounds included unsaturated hydrocarbons, higher ketones (hexanone and heptanone), esters, and aromatic compounds.

Demertzis and co-workers (1999) reported that the irradiation (44 kGy) of LDPE films resulted in the formation of 1,3-di-*tert*-butylbenzene and 2,4-di-*tert*-butyl phenol, both degradation products from Irgafos and Irganox 176.

Jeon et al. (2007) investigated the effects of γ -irradiation on residual and migration levels of the antioxidants tris-(2,4-di-*tert*-butylphenyl) phosphite (Irgafos 168) and octadecyl-3-(3,5-di-*tert*-butyl-4-hydroxyphenyl) propionate (Irganox 1076) and their radiolysis products in the linear low-density polyethylene (LLDPE) packaging samples treated at doses of 0–200 kGy. The content of Irgafos 168 was not detected in 5-kGy treated samples, and the content of Irganox 1076 decreased by 34.9% from the initial level in 10-kGy treated samples. The radiolysis products 2,4-di-*tert*-butylphenol, 1,3-di-*tert*-butylbenzene, and toluene were identified and their concentrations gradually increased with an increase in radiation dose. Migration of Irgafos 168 from the LLDPE pouch into food simulants, distilled water, acetic acid (4 ml/100 ml distilled water), or ethanol (20 ml/100 ml distilled water) was not detected at dose levels up to 200 kGy, whereas that of Irganox 1076 was detected in a decreasing mode with increasing dose.

Goulas and co-workers (2003) studied the effect of γ -irradiation (5, 10, and 30 kGy) on the physical properties (mechanical and permeation) and overall migration of LLDPE, PP, ethylene vinyl alcohol (EVOH), and PA into distilled water, 3% acetic acid, and iso-octane. The overall migration from all multilayer materials into distilled water was 0.5–2.0 mg/dm², well below the current European Union upper limit of 10 mg/dm² for food-approved plastics packaging materials (European Economic Community, 1990). The same was observed for migration values from PA/LDPE, PP/EVOH/LDPE–LLDPE, and LDPE/EVOH/LDPE films into 3% acetic acid (1.0–2.3 mg/dm²). In contrast, the overall migration from ionomer/EVOH/LDPE and LDPE/PA/ionomer materials into 3% acetic acid (10.9 and 16.4 mg/dm², respectively) was higher than the overall migration limit (Figure 3.2). The high migration values of these two multilayer materials could be due to ionomer film properties, the structure of which consists of crystalline, amorphous, and a third ionic phase composed of metal and carboxylate ions.

Roy et al. (2006) synthesized two cobalt complexes, cobalt styrene maleate copolymer (CSMA) and cobalt stearate (CS), in an attempt to study the effect of these complexes on the degradation behavior of LDPE films. LDPE films have TS and elongation at break of 12.8 MPa and 149 mm, respectively. All the formulations exhibited initial mechanical properties in the same range, indicating that these additives do not induce degradation during the processing stage. Films containing CS, however, lost 90% E within 100 h of thermal exposure, whereas PE films alone and those containing CSMA showed 60–70% loss even after 600 h of exposure. The effect of photooxidation time on $EB(t)/EB(0)$ is shown in Figure 3.3. It is noteworthy that films containing CS became completely fragile after 100 h of thermo-oxidative treatment and could not be tested any further.

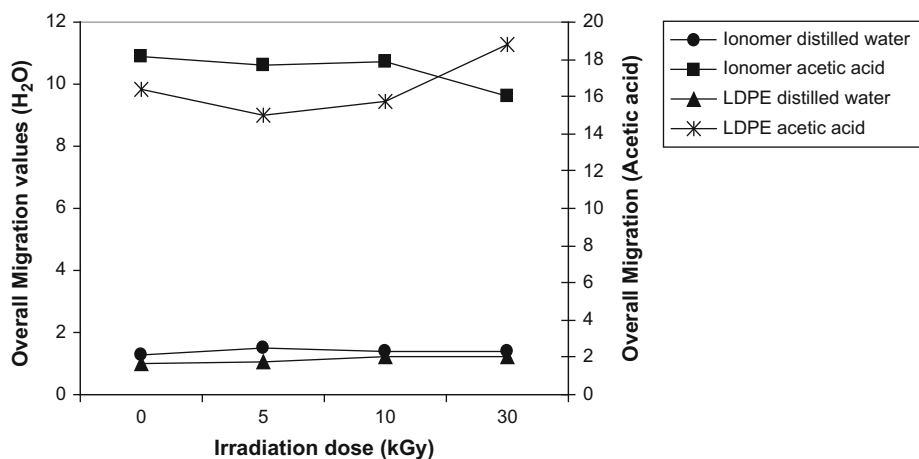


Figure 3.2: The impact of irradiation dose on the overall migration values of multilayer films (ionomer/EVOH/LDPE) (adapted from Goulas et al., 2003).

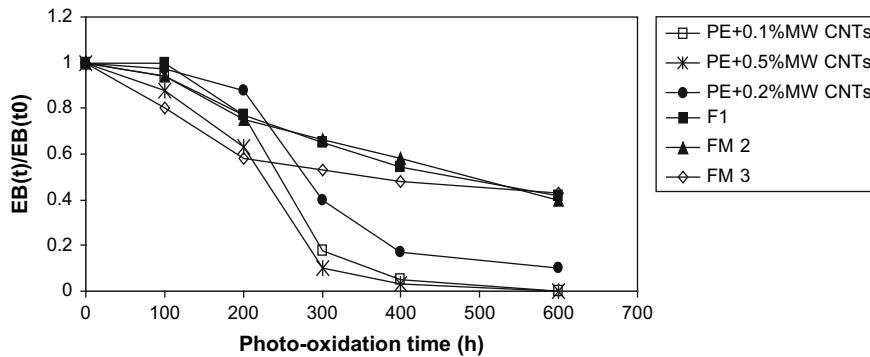


Figure 3.3: The effect of photooxidation time on $EB(t)/EB(0)$ when cobalt styrene maleate copolymer (CSMA) and cobalt stearate (CS) were included in LDPE (adapted from Roy et al., 2006).

Reale et al. (2008) investigated the quality and the freshness of γ -irradiated packaged sea bass by assessing its microbiological, sensory, and chemical properties. Major MDA containment and microbial decontamination in irradiated samples at 3 kGy were found compared to the control sample. The ionizing irradiation, although extremely efficient with regard to MDA containment and microbial decontamination, was shown to be less effective for preserving the sea bass sensorial quality because the γ -rays caused considerable alterations in color, odor, and texture. The effect of storage time on the rigor index and MDA content of irradiated fish at 3 kGy is shown in Figure 3.4.

Koszinowski and Piringer (1986) studied the odor threshold and aroma character for several unsaturated carbonyl compounds and proposed that these compounds were responsible for off-odors resulting from PE-coated paperboard. It was clearly shown that many of these compounds had high odor activity at very low concentrations.

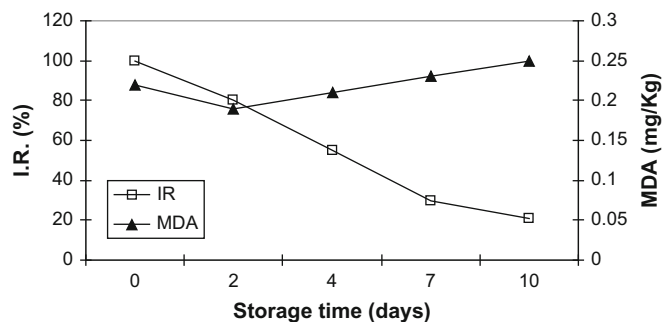


Figure 3.4: The effect of storage time on the rigor index and MDA content of irradiated fish with 3 kGy (adapted from Reale et al., 2008).

De Gante and Pascat (1990) irradiated LDPE and oriented polypropylene (OPP) films in air at doses of 10 and 25 kGy and obtained similar results. Irradiation in air produced 100 volatiles in LDPE (e.g., several ketones, aldehydes, alcohols, hydrocarbons, and carboxylic acids) and 58 volatiles in OPP films.

The thermal desorption of HDPE was studied with GC/MS by Krzymien and co-workers (2001). This methodology allowed the rapid identification of volatile products resulting from the γ -irradiation of stabilized HDPE packaging and pure stabilizers. The stabilizers were tris(2,4-di-*tert*-butylphenyl) phosphite, octadecyl β -(2,6-di-*tert*-butylphenol)-propionate, and 2,4-di-*tert*-butylphenol, with the latter resulting from phosphite hydrolysis. Thermal desorption indicated the formation and release of *tert*-butylbenzenes, such as 1,3-di-*tert*-butylbenzene, upon γ -irradiation of the HDPE. A comparison of the products from γ -irradiation of additive-free polyethylene, of various pure stabilizers, and of related compounds revealed that the *tert*-butylbenzenes resulted from the irradiation of the phosphite stabilizer and its phosphate conversion product.

3.2.2 Polypropylene

Mizani and co-workers (2009) reported no significant difference in TS of non-irradiated and irradiated biaxially oriented polypropylene/cast polypropylene (BOPP/CPP) film at 0–15 kGy. Percentage elongation at break was not significantly affected up to 10 kGy. However, irradiation at 15 kGy increased %E by 40% compared to control (Figure 3.5). It appears that irradiation has different effects on BOPP and CPP layers of this multilayer film. The BOPP layer may be affected by rearrangement of its oriented structure, which results in increased TS and %E. Water vapor transmission rate (WVTR) of the BOPP/CPP film was not considerably affected at applied doses, but the oxygen permeability increased by 25% at 15 kGy, as shown in Figure 3.6. The obtained results are in agreement with those of a study by Yaghoubi et al.

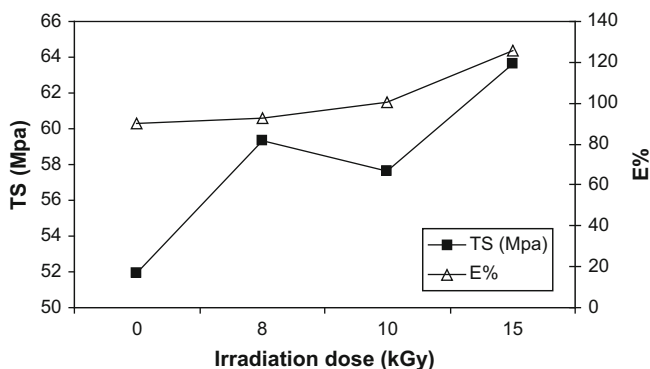


Figure 3.5: The impact of irradiation dose on TS and %E of BOPP/CPP (adapted from Mizani et al., 2009).

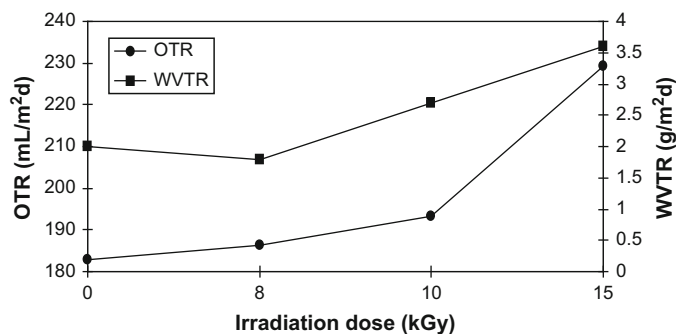


Figure 3.6: The effect of irradiation dose on water vapor transmission rate (WVTR) and oxygen transmission rate (OTR) of BOPP/PP films (adapted from Mizani et al., 2009).

(1999) on the effect of irradiation on the amorphous segment of the CPP layer, which is more susceptible to degradation after irradiation treatment.

For some years, there has been an ongoing debate regarding the effect of aging on PET. According to some researchers (Jeon et al., 2004; Sun et al., 1999), the effect of γ -irradiation on the physicochemical properties (thermal, mechanical, and gas/water permeation) is hardly perceived, whereas other authors (Fechine et al., 2004; Lee et al., 2004) claim exactly the opposite.

According to Tarantili and Kiose (2008), the effect of aging on the mechanical properties of PE is very limited. In their study, they noted the following results. As with BOPP, the tensile modulus of PE showed an increase of 15%. However, an essentially smaller decrease in TS of PE, compared with that of BOPP, was recorded, accompanied by a decrease of 89% in %E. These data probably suggest that some cross-linking did occur upon irradiation, thereby contributing to the increase of modulus, whereas for BOPP the main reaction introduced by UV was chain scission. This hypothesis was further supported by the recorded decrease in TS of PE, which proceeded very smoothly in comparison with that of BOPP; this may imply a competitive action of chain scission and cross-linking. The obtained data displayed a significant decrease in the mechanical properties of the films upon exposure to aging conditions. Specifically, the specimens became brittle after 200 h of irradiation, and this effect depended on the type of film. BOPP showed the maximum decrease in TS and %E, which was attributed to the susceptibility of PP to UV radiation. The BOPP specimens exhibited an increase in the modulus that can be attributed to the brittleness of the irradiated sample rather than to an increase in its stiffness. Most of the problems in these two types of PP film occurred within the first 50 h of exposure. The information obtained by DSC analysis suggested that chain scission during the first 50 h of aging still allowed the packing of polymer chain fragments; therefore, the crystallinity of BOPP remained constant within this period.

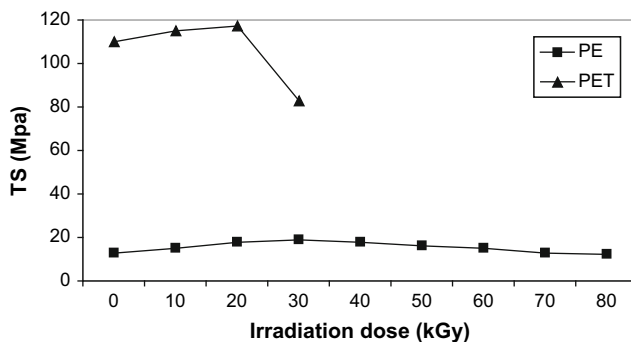


Figure 3.7: The effect of accelerated aging on the TS of PE and PET (adapted from Tarantili and Kiöse, 2008).

The effect of accelerated aging on the TS of two polymers (PE and PET) is displayed in Figure 3.7.

The bactericidal effects of sodium hypochlorite and γ -irradiation on *Pseudomonas aeruginosa*, *Listeria innocua*, and *Escherichia coli* biofilm formed on PP, PET, and PC was investigated by Byun et al. (2007). The *P. aeruginosa* attached to the biofilm in PP and PC was not detected after 3 kGy of irradiation. Irradiation of 3 kGy reduced the bacterial counts to an undetectable level in the suspension or PP and PET, which were originally inoculated by approximately 7 log CFU/ml or CFU/cm², respectively (Figure 3.8). Irradiation of 1 kGy was enough for inactivation of the microbial cells attached to PC. Irradiation reduced the number of bacterial cells in a dose-dependent manner. Regarding the effect of sodium hypochlorite, a 100 ppm concentration had a negligible effect (0.1 reduction), whereas the bacterial cells that were eliminated required a concentration of 200 ppm.

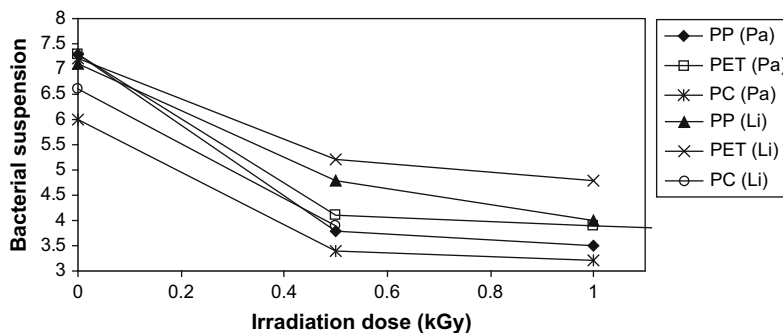


Figure 3.8: The effect of irradiation dose on bacterial counts of *Pseudomonas aeruginosa* (Pa) and *Listeria innocua* (Li) for various polymers PP, PET, and PC (adapted from Byun et al., 2007).

Ultra-high molecular weight PE powder (GUR 1020) was blended with a high concentration (20%) of vitamin E [α -tocopherol (α -T)] for direct detection of α -T radicals in the presence of PE radicals. Samples were γ -irradiated in sealed packages filled with N₂ or in open air. Free radicals were measured in an open air environment for 71 days using electron spin resonance (ESR). When irradiated in air, both α -T and α -T resin produced identical ESR signals characteristic of tocopheroxyl radicals (α -T-O \cdot), suggesting that PE radicals were quenched by α -T (Ridley and Jahan, 2008).

Irradiation of 44 kGy on PP resulted in the formation of a greater number and larger amount of low-molecular-weight substances, which were attributed to the branched backbone structure of the PP carbon chain (Demertzis et al., 1999).

3.2.3 Polyamide-6

Deschenes et al. (1995) used a panel of 16 experienced judges to confirm that irradiated water packaged in test pouches made of nylon/PVDC/EVA exhibited taint after taste that was noticeable at a dose as low as 1 kGy. Four main attributes were used to describe the irradiated samples: metallic, plastic, penetrating, and acidic. This effect, however, decreased with storage time and was not perceptible after 3 weeks for e-beam-treated samples. In the case of water packaged samples treated with γ -radiation, the undesirable taste was still perceptible after 4 weeks, suggesting that irradiation induced mass transfer. The formation of chemical species affecting the organoleptic quality of the packaged water seemed to be favored by γ -treatment. They observed that in the dynamic head space analysis of the plastic, hexanal, heptanal, octanal, and nonanal were present in higher concentrations in irradiated samples. Bravo et al. (1992) had previously identified odor-active compounds resulting from thermal oxidation of PE, one of the polymers comprising the investigated food-contact layer. Irradiated samples were found to contain other compounds, such as hexane, hexanone, and benzene—mainly species derived from PE degradation.

Polyamide-6 (PA-6), a food packaging polymer, was irradiated with a dose range of 5–200 kGy. The dose of γ -irradiation significantly ($p < 0.05$) increased the formation of ϵ -caprolactam in PA-6, ranging between 122 and 164 ppm in the dose range 5–200 kGy (Park et al., 2006).

Solvent extraction at elevated temperatures (e.g., with acetone at 80°C for 24 h) appears to produce much more pentanamide (target compound), plus a variety of other products in both the non-irradiated control and the irradiated PA-6. Quantitation using a standard additions technique indicated concentrations of pentanamide of approximately 75 ppm (determined with dissolution precipitation) and of greater than 200 ppm (solvent extraction at 80°C). Although overestimation of radiolysis products might occur, this would be a problem only if the levels reached unacceptable concentrations (Buchalla et al., 1999, 2000, 2002).

Araujo and co-workers (2008) applied a GC method to determine ϵ -caprolactam in multilayer PA-6 films employed for meat foodstuffs and cheese. Irradiated (3, 7, and 12 kGy) and non-irradiated commercial films were analyzed. The results revealed that the effect of irradiation in the multilayer PA-6 films might promote an increase, reduction, or no modification of the residual level of caprolactam compared to non-irradiated multilayer PA-6 films used for meat foodstuffs and cheese. The enhancement in ϵ -caprolactam level could be attributed to polymer degradation, whereas the reduction could be due to cross-linking of residual ϵ -caprolactam with other compounds. The different behavior of multilayer PA-6 films may be due to the different packaging compositions and, in particular, to the doses and dose rates.

Han et al. (2007) evaluated the effects of ionizing radiation (1–3 kGy) and incorporation of antimicrobials on the functional properties of PA/LDPE films. All films displayed inhibition zones in an agar diffusion test against *L. innocua* ATCC 33090 and *E. coli* ATCC 884. In the liquid culture test, the antimicrobials significantly ($p = 0.05$) reduced the specific growth rate of *L. innocua* by 3.8–8.5% and decreased the final cell concentration of both strains by 5.7–14.6% and 7.2–16.8%, respectively. All active compounds retained their antimicrobial activity when exposed to 1–3 kGy. Irradiation exposure at the dose levels used in this study (1–3 kGy) was found not to affect ($p > 0.05$) the mechanical properties of the films. Addition of active compounds in coating solution (100 mg active compound/10 g PA solution) caused only slight changes ($p > 0.05$) in TS. On the other hand, the films became significantly ($p < 0.05$) more ductile (increased %E) by 20.3–39.6 when incorporated with sorbic acid, carvacrol, and rosemary oleoresin due to the plasticizing effect of the added compounds (Arvanitoyannis and Biliaderis, 1998; Arvanitoyannis et al., 1996, 1997).

3.2.4 Polycarbonate

Park et al. (2006) extracted monomeric bisphenol-A residues from the non-irradiated PC film, and the level of extracted bisphenol-A was 124 mg/g of PC films. The low doses of γ -irradiation (5–10 kGy) did not significantly ($p > 0.05$) affect the bisphenol-A level in PC film. However, its level increased to 473 mg/g when the PC film was exposed to 30 kGy, and this value did not change even when higher doses were used (60, 100, and 200 kGy). The increase in bisphenol-A level in PC film exposed to 30 kGy could be attributed to the predominant cross-linking effect of small doses of γ -irradiation (5–10 kGy) and the pronounced scission of the main chain at higher doses (30–200 kGy) by the cleavage of the weak carbonyl bond between the phenyl rings.

Byun et al. (2007) reported that the amount of *E. coli* attached to PC was 4.0 log CFU/cm² by 3 kGy of irradiation. Based on these results, it can be concluded that biofilms attached to PC are more resistant to irradiation for *E. coli* and *P. aeruginosa* than that for *L. innocua*. Therefore, a low dose of γ -irradiation is a useful tool for inactivating microbial biofilms attached to food containers.

3.2.5 Polyethylene Terephthalate (PET)

Migration results obtained by [Thompson et al. \(1997\)](#) for Co, Cr, Zn, Sb from PET and to 95% confidence showed that no migration was detectable with the radiotracer method. According to this method, a sample of material was irradiated in a thermal neutron flux of $10^{16} \text{ n m}^{-2} \text{ s}^{-1}$ to activate the trace elements and produce a range of radionuclides. The corresponding conventional method results also displayed no significant migration after the blank value subtraction. Positive values were obtained for Sb in one case, but this was not statistically significant when the error on the data was taken into consideration. However, it is noteworthy that the radiotracer method generally gives better detection limits than the classical method. This study confirmed the data obtained in the PET study and put forward the assumption that migration behavior was not significantly enhanced by interaction of neutrons with the sample.

[Riganakos et al. \(1999\)](#) investigated the VCs produced in flexible food packaging materials (PET/PE/EVOH/PE) during e-beam irradiation. The released VCs were isolated with the purge and trap technique and identified with combined GC/MS after thermal desorption and evaporation. Film samples were irradiated at low (5 kGy, corresponding to cold pasteurization), intermediate (20 kGy, corresponding to cold sterilization), and high (100 kGy) doses. Primary (methyl-derivatives, etc.) as well as secondary (i.e., oxidation—ketones, aldehydes, alcohols, carboxylic acids, etc.) products were produced upon irradiation. These products affected the organoleptic properties and thus the shelf life of prepackaged irradiated foods.

[Komolprasert and co-workers \(2003\)](#) used three doses (5, 25, and 50 kGy) of both γ -ray and E-beam radiation on two semi-rigid amorphous 1,4-cyclohexane-dimethanol PET copolymers in an attempt to determine the effects of both γ -irradiation and e-beam irradiation at three doses on the levels of volatile and nonvolatile compounds present in these copolymers. It was found that in PET specimens exposed to γ -radiation and e-beam radiation in the 5- to 50-kGy dose range, as the radiation dose level increased: (i) the concentration of 2-methyl-1,3-dioxolane decreased ($p < 0.05$) to a low of 0.6 mg/kg after exposure to 50 kGy γ -radiation; and (ii) the concentration of acetaldehyde significantly increased to a maximum value of 8.6 mg/kg after exposure to 50 kGy γ -radiation ([Figure 3.9](#)).

The effect of γ -irradiation and sodium hypochlorite on the microorganisms attached to food containers made from PET was investigated by [Byun et al. \(2007\)](#). Application of γ -irradiation reduced the number of bacterial cells in a dose-dependent manner, whereas the sodium hypochlorite treatment displayed a negligible reduction at concentration levels lower than 100 ppm and bacterial elimination was possible at 200 ppm. Irradiation of 3 kGy reduced the bacterial counts to an undetectable level in the suspension PET, which was originally inoculated by approximately 7 log CFU/ml or CFU/cm², respectively.

[Soares and Saiki \(2009\)](#) applied a radiometric method for element migration determination from PET packaging to food simulants. According to these authors, the exposure time of

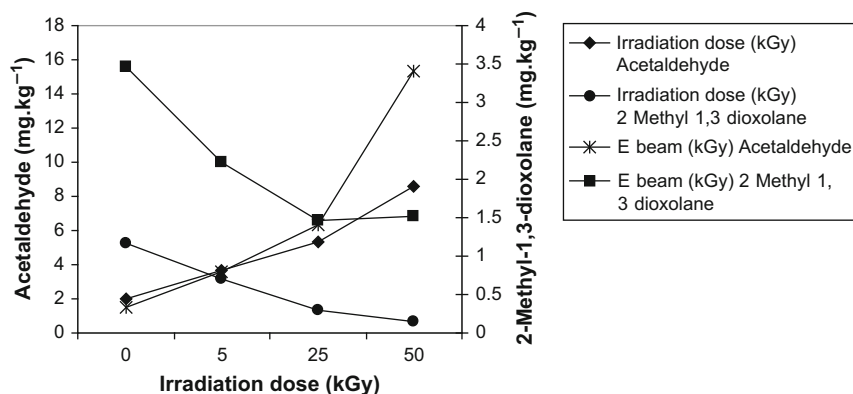


Figure 3.9: The effect of γ - and e-beam irradiation on the concentration of acetaldehyde and 2-methyl-1,3-dioxolane in PET (adapted from Komolprasert et al., 2003).

irradiated plastic samples (PET and HDPE) for migration was 10 days at a temperature of 40°C in an oven. The following simulants were used: water for water packaging and 3% acetic acid solution (w/v) for testing materials of juice, soft drinks, acidic fatty food, and dairy product packages. All the ^{60}Co irradiated soft drink packages showed Co (0.037–0.25 $\mu\text{g}/\text{dm}^2/\text{kg}$) and Sb (0.78–0.93 $\mu\text{g}/\text{dm}^2/\text{kg}$) migration levels. The package of water displayed only Sb migration. The juice and acidic fatty food packages (PET and HDPE) presented Co and Sb migration depending on the sample. Although the HDPE of dairy product packaging presented Co and Cr migration, the PP packaging did not show the expected migration for these two elements. Compared to the rest of the food packaging materials, the PET film was found to be very resistant toward irradiation treatment because only a few substances at low concentrations could be extracted.

3.2.6 Polystyrene

Although the effects of irradiation on many polymer stabilizers have been investigated, the results have been limited to quantitative determination of radiolytic products from the most conventional phenolic antioxidants, phosphites, UV stabilizers (Deschenes et al., 2004; Kawamura, 2004), and plasticizers (Goulas et al., 2003). Komolprasert et al. (2006) studied the impact of 10- and 20-kGy γ -irradiation on chromophthal yellow 2RLTS (Yellow 110-2,3,4,5-tetrachloro-6-cyanobenzoic acid) and Irgalite Blue GBP [copper (II) phthalocyanine blue] colorants, which were added to PS material used for food packaging prior to irradiation. Based on polymer analysis, it was concluded that irradiation generated no new chemicals in the PS containing either yellow or blue colorant at a concentration of up to 1% (w/w) because both yellow and blue colorants are relatively stable to γ -irradiation.

Singh et al. (2007) irradiated thin PS films with protons (3 MeV) under vacuum at room temperature with a dose ranging from 2×10^6 to 2×10^7 Gy. The changes in physical

properties and induction of microstrain on the surface of proton-irradiated PS were investigated using UV-VIS, FTIR spectroscopy, and X-ray diffraction techniques.

Based on the spectrometric findings, it was shown that the reported changes in the color, cross-linking, and induction of microstrain on the surface of proton-irradiated (up to 6×10^6 Gy) PS samples may be due to the presence of aromatic groups in PS. It is noteworthy that these minimal changes occurred at a dose of 25 kGy, much higher than that required for sterilization. However, an overall structural degradation was observed only at the highest absorbed dose of 2×10^7 Gy. Moreover, the PS samples turned from transparent to yellow at a dose of 2×10^6 Gy and then to light brown at 6×10^7 Gy.

The styrene residues in PS increased from 742 to 828 ppm at low doses up to 10 kGy, whereas these values decreased to 73 ppm at high doses. The presence of aromatic groups in PS increased the resistance to irradiation and stabilized the excited species formed by irradiation (Park et al., 2006).

PS was found to be more stable against the irradiation treatment than the polyolefines. Only a few radiolysis products were formed, most of which, due to their low concentrations and unspecific mass fragments, could not be identified.

3.2.7 Polyvinyl Chloride

PVC is used in a wide range of applications because of its compatibility with several types of additives, such as plasticizers, stabilizers, and lubricants. Park et al. (2006) found that the amount of vinyl chloride extracted from PVC significantly ($p < 0.05$) increased from 8 to 18 ppm as the dose of irradiation increased to 200 kGy. The dose-dependent formation of vinyl chloride in PVC could be due to the extensive main chain scission effect with increasing irradiation dose.

Vinhas et al. (2004) conducted a study on the stability of PVC compounded with di-2-ethylhexyl phthalate (DEHP), a plasticizer commonly added to make PVC flexible enough for medical and pharmaceutical devices, and 2,2-hydroxy-5-*tert*-octyl-phenyl benzotriazole (Tinuvin P), a stabilizer of the amino class normally used to protect PVC from UV light. The PVC/DEHP system displayed a decrease in TS especially at the dose of 25 kGy, whereas the PVC/DEHP/Tinuvin P systems exhibited a rather small variation in TS. The %E in DEHP plasticized and Tinuvin P stabilized PVC films decreases with increasing radiation doses. The effect of irradiation dose on TS and %E of PVC in the presence of several plasticizers in different content is shown in Figure 3.10.

Demertzis et al. (1999) reported that the PVC sheet used in their study was very sensitive toward γ -irradiation because the blue-colored sheet turned brown and released a strong off-odor. Moreover, high amounts of radiolysis products could be extracted, but their identification was not effective.

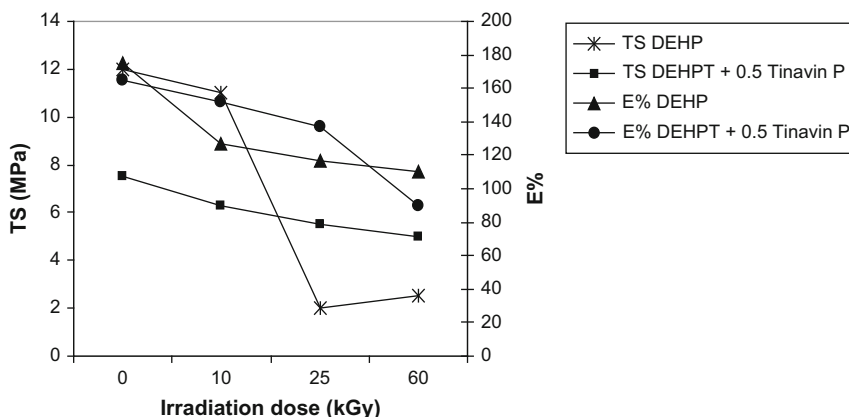


Figure 3.10: The effect of irradiation dose on plasticized PVC (adapted from Vinhas et al., 2004).

3.2.8 Laminated/Composite/Blend Films

Mizani et al. (2009) investigated the physicochemical properties of POE/PET/LLDPE and BOP/COP laminated films, commercially used for spice packaging, after γ -irradiation at 8, 10, and 15 kGy. TS and %E at break of the second film (PET/PET/LLDPE), at 15 kGy, decreased by 21 and 59%, respectively. Therefore, the significant decrease in mechanical properties of PET/PET/LLDPE may be due to the additives used to compound the plastics. Kawamura (2004) proved that antioxidants play an important role in stabilization of polyolefins, and their presence may greatly decrease the decline of mechanical properties. Therefore, degradation of these additives eventually resulted in reduction of film TS. OTR and WVTR data of the PET/PET/LLDPE were not significantly affected by irradiation up to 10 kGy, in agreement with previous reports by Riganakos et al. (1999) and Jeon et al. (2004).

Goulas et al. (2003) found that although radiation doses of 5 and 10 kGy triggered no statistically significant differences in all laminated polymeric films (PA/LDPE, LDPE/EVOH/LDPE, and LDPE/PA/ionomer), irradiation at 30 kGy induced differences in the mechanical properties. Furthermore, the same dose displayed considerable differences in the overall migration from ionomer/EVOH/LDPE and LDPE/PA/ionomer films into 3% acetic acid and iso-octane.

Oliveira et al. (2009) investigated the impact of e-beam irradiation on mechanical properties of commercial multilayer flexible packaging materials based on coextruded and laminated PP, LDPE, EVOH, and PET irradiated with doses up to 120 kGy. The TS and %E at break of the irradiated PET/PP film increased, whereas the penetration and sealing resistance decreased. Moreover, the irradiated PET/LDPE/EVOH/LDPE film displayed a pronounced increase in the TS on certain radiation doses and a decrease in penetration and sealing resistance; except for sealing resistance at a radiation dose of 15 kGy that resulted in a slight increase of

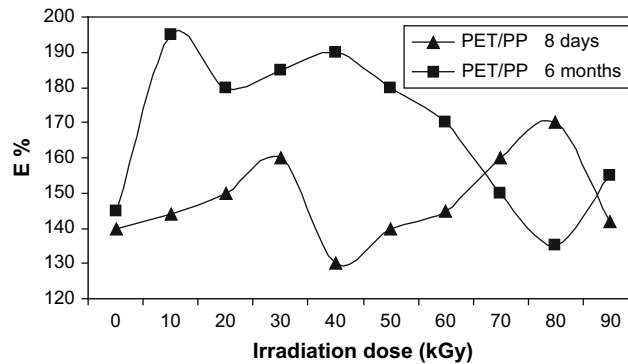


Figure 3.11: The impact of irradiation dose on %E of PET/PP at two storage times (adapted from Oliveira et al., 2009).

approximately 4%. In general, the mechanical properties of irradiated PET/LDPE/EVOH/LDPE deteriorated more than PET/PP. E-beam irradiation at doses up to 45 kGy induced an increase in %E at break of the PET/PP but had a limited effect on TS and penetration resistance, whereas the irradiation effect on the mechanical properties of PET/LDPE/EVOH/LDPE led to a decrease of between 30 and 45%, as shown in Figures 3.11 and 3.12.

According to Deschenes et al. (1995), water packaged in test pouches made of nylon/PVDC/EVAc and subsequently irradiated, exhibited a taint aftertaste that was noticeable at a dose of 1 kGy. Four main attributes were used to describe irradiated samples: metallic, plastic, penetrating, and acidic. They observed that this effect decreased with storage time and was not perceptible 3 weeks after irradiation with an e-beam, whereas in the case of γ -radiation the undesirable taste was still perceptible after 4 weeks of storage (Figure 3.13).

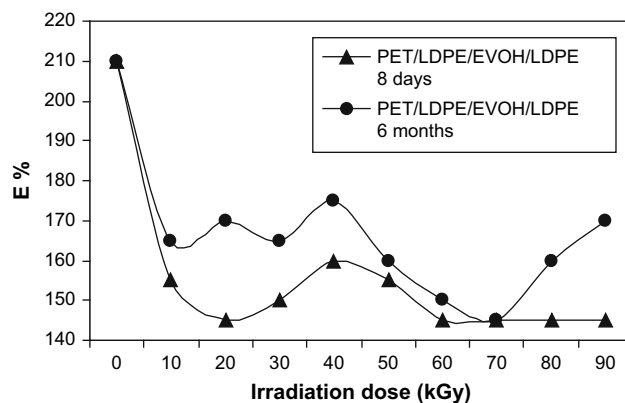


Figure 3.12: The impact of irradiation dose on %E of PET/LDPE/EVOH/LDPE at two storage times (adapted from Oliveira et al., 2009).

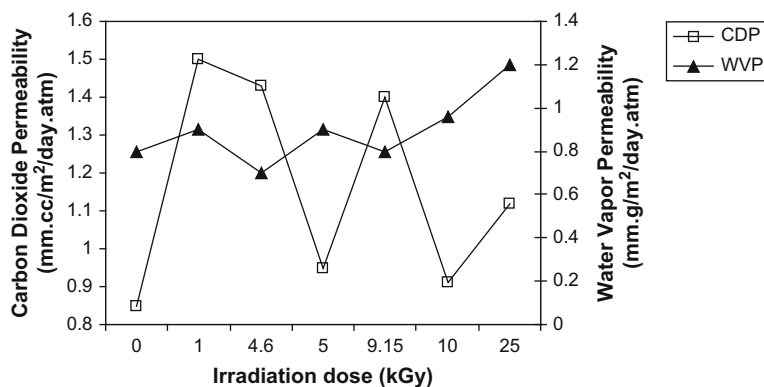


Figure 3.13: The effect of irradiation dose on carbon dioxide permeability and water vapor permeability of nylon/PVDC/EVAc (adapted from Deschenes et al., 1995).

Transparent PHB/PEG (95:5) blend films, flexible in comparison with the brittle pure PHB films, were irradiated at 5, 10, and 40 kGy. The TS and %E at break of the blend improved up to 10 kGy, thereby indicating that some cross-linking occurred within the 5- to 10-kGy dose range. At higher irradiation doses (40 kGy), mechanical properties testing was not possible because of film degradation (Parra et al., 2005). The vapor barrier property of the PHB/PEG blend was enhanced at low irradiation doses, probably due to the cross-linking effect that reduced the pore size within the blend structure (Figure 3.14).

Oliveira and co-workers (2009) reported the following results. Eight days after irradiation occurred, there were no significant differences ($p > 0.05$) in TS at break of PET/PP irradiated at 25, 30, and 45 kGy, but for the other irradiation doses an increase of up to 16% was reported. In contrast, 6 months after irradiation occurred, the TS of the PET/PP film increased ($p < 0.05$)

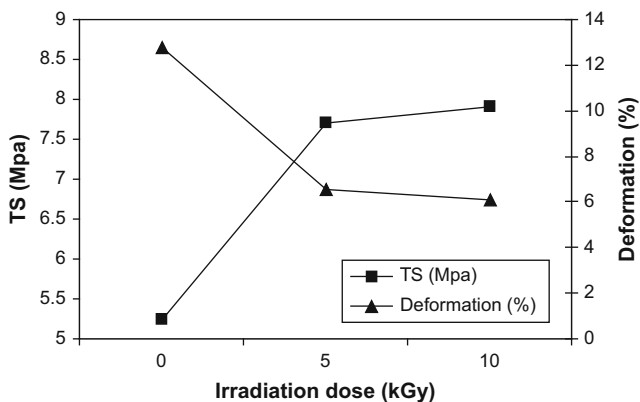


Figure 3.14: The impact of γ -irradiation dose on TS and percentage deformation of PHB/PEG blend films (adapted from Parra et al., 2005).

in the dose range of 5–15 kGy up to 13%, at 90 kGy approximately 7%, and at 105 kGy approximately 9%. In the case of PET/LDPE/EVOH/LDPE, the results of the tensile tests, 8 day and 6 months after irradiation, showed significant differences ($p < 0.05$) to some irradiation dose, but the TS of the film was slightly affected by irradiation, as indicated by changes lower than 5%. With regard to %E at break, 8 days after irradiation the PET/PP showed an increase ($p < 0.05$) up to 15% at lower doses (5–30 kGy), approximately 24% at 75 kGy, and approximately 32% at 105 kGy. Six months after irradiation, it was still higher, as indicated by an increase between 22 and 41% (approximately 41% at 5.15 kGy), except for the dose range of 75–120 kGy (rise at 90 kGy of approximately 12%; loss at 75 kGy of approximately 8%). Electron-beam irradiation (doses up to 45 kGy) caused a major improvement in %E at break of PET/PP, had almost zero effect on TS and penetration resistance, and caused a substantial drop in the sealing properties.

Volatile and nonvolatile radiolysis products and sensory changes of five-layer food packaging films [PA/ie (anhydride modified ethylene vinyl acetate copolymer)/100% virgin or 100% recycled LDPE or 50% virgin + 50% recycled L (3 options)/LDPE/LDPE] were investigated after exposure to γ -irradiation doses varying from 5 to 60 kGy (Chytiri et al., 2008). Of the 49 detected radiolysis products, 43 were identified and the structure of only 6 remained unknown. The 43 compounds were detected by means of migration testing involving contact of food stimulant with films irradiated at 5 and 10 kGy. It was found that an application of recycled LDPE had a favorable effect on both limiting radiolysis products and minimizing the effect on the sensory properties of table water in contact with films.

3.3 Natural Polymers

3.3.1 Zein/Corn

The impact of γ -irradiation (10, 20, 30, and 40 kGy) on zein, a predominant corn protein used to improve performance of the zein films in packaging applications, was investigated by Soliman et al. (2009). Gamma-irradiation of zein solutions initiated a disruption and/or an aggregation of the zein molecules based on viscosity measurements. The TS of zein films decreased with increasing radiation doses. A slight increase in TS was reported at a radiation dose of 20 kGy, whereas a more pronounced increase in %E was recorded with increasing radiation dose. The non-irradiated zein film had the highest WVP compared with the films prepared from irradiated solutions. Moreover, the WVP and Hunter b^* (color) values decreased with increasing irradiation doses.

Soliman and Furuta (2009) studied the effect of γ -irradiation on improving the performance of zein films. Film-forming solutions were irradiated with various γ -ray doses, namely 10, 20, 30, and 40 kGy, using Co^{60} γ -irradiation source. The obtained results of physical properties

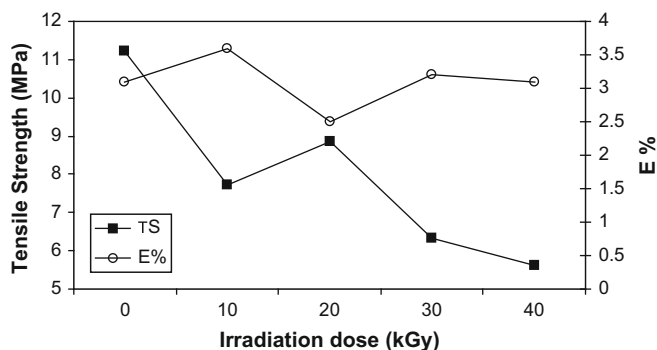


Figure 3.15: The effect of γ -irradiation dose on TS and %E of zein films (adapted from Soliman and Furuta, 2009).

revealed that γ -irradiation, apart from sterilization, was very effective at improving the water barrier properties, color, and appearance of the zein films (Figure 3.15).

3.3.2 Calcium Caseinate

Solutions of calcium caseinate (5%) with propylene glycol or triethylene glycol (0, 2.5, and 5%) were irradiated at doses between 0 and 128 kGy. Solutions were chromatographed through Toyopearl HW 55F resin to observe the effect of irradiation on cross-link reactions. In non-irradiated calcium caseinate solutions, two peaks could be observed (fractions 30 and 37), whereas samples irradiated at 64 and 128 kGy showed one shifted peak at fraction 32 and fraction 29, respectively. No effect of the plasticizers was observed. According to proteins standards of known molecular weights, the molecular weight of calcium caseinate increased approximately 10 times when irradiated at 128 kGy and 5 times when irradiated at 64 kGy. The physicochemical properties of biofilms prepared with the irradiated solutions demonstrated that TS at break increased with increased irradiation dose due to cross-linking (Lacroix et al., 1998).

3.4 Conclusions

Synthetic polymers such as PS, PET, and PA are more recalcitrant to γ -irradiation and e-beam irradiation than PE, PP, PVOH, and PVC. The resistance of PS and PET to irradiation is due to their aromatic polymeric structure, whereas polyolefins such as PE and PP have a less branched polymeric chain and, as a result, are more susceptible to degradation. PE is more resistant than PP because the former is more branched than the latter. Some typical radiolysis products that can act as migration indices for polyolefins are 1,3-di-*tert*-butyl-benzene and 2,4-di-*tert*-butylphenol due to Irgafos 168 degradation (Demertzis et al., 1999). For laminated films, the mechanical properties of PET/LDPE/EVOH/LDPE deteriorate more by irradiation than do PET/PP, except for the sealing properties that result in a greater loss for both irradiated

polymeric compositions (Oliveira et al., 2009). Regarding the edible films, at doses below 20 kGy, both TS and %E increase, whereas at higher doses TS exhibits a small decrease (Soliman and Furuta, 2009).

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Irradiation Detection

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4.1 Introduction

Irradiation has become one of the successful techniques to preserve food with minimum change to the functional, nutritional, and sensory properties of food products. This processing of food involves controlled applications of energy from ionizing radiations such as γ -rays, X-rays, and electron-beam (e-beam) for food preservation. The development of analytical methods for correct identification of irradiated samples from non-irradiated samples has thus become important for upholding regulatory controls, checking compliance against labeling requirements, facilitating international trade, and reinforcing consumer confidence (Chauhan et al., 2009).

According to Delincée (1999, 2002), European consumers have remained skeptical about food irradiation, and it is therefore not surprising that Europe took the lead in developing detection methods. An enormous effort, both on an international level (McMurray et al., 1996) and by the European Union (EU) (Raffi et al., 1994), was made toward identifying whether or not a food product has been irradiated. More than 30 interlaboratory blind trials were conducted to validate the proposed detection methods (Delincée, 1999).

Food such as chicken, shrimp, frog legs, spices, different dried vegetables, potatoes, and fruits is legally irradiated in many countries and is probably also exported into countries that do not permit irradiation of any food. Therefore, all countries must have in place analytical methods to determine whether food has been irradiated or not (Meier, 1991).

Food irradiation is the process of exposing food to a controlled source of ionizing radiation for the purposes of reduction of microbial load, destruction of pathogens, extension of product shelf life, and/or disinfestation of produce. Irradiation has received approval for use in several food categories from the U.S. Food and Drug Administration (FDA) and has been proven to be an effective food safety measure based on more than 50 years of research. However, food irradiation continues to generate controversy, inhibiting broad acceptance and use (Scott Smith and Pillai, 2004).

Although known in principle since the 1900s, irradiation of food with X-rays or γ -rays and by e-beam was only recently introduced as a technological process, mainly to reduce spoilage losses in food and to improve its hygienic quality. The radiation treatment of various foods is now legally accepted in more than 40 countries, but it is still prohibited in others (International Atomic Energy Agency [IAEA]/Food and Agriculture Organization [FAO]/World Health Organization [WHO], 1993; Vasseur, 1991).

Within Codex, food irradiation is classified as an additive. Thus, food irradiation falls under the jurisdiction of the Codex Committee on Food Additives and Contaminants (CCFAC). CCFAC depends on several sources of information in evaluating food additives. In the case of irradiation, CCFAC draws from the Joint FAO/WHO Expert Committees on Food Additives as well as the IAEA and the International Consultative Group on Food Irradiation. The original Codex General Standard for Irradiated Foods was developed in 1983. In 1999, the Codex Commission took the first step and decided to re-examine the standard by assigning the work to the CCFAC. During the following 4 years, seven more steps were taken before the new Codex General Standard for Irradiated Foods was finally accepted during the full Codex Commission meeting in Rome in 2003 (see www.codexalimentarius.net).

The joint FAO/IAEA/WHO expert committee reported that irradiation of food up to an overall average dose of 10 kGy presented no toxicological, nutritional, or microbiological hazard (WHO, 1999). Irradiation of foodstuffs is now permitted; however, it is compulsory to indicate on the label that foods have been irradiated even when the irradiated ingredients constitute <1% of the final product (Codex Alimentarius Commission, 1991; Ehlermann, 2002; European Commission, 1999; Luckman, 2002; Morehouse, 2002).

A further development in this area of food technology was the continued efforts of FAO, IAEA, and WHO to update existing knowledge in this field. These efforts resulted in a further review by WHO of the safety and nutritional adequacy of irradiated food, based on an appraisal of all relevant scientific studies carried out since 1980, at the request of one of the WHO member states, to establish whether any of the controversial issues and claims of adverse nutritional effects of irradiated foodstuffs had been substantiated in the intervening period (WHO, 1994).

A re-examination of the list of 63 unique radiolytic products extracted from the literature by the FDA in its initial assessment of food irradiation showed that only three volatile hydrocarbons deriving from food lipids had not been subsequently found in non-irradiated foods. These had a chain length of 1 C atom less than their homologs in untreated foods. In the view of WHO, it was likely that most nonvolatile radiolytic products would be found among the constituents of non-irradiated foods as well (WHO, 1999).

Since 1985, there has been a very strong interest in irradiated food, thereby reflecting an increased awareness about the benefits of food irradiation. Treatment of food with ionizing

radiation is increasingly being recognized as a means of reducing foodborne illnesses and associated medical and other costs (WHO, 1994).

The plethora of techniques suggested for the identification of irradiated food may be classified under three broad categories: physical, chemical, and biological (Haire et al., 1997).

4.2 Detection Standards

An important landmark regarding the detection standards occurred in December 1996 when the European Committee for Standardization (CEN) adopted five methods as European standards for the detection of irradiated food. The procedures adopted were electron spin resonance (ESR) spectroscopy methods for food containing bone and food containing cellulose, thermoluminescence (TL) for spices and herbs, and chemical methods based on isolation and detection of hydrocarbon and cyclobutanones in food containing fat (Stewart et al., 2000).

The Australia New Zealand Food Standards Council approved Standard A-17- Food Irradiation for inclusion in the Australian Food Standards Code (1991) in compliance with the publication of the Australian House of Representatives' report (Statutory Instrument 1990 No. 2490; see also IAEA/FAO/WHO, 1993; WHO, 1994) on food irradiation. This Standard referred to "dried aromatic herbs, spices, and vegetable seasonings" that may be irradiated up to an overall average absorbed dose of 10 kGy. In Canada, the irradiation of spices, herbs, and dry vegetable seasonings has been approved to a maximum dose of 10 kGy. Approximately 90 million pounds of herbs, spices, and vegetable seasonings are irradiated in the United States per year.

TL has been validated as a qualitative analysis method (EN 1788:2001) for the detection of irradiation treatment. It is based on the evaluation of the ratio between the TL intensity of the minerals separated from the food sample under investigation and of the same minerals after irradiation at 1 kGy. The sample is considered irradiated if the TL ratio is greater than 0.1, whereas it is considered not irradiated if it is lower than 0.1. However, this procedure cannot provide information on the original dose received by the food (D'Oca et al., 2009).

A concerted research study carried out by the Community Bureau of Reference (Brussels) from 1989 to 1993 (Raffi et al., 1994) resulted in the proposal of five methods of detection to the European Committee for Standardization that were later validated by the latter. These methods, based on the study of primary radiolytic products with ESR and TL or on the analysis of certain chemical compounds [volatile hydrocarbons and 2-alkylcyclobutanones (2-ACBs)] formed by the radiolysis of triglycerides, were validated on foodstuffs irradiated at doses usually higher than 0.5 kGy (microbial disinfection). The limit of detection of the CEN method (signal:background noise signal of 3:1) was estimated to be 0.2 pmol, irrespective of the 2-ACBs analyzed (measurements carried out on samples of cheese, chicken, sardine, and mango). The minimal detectable doses may

vary between 0.2 and 0.4 kGy depending on the major precursor fatty acid content. By accepting a maximal value of 0.5, this range becomes 0.4–0.8 kGy. The detection of this treatment is then easy in foodstuffs with a fat content higher than 1 g% and will certainly remain so as long as the fat content remains higher than 0.5 g% (low-fat fish). It is noteworthy that it was not possible to detect such treatment in rice samples irradiated at 0.1 kGy (thus confirming the validity of formula that indicates in this case a minimal detectable dose of 0.2 kGy). [Ndiaye et al. \(1999a\)](#) noted:

An extension of the field of application of the CEN method to the detection of foodstuffs with low fat contents (<1 g%) irradiated at doses lower than 0.5 kGy or to that of irradiated at doses lower than 0.5 kGy or to that of irradiated ingredients incorporated at a low percentage in a non-irradiated foodstuff seemed, however, particularly attractive (and desirable) since the detection of 2-alkylcyclobutanones currently seems to be a very specific test for an irradiation treatment. Such an objective will nonetheless require an increase in the sensitivity of this method by a factor of 10 to 20, for example by achieving a more specific extraction of the 2-alkylcyclobutanones from the food sample by performing a pre-column purification of the extract to be analyzed (with concentration of 2-ACB) and/or by using a more sensitive detection device than the mass spectrometer.

[Ndiaye et al. \(1999b\)](#) included a purification step by silver ion chromatography in the EN 1785 analytical protocol for 2-ACBs (validated by the European Committee for Standardization for the detection of ionizing radiation treatment). As a result, the quality of the chromatograms obtained improved, thereby enabling the detection of food samples irradiated at very low doses (0.1 kGy) or irradiated ingredients included in low proportions in non-irradiated foodstuffs.

EN 1784:1996 specified a method for the identification of irradiation treatment of food containing fat. The method was successfully tested in interlaboratory tests on raw chicken, pork, and beef as well as on Camembert cheese, avocado, papaya, and mango. Detection of irradiated raw meat and Camembert cheese has been validated for doses of approximately 0.5 kGy and higher, whereas detection of irradiated fresh avocado, papaya, and mango has been validated for doses of approximately 0.3 kGy and higher.

EN 1785:2003 was prepared by Technical Committee CEN/TC 275. This European standard specifies a method for the identification of irradiation treatment of food containing fat by means of gas chromatography–mass spectrometry (GC/MS). The method has been successfully tested in interlaboratory trials on raw chicken, pork, liquid whole egg, salmon, and Camembert cheese, whereas it failed in the case of mangoes and papayas. The 2-ACBs that were analyzed in interlaboratory studies were 2-dodecylcyclobutanone (DCB) and 2-tetradecylcyclobutanone (TCB), which are formed from palmitic and stearic acid, respectively, during irradiation ([Stevenson, 1992, 1994](#)).

EN 1786:1997 specifies a method for the detection of meat containing bone, and fish containing bone that have been treated with ionizing radiation, by analyzing the ESR

spectrum, also called the electron paramagnetic resonance (EPR) spectrum, of the bones. Interlaboratory studies have been successfully carried out with beef bones, trout bones, and chicken bones. In the case of meat bones, the results of this detection method are not significantly influenced by heating of the sample (e.g., boiling in water). Detection of irradiation treatment is not significantly influenced by storage times of up to 12 months.

EN 1787:2000 specifies a method for the detection of food containing cellulose that has been treated with ionizing radiation, by analyzing the ESR spectrum of the food. Interlaboratory studies have been successfully carried out with pistachio nutshells, paprika powder, and fresh strawberries. Detection of irradiated pistachio nuts has been validated for doses of 2 kGy and higher, whereas paprika powder has been validated for doses of 5 kGy and higher. Moreover, fresh strawberries have been validated for doses of 1.5 kGy and higher.

EN 1788:2001 specifies a method for the detection of irradiation treatment of food and/or food ingredients by TL analysis of contaminating silicate minerals. The method has been successfully tested in interlaboratory tests with herbs and spices as well as their mixtures, shellfish including shrimps and prawns, both fresh and dehydrated fruits and vegetables, and potatoes. Detection of irradiated shellfish has been validated for the range of 0.5–2.5 kGy, whereas it has been validated for doses of approximately 1 kGy for fresh fruits and vegetables.

EN 13708:2001 specifies a method for the detection of foods containing crystalline sugars that have been treated with ionizing radiation, by analyzing the ESR spectrum of the food. Interlaboratory studies have been successfully carried out on dried figs, dried mangoes, dried papayas, and raisins. Detection of irradiated dried figs, dried mangoes, dried papayas, and raisins has been validated.

EN 13751:2002 specifies a method for the detection of irradiated foods using photostimulated luminescence (PSL). It is necessary to confirm a positive screening result using calibrated PSL or another standardized (e.g., EN 1784–EN 1788) or validated method. The method has been successfully tested in interlaboratory trials using shellfish, herbs, spices, and seasonings.

EN 13783:2001 specifies a microbiological screening method for the detection of irradiation treatment of herbs and spices, using the combined direct epifluorescent filter technique (DEFT) and aerobic plate count (APC). It is recommended to confirm positive results using a standardized method (e.g., EN 1788 and prEN 13751) to specifically prove an irradiation treatment of the suspected food. The method has been successfully tested in interlaboratory tests with herbs and spices. Some spices such as cloves, cinnamon, garlic, and mustards contain inhibitory components with an anti-microbial activity that may lead to decreasing APC (false-positive result).

EN 13784:2001 specifies a screening method for foods that contain DNA. The DNA comet assay is not radiation specific; therefore, it is recommended to confirm positive results using a standardized method to specifically prove an irradiation treatment of the respective

food (e.g., EN 1784–EN 1788, EN 13708, and prEN 13751). Interlaboratory studies have been successfully carried out with a number of food products, both of animal and of plant origin, such as various meats, seeds, dried fruits, and spices.

EN 14569:2004 specifies a microbiological screening method comprising two procedures, which are carried out in parallel. It permits the identification of an unusual microbiological profile in poultry meat. It is recommended that a positive result be confirmed using a standardized reference method for the detection of irradiated food (e.g., EN 1784–EN 1786). This screening method has been successfully tested by interlaboratory trials, and the procedure is generally applicable to whole or parts of poultry (e.g., breast, legs, and wings of fresh, chilled, or frozen carcasses with or without skin).

Table 4.1 presents the EN standards applicable to food irradiation detection in foods.

4.3 Detection Methods

Detection methods for irradiated foods are being developed continuously. Ideally, such methods should be simple, accurate, easy to perform, rapid, and inexpensive. It is considered that availability of such detection methods would improve standard regulatory procedures, which would help to strengthen the national regulations on the irradiation of specific foods and would be of assistance in establishing a system of legislative control and enhance consumer confidence in such regulations and acceptance of irradiated foods. Unfortunately, no single method can be applied to all food systems. Different foods vary in their chemical composition and physical and quality attributes (Chauhan et al., 2009).

The various mechanisms of radiolysis have been widely studied, and its results can be used in identifying potential identification tests. However, the most difficult problem has been the fact that the changes that occur in irradiated foodstuffs are rather slight and are generally similar to those produced by classic food treatment processes (heating and freezing) or natural spoilage (autoxidation). Most detection methods have been thoroughly discussed in the literature (Bögl et al., 1988; Raffi et al., 1996).

Detection methods based on EPR (ESR) spectroscopy seem particularly promising with respect to foods that contain solid constituents such as bones, seeds, and husks. Early EPR studies on bone and other kinds of mineralized tissues exposed to radiation are discussed in the literature (Dodd et al., 1985; Raffi and Angel, 1989).

According to Stevenson and Stewart (1995), the most common methods for the detection of irradiated food are the physical techniques of ESR and TL; the chemical approach of cyclobutanones and hydrocarbons; and the biological assays DEFT/APC, DNA comet, enzyme-linked immunosorbent assay (ELISA), and limulus amoebocyte lysate.

TABLE 4.1 EN Standards Application for Irradiation Detection in Food

| Standard | Pretreatment | Determination Methods | Identified Compound | Applied Successfully in Foods | Limitations | Validation |
|--|--|-----------------------|------------------------|---|--|---|
| EN 1784:1996 | The fat is isolated from the sample by melting it out or by solvent extraction | GC Hydrocarbons | Radiolytic products | Raw chicken, pork, beef, camembert, avocado, papaya, mango | Only for doses >0.5 kGy and in some foods >0.3 kGy | 4, 8, 17, and 22 laboratories of BCR respectively analyzed 160 samples of chicken (5 kGy), 126 samples of chicken meat (0.5–5 kGy), 140 samples of pork and 136 samples of beef (0.8–7 kGy), and 126 samples of Camembert, 103 samples of avocado, 104 samples of papaya, and 98 samples of mango (0.3–1 kGy) |
| EN 1785:2003 (supersedes EN 1785:1996) | Extraction of fat with <i>n</i> hexane, <i>n</i> pentane | GC/MS | DCB TCB | Raw chicken, pork, liquid whole egg, salmon, Camembert (nonapplicable in mangoes and papayas) | Only for doses >0.5 kGy and in some foods >1 kGy | 5, 11, and 7 laboratories of BCR respectively analyzed 99 samples of chicken (0.5–5 kGy), 99 samples of liquid whole egg and 72 samples of pork (1–3 kGy), and 63 samples of salmon and 63 samples of Camembert (1–3 kGy) |
| EN 1786:1996 | Production of quite stable radicals in solid and dry components | ESR EPR | Paramagnetic compounds | Beef bones, trout bones, chicken bones | Some foods are affected by the degrees of mineralization and crystallinity of hydroxyapatite. The bones of larger animals and species are highly mineralized with low minimum detectable doses. Not significantly influenced by heating and storage times of up to 12 months | 21 and 18 laboratories of BCR respectively analyzed 84 samples of beef bones and 84 samples of trout bones (2–7 kGy) and 108 samples of chicken and 108 samples of trout bones of (2–6 kGy) |

(Continued)

TABLE 4.1 EN Standards Application for Irradiation Detection in Food—cont'd

| Standard | Pretreatment | Determination Methods | Identified Compound | Applied Successfully in Foods | Limitations | Validation |
|---------------|---|-----------------------|------------------------|---|--|---|
| EN 1787: 2000 | Production of quite stable radicals in solid and dry components | ESR EPR | Paramagnetic compounds | Pistachio nut shells, paprika powder, fresh strawberries | Crystalline cellulose content and the moisture content altered in pistachio nuts >2 kGy, in paprika powder >5 kGy, and in fresh strawberries >1.5 kGy | 21, 17, 20, and 23 laboratories of BCR respectively analyzed 84 samples of pistachio shells (2-7 kGy), 68 samples of pistachio shells (4-6 kGy), 160 samples of paprika powder (5-10 kGy), and 184 samples of strawberries (1.5-3 kGy) |
| EN 1788:2001 | Silicate minerals are therefore isolated from the foodstuffs | TL | Silicate minerals | Herbs, spices, shrimp, prawns, fresh and dehydrated fruits and vegetables, potatoes | Depend on the quantities and types of minerals recovered from individual samples; in herbs and spices >6 kGy, in shellfish 0.5-2.5 kGy, in fresh and dehydrated fruits and vegetables >1 kGy, in fruits >8 kGy | 7 and 9 laboratories of BCR respectively analyzed 103 samples of prawns (Norway lobsters), black tiger prawns, brown shrimps, mussels, and king scallops (0.5-2.5 kGy) and 327 samples of fruits and vegetables (1 kGy); 1 laboratory analyzed 220 samples of apple cubes, sliced carrots, leeks and onions, and powdered asparagus (8 kGy) |
| EN 13708:2001 | — | ESR EPR | Paramagnetic compounds | Dried figs, dried mangoes, dried papayas, raisins | The lower limit of detection mainly depends on the crystallinity of the sugar in the sample. Irradiation treatment is not significantly influenced by storage of at least several months, the presence of sufficient quantities of crystalline sugar in the sample | 2 and 17 laboratories of BCR respectively analyzed 126 samples of raisins and 126 samples of dried papayas (0.5-7 kGy) and 184 samples of dried mangoes and 184 samples of dried figs (1-5 kGy) |

| | | | | | | |
|---------------|---|---|---|--|---|---|
| EN 13751:2002 | — | PSL | Mineral debris | Shellfish, herbs, spices and seasonings | The presence of salt in a product may dominate the PSL intensity. Hydration of the product followed by re measurement | 5 laboratories of MAFF analyzed 120 samples of shellfish, 320 herbs and spices, and 344 seasonings and blends (0.5 2.5 kGy) |
| EN 13783:2001 | — | DEFT APC Comparison of the APC with the count obtained using DEFT | Viable micro organisms stained with acridine orange | Herbs, spices | The presence of too few microbes in the sample (APC < CFU/g). The presence of spices, peppers, and cardamom may lead to positive results | 8 laboratories of BCR analyzed 192 samples of whole all spice, whole and powdered black peppers, whole white pepper, paprika powder, cut basil, cut marjoram, and crushed cardamom (5 10 kGy) |
| EN 13784:2001 | — | DNA comet assay Electrophoresis time and field strength | Microgel electrophoresis (agarose) | Chicken, duck, quail, pheasant, pork, boar, beef, veal, lamb, deer, fish (trout, salmon), almonds, figs, lentils, soybeans, carioca and macaçar beans, strawberries, grapefruit, linseed, sesame seeds, sunflower seeds, rosé pepper | Insufficient lysis of the cells Determination of proper conditions (lysis time, electrophoresis time, field strength) In some species (nuts, fish), it may be difficult to obtain cells | 9 laboratories in Sweden analyzed three kinds of cell suspensions of irradiated (0 5 kGy) and non irradiated samples; 138 out of 148 samples were correctly identified |
| EN 14569:2004 | — | Limulus amoebocyte lysate Gram negative bacteria | Endotoxin Lipopolysaccharides | Parts of poultry (e.g., breast, legs, wings of fresh chilled or frozen carcasses with or without skin) | Indication of possible treatment Freezing after irradiation can affect the ratio of GNB to EU due to microorganism loss | 20 laboratories in the United Kingdom participated in the trial 100% of non irradiated, 27% of chicken with skin (2.5 kGy), 88% of skinless fillets (2.5 kGy) |

BCR, Community Bureau of Reference; MAFF, Ministry of Agriculture, Fisheries and Food.

4.3.1 Physical

4.3.1.1 ESR or EPR

ESR is a spectroscopic method that permits the observation of unpaired electrons, especially free radicals induced by irradiation. ESR can be used as an identification test if the radicals are stable during commercial storage of the food. This only occurs in the solid and dry components of the food, where the reactivity of the radicals with each other or with water is low (Raffi, 1992; Raffi and Benzaria, 1994; Swallow, 1990).

EPR is a user-friendly technique because the measurement is facile and the sample under test does not require any preparation. There is an increasing interest in extending the EPR methodology to various types of food. The main problem concerns the instability of the relatively weak radiation-specific signals. In order to extend the applicability of EPR for identification of irradiated food, an approach based on thermal treatment and EPR saturation has been used when radiation-induced signals disappear due to a long period of time elapsed after treatment (Yordanov and Gancheva, 2000; Yordanov et al., 2005).

Foods of plant origin

Various vegetable food materials (dried cabbage, carrot, chunggyungchae, garlic, onion, and green onion) were first irradiated and then detected with ESR. Pre-established threshold values were successfully applied to the detection of 54 coded unknown samples of dried clean vegetables (chunggyungchae, *Brassica campestris* var. *chinensis*), both non-irradiated and irradiated. The ESR signals of irradiated chunggyungchae, even after 6 months of ambient storage, were still distinguishable from those of non-irradiated samples. The most successful estimates of absorbed dose (5 and 8 kGy) were obtained immediately after irradiation using a quadratic fit, with average values of 4.85 and 8.65 kGy being calculated (Kwon et al., 2000).

Helle et al. (1992) noted:

Irradiated dried fruit were identified easily, because non-irradiated samples gave no ESR spectra, while irradiated fruit show a partially resolved spectrum, due to the radiation-induced sugar radicals. Interestingly, the structure of the resulting spectra is not identical for all irradiated species of fruit. Irradiated nutshells showed an ESR spectrum which revealed two additional lines (from cellulose radicals) beside the main signal, while non-irradiated samples showed only the main signal. Irradiation-specific ESR signals of the cellulose radical were not only found for nutshells but for fresh fruit and some spices as well, while most of the irradiated spices and herbs could not be identified by ESR measurements.

Promising results were also obtained with pressed dates and figs irradiated with doses between 0.6 and 2 kGy. In seeds separated from irradiated fruits, multicomponent signals of much higher intensity than those of non-irradiated samples were recorded. The hygiene quality of dried mushrooms is often not satisfactory, and irradiation is one of the methods

recommended for preservation treatment. Stachowicz et al. (1992) reported that the exposure of mushrooms to a dose of 7 kGy produced the complex EPR signal with strong singlet. According to Stachowicz et al. (1993), the EPR signal in gelatin irradiated with 7 kGy is isotropic doublet with $g_0 = 2.0032$ and $A = 1.8$ mT. The signal was stable and was registered in gelatin after several months of storage. In dehydrated macaroni, a broad EPR signal with $g_0 = 2.008$ and $\Delta H_{pp} = 2.1$ mT was registered after irradiation at a dose of 7 kGy.

One variety (Apple) of Libyan dry dates (*Phoenix daetylifera* L.) was irradiated by means of a cobalt-60 (^{60}Co) source at doses of 0.8, 1.0, 1.5, and 2.0 kGy. Non-irradiated date stone contained a radical with a single line $g = 2.0045$. Irradiation to a dose of 2.0 kGy induced the formation of additional radicals with signals $g = 1.9895$ and 2.0159 . The single line having $g = 2.0045$ decayed in both unirradiated and irradiated samples, whereas the signals $g = 1.9895$ and 2.0159 remained almost unaltered during 15 months stored at room temperature and 4°C (Ghelawi et al., 1996).

According to Polat and Korkmaz (2003), an ESR investigation on irradiated dry broad bean gave a spectrum composed of an equally spaced sextet and a single resonance line. These lines appeared at $g = 2.0045$ and originated from Mn^{2+} ions and radiation-induced radicals, respectively. Ground broad beans were used throughout to avoid any artifacts arising from microwave cavity filling factor. Free radical signal intensity increased exponentially in relation to the increase in absorbed dose over the dose range 1.25–15 kGy. More rapid decays of ESR signals were observed at high annealing temperatures. An increase in the radical signal intensity was obtained above a critical annealing temperature due to thermal induction of new radical species with similar spectroscopic features as those of the radical species observed for non-irradiated samples.

Employment of ESR revealed free radicals in wheat flour before and after γ -irradiation and their thermal behavior during heat treatment. According to Shimoyama et al. (2006), the ESR spectrum of wheat flour before irradiation consists of a sextet centered at $g = 2.0$ and a singlet signal at the same g -value position. The first one is attributable to a signal with hyperfine (HF) interactions of Mn^{2+} ion (HF constant = 7.4 mT), whereas the second originated from carbon-centered radical. However, upon γ -ray irradiation, a new signal with two triplet lines at the low and high field ends was detected in wheat flour on top of the Mn^{2+} sextet lines. The triplet ESR lines were analyzed as powder spectra (rhombohedral g -tensor symmetry) with nitrogen (N-14) HF interactions. This indicates that a new organic radical was induced in the conjugated protein portion of wheat flour by the γ -ray irradiation. Intensity of the organic free radical at $g = 2.0$ detected in irradiated wheat flour increased monotonically by the thermal treatment. Analysis of the time-dependent evolution and decay process based on the theory of transient phenomena as well as the nonlinear least-squares numerical method provided a unique time constant for the radical evolution and decay in wheat flour during the heat treatment.

Polat and Korkmaz (2003) reported on an ESR investigation of time stability and temperature dependence of the free radicals produced in a species of rice seeds irradiated at doses of up to 5 kGy by a γ -source. Three different radicals were tentatively identified as hydroxyalkyl (I), aldehydalkyl (II), and an unknown species (III). Peak-to-peak intensity of this signal was found to depend linearly on the absorbed dose in the radiation dose range 0.5–5.0 kGy. From the analysis of the ESR signal, dependence was shown on absorbed dose and elapsed time after irradiation and temperature. It was concluded that I13 signal intensity could be used to distinguish the irradiated rice seed from unirradiated seeds even 2 months after irradiation.

A protocol dealing with detection (ESR and TL) of irradiated ingredients included at low content in non-irradiated food was put forward by Marchioni et al. (2005). According to this protocol, an enzymatic method was developed (at 88°C) for the extraction of silicate minerals and bone fragments, followed by purification of extracts with an aqueous solution of sodium polytungstate. This protocol, in conjunction with TL, enabled the effective detection of irradiated spices at low concentrations contained in several foods.

Monsooned coffee beans packed in BOPP (25 μ m) bags were subjected to γ -radiation doses (for hygienic and quarantine purposes) of 0.25, 0.50, 0.75, and 1 kGy in a Gammacell 220. Free radicals in two cultivars of irradiated Indian monsooned coffee beans were examined by entrapping the small amount of samples in potassium chloride powder in ESR quartz tubes. The ESR signal was found to be more prominent in the spermoderm than in the whole seed portion of the normal coffee beans. Common practices of roasting and powdering were shown to generate quantitatively more free radicals in coffee beans than γ -irradiation. Phenols responsible for the formation of free radical signals in coffee beans were significantly different in monsooned coffee beans due to their inherent possession of high water activity, thereby favoring the decay of free radicals produced. Further textural studies on monsooned coffee beans, both before and after mild heat treatments, supported the authors' findings (Bhushan et al., 2003).

Dried almonds, raisins, dates, and pistachio were irradiated using either γ -radiation or e-beam at an average absorbed dose of 5 kGy. To detect the radiation level to which they were exposed, the dried fruits (skin, dried pulp and stone, and nutshell) were analyzed with ESR spectroscopy. Analyses were carried out 2 or 3 months and 6 months after irradiation. A series of signals tentatively described as “cellulose-like” (almond skin and pistachio shell), “sugar-like” (raisin and dried pulp), and “complex” (date stone) were recorded (Esteves et al., 1999), and some slight differences between spectra from samples irradiated with γ -rays and e-beam were reported.

Sünnecioglu and Dadayli (2000) performed an EPR spin probe study of wheat seeds irradiated at different doses. The spectra of dry seed embryos kept for 150 min were recorded at various times during the air-drying process. The simulation of these spectra indicated a decrease in the water content of the embryos depending on the increasing

irradiation dose. This implied that the increase in membrane permeability was a result of the radiation damage. The recorded spectra for control and irradiated samples indicated a change in the spectrum shape depending on irradiation dose. This change was especially effective at $m_1 = 1$ high field line, which was split into lipid and aqueous parts. These relative changes in spectra were due to changes in the membrane permeability as a result of irradiation.

Gamma ray irradiation is a food preservation technique with the potential to protect cereal grains from insect infestation and microbial contamination during storage. The decay of the radicals produced by irradiation makes application of the EPR technique impractical for the detection of irradiated wheat when the storage time is excessive (Sünnetcioglu et al., 1997). Sünnetcioglu and co-workers irradiated durum wheat samples (cv. Kunduru-1149) with doses of 1, 2.5, 5, 10, and 20 kGy using γ -radiation from a ^{60}Co source. The absorbed dose rate was 6 kGy/h. Experiments were carried out using embryos of the wheat kernels stored for 4 months prior to EPR study. Dadayli et al. (1997) reported that EPR could not effectively detect wheat samples irradiated at doses of 10 and 20 kGy once they were stored for 6 months after the irradiation processing. It was shown that the limit of detection of irradiation in wheat was as low as 2.5 kGy. Although the decay of EPR signal in cereals was rapid, the introduction of the EPR spin probe technique abolished the time limitation factor and irradiated factors, and it became possible to detect irradiated samples even after long storage periods.

Black pepper is irradiated at 10, 30, and 50 kGy at room temperature following IAEA/WHO standards (Joint FAO/IAEA Division, 1994). Ukai et al. (2006) conducted ESR measurements at the Xband (9.3 GHz). Although free radicals were found in non-irradiated pepper, upon irradiation, ESR revealed five distinct signals. The progressive saturation behavior (PSB) at different ESR microwave power levels showed quite different relaxation behaviors. A new protocol for the ESR detection of irradiated foods was proposed for the PSB method at different microwave power levels.

Raffi et al. (2000) applied official EPR and TL European protocols to perform a systematic study on storage time and determine the respective advantages and disadvantages of EPR, direct TL, and TL after extraction of silicate mineral contamination. Non-irradiated samples of all studied plants exhibited a very weak EPR singlet line, whereas the appearance of the triplet feature was considered to be unambiguous evidence for the previous radiation processing of the sample under investigation and is used as such in the CEN protocol EN 1787. EPR is a very useful tool for unambiguous identification of radiation treatment for stone or shell containing fruits for more than a 1-year period.

EPR was applied to fresh fruits (whole pulp of pears, apples, peaches, apricots, avocado, kiwi, and mango) before and after γ -irradiation using two drying procedures. The removal of water from irradiated and non-irradiated samples was carried out by pressing the pulp of fresh fruit, washing it with alcohol, and drying. The second method consisted of drying the fruits in the

oven at 40°C. All showed a single EPR line with $g = 2.0048$ before irradiation. Irradiation gave rise to the typical “cellulose-like” EPR spectrum featuring one intensive line with $g = 2.0048 \pm 0.0005$ and two very weak satellite lines situated 3 mT to the left and right of the central line. When the irradiated fruit samples were stored in their natural state and dried just before each EPR measurement, the satellite lines were measurable for less than 17 days of storage. The obtained results showed that the presence of the satellite lines in the ERP spectra could be effectively used for identification of radiation processing of fresh fruits, thereby supporting the validity of European Protocol EN 1787:2000 (Yordanov and Aleksieva, 2009).

Oliveira and del Mastro (2007) used EPR spectroscopy to investigate free radicals formed in γ -irradiated Brazilian soybean (*Glycine max*) cultivars. The beans were irradiated with a ^{60}Co source with doses ranging from 1 to 15 kGy. Before irradiation, the representative soybean EPR spectrum was composed of a sextet centered at $g = 2.0$ and a sharp singlet at the same g value. The stability of the EPR signal of 10-kGy irradiated samples remained for more than 7 months after irradiation. Radiation was observed to cause an exponential increase in the intensity of the singlet resonance line but did not create any effect on Mn^{2+} ion resonance line intensities in the range of 1–15 kGy. For higher doses, its EPR intensities remained considerably higher than those observed in non-irradiated samples even several months after irradiation.

Four different spices produced in Mexico, namely black pepper and two kinds of chili and oregano, were studied by EPR technique for detection purposes (Bortolin et al., 2006). The irradiation of herbs and spices induced at least two EPR signals overlapping the native signal: an intense singlet and a weak triplet with hyperfine splitting of 3 mT due to cellulose free radicals. The cellulose signal was not detectable in oregano, indicating a low content of cellulose in the product. Although the difficulty in detecting the cellulose signal in black peppers has been widely reported, the signal of respective samples of Mexican origin was visible for several months irrespective of the irradiation dose. The stability of the cellulose signal was restricted to a few months. Although signal fading may prevent the application of CEN standard EN 1787 for the entire shelf life of the product, EPR can still be used as a major detection tool to determine the potential importation. TL could be employed in conjunction with EPR because the former gave valid results for all spices even 2 years after irradiation.

Ukai and co-workers (2006) tried to detect by means of ESR the irradiated black pepper at 50 kGy. In fact, these researchers put toward a modification of the original CEN protocol for irradiation detection by including a thermal microwave (MW) treatment. These authors derived the following conclusions:

Application of ESR spectroscopy revealed three radical components in the commercially available pepper in Japan. After irradiation, however, five distinct signals were identified in the same pepper. The progressive saturation behavior of the ESR MW power demonstrated quite different relaxation

behaviors of the radicals in the non-irradiated black pepper. The peak intensity of the free radical component decreased in a monotonic fashion, whereas the Mn^{2+} component was substantially kept constant. A protocol for the ESR detection of irradiated foods was proposed with the PSB method at different microwave power levels, which calls for a major modification of the EU protocol.

Yordanov and co-workers (2005) found that naturally present and radiation-induced EPR signals in plants have equal γ -factors in X- and Q-band spectra and thus are indistinguishable independently of their different origins. They demonstrated that both species could be distinguished by using the effect of partial saturation of their EPR signals with increasing MW power incident in the EPR cavity. This method was based on the difference in the temperature dependence and EPR saturation behavior of their signals. The new observation was that the intensity of the EPR spectrum of irradiated sample recorded at low MW power decreased upon heating (60°C, 60 min). The kinetic curve of increasing EPR intensity of dry plants recorded at 100 and 1 mV MW power is shown in Figure 4.1.

The status of free radicals present naturally, after irradiation, and after conventional processing was determined by entrapping small quantities of seed samples in potassium chloride powder in ESR quartz tubes. The ESR signal intensity was more pronounced in seed coat than in the cotyledon portion. Seed irradiation (0, 2.5, 5, 7.5, 10, 15, and 30 kGy) revealed a dose-dependent increase of signal intensity both in seed coat and in cotyledon. The considerable decrease in cotyledon ESR signals (irradiation dose of 15 and 30 kGy) could be related to the release of a high amount of polyphenols, which act as radical scavengers (Bhat et al., 2007). The impact of γ -irradiation on total phenolics (g/100 g) and ESR signal intensity in seed coat and the cotyledon portion of *Mucuna* seed is displayed in Figure 4.2.

An ESR study of free radicals in spicy paprika in various phases of grinding and in samples of different particle sizes as a function of the absorbed gamma dose and storage time was carried

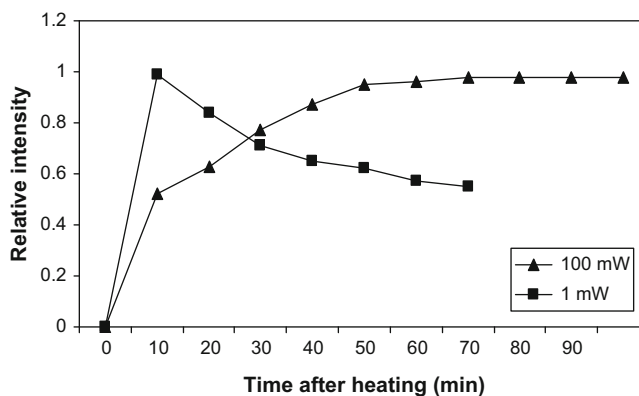


Figure 4.1: Typical kinetic curve of increasing EPR intensity of a dry plant recorded at 100 and 1 mV microwave power on heating at 60°C (adapted from Yordanov et al., 2005).

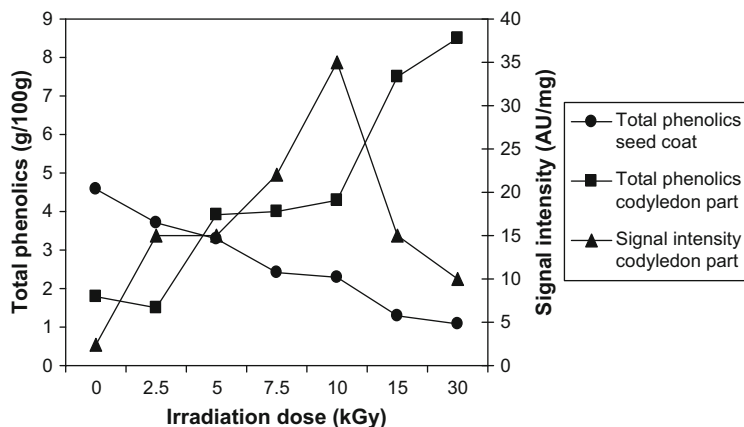


Figure 4.2: Radiation dose-dependent changes in total phenolics (g/100 g) and free radicals (ESR signal intensity) in the seed coat and cotyledon portion of *Mucuna* seed (Bhat et al., 2007).

out by Kispeter et al. (1999). In the seventh phase of grinding, the ESR intensity first increased and then decreased after conditioning. The ESR intensity of each fraction decreased to a similar low level within 4 weeks. The ESR intensity increased with the absorbed dose in each case and then decreased in two steps (a rapid one and a slow one), implying that the changes induced by irradiation produce free radicals with short and long half-lives.

EPR spectra of biological substances treated with ionizing radiation were first recorded by Gordy et al. in 1955. Sixteen years passed before these measurements were used to produce a practical method for detecting irradiated foods (Boshard et al., 1971).

Foods of animal origin

Generally, it is advisable for mechanically recovered chicken to undergo cooking directly after manufacturing for consumer safety purposes. Marchioni et al. (2005) included an enzymatic hydrolysis in the protocol EN 1786 in order to detect irradiation bone-containing ingredients. After purification of the extracts with an aqueous solution of sodium polytungstate, this method made possible the detection of irradiated mechanically recovered poultry meat (MRM) at very low inclusions (0.5% w/w by ESR) in various meals (quenelles and precooked meals). Due to the high sensitivity and selectivity of the analysis method, it was possible to detect fish fillets containing 10 times less bone (0.3 mg of fish bone/g of fish) than MRM, as well as complex food containing a large number of plants.

Meat and seafood samples (frog leg bone, wingtip bone of chicken, rib of black rockfish, and shells of clams) were irradiated at several doses (0.05, 1, and 3 kGy) at 10°C. Based on the ESR spectra, the minimum detectable doses for frog leg bone, wingtip bone of chicken, rib of black rockfish, and shells of clams were 1, 1, 1, and 0.5 kGy, respectively (Miyahara et al., 2004). According to Miyahara and co-workers, the intensities of the peaks at 2.004

in the ESR spectra of frog leg bone and at 2.0057 of black rockfish rib did not change as the dose increased. In contrast, the corresponding peaks of wingtip bone of chicken ($g = 2.0087$) and shells of clams ($g = 2.0125$) slightly increased as the dose increased. The ESR method can successfully identify the irradiated frog leg bone, wingtip bone of chicken, rib of black rockfish, and shells of clams. The absorbed dose of some samples can be estimated by dose–response curves. However, the ESR spectrum of an irradiated sample can vary considerably from sample to sample.

A series of experiments were performed to investigate the effect of irradiation dose and chicken storage time on the intensity of the recorded ESR signal. Seventy-two pairs of drumsticks from broilers of the same age and reared in the same commercial facility were used. Twenty-four pairs of drumsticks per batch were further divided into six groups, and five of them were irradiated with one of five doses (2, 4, 6, 8, and 10 kGy), whereas the remaining group served as control. A clear detectable difference in the shape of signals from irradiated and non-irradiated samples was recorded, and signals from irradiated ones had a characteristic shape. The different storage times did not significantly affect the response of ESR signal intensity along the shelf-life of chicken (Dulkan et al., 1998).

Frozen samples of chicken drumsticks were individually sealed with domestic plastic and irradiated to ambient temperature using a ^{60}Co Gamma cell 220 with a dose rate of 571.3 Gy/h. To obtain the dose–response curve, samples were irradiated with the following doses: 0.25, 0.5, 1.0, 2.0, 4.0, 6.0, 8.0, and 10.0 kGy. After irradiation, the bones were separated from flesh, frozen and lyophilized by 12 h, milled, and sifted in 16 mesh. The ESR signal increased linearly with dose over the range 0.25–8.0 kGy. Free radicals evaluated for 30 days after irradiation remained stable during this period (Duarte et al., 1995).

Stachowicz and co-workers (1995) worked out a reliable method for the detection of irradiated (with 1 or 2 kGy) poultry carcasses (chilled and frozen) and bones dissected from raw fish (carp, roach, trout, cod, and sheatfish). The specific radiation-induced EPR signal observed in poultry bones is an asymmetric singlet, with $g_1 = 2.0017$, $g_2 = 1.9973$, and $\Delta H_{pp} = 0.85$ mT derived from paramagnetic entities localized in crystalline hydroxyapatite. The stability of this species was very high because it managed to survive in irradiated bone stored at room temperature in air without noticeable concentration changes for several years. The ERP identification points of this signal are two peaks at $g_1 = 2.0030$ and $g_2 = 1.9973$, respectively. In non-irradiated bone samples, there was either no EPR signal or a very small symmetric one with a g factor of approximately 2.04.

The hard tissues of sea snails and snails were washed, dried, crushed into small pieces, and finely powdered using agate mortar. Four samples of each set were irradiated with absorbing doses of 1, 3, 6, and 9 kGy, respectively, with the fifth non-irradiated sample being used as control. The results showed that the appearance of characteristic EPR signal with $g_1 = 2.0055$, $g_2 = 2.003$, $g_3 = 2.002$, $g_4 = 2.000$, and $g_z = 1.996$ was common for the calcified

tissues of the sea snails studied and *Helix lukorum*, and their presence can be considered as clear evidence of their previous radiation treatment. These signals remained stable for at least 1 year. They can be very easily detected with EPR, thereby enabling the testing of the foodstuffs with respect to previous radiation treatment (Yordanov and Mladenova, 2001).

Chawla et al. (1999) investigated the effect of γ -irradiation doses of 1, 2, 4, and 5 kGy on ESR signal intensity in prepacked irradiated meat chunks containing bones. Irradiation induced a characteristic ESR signal in bone the intensity of which was proportional to irradiation dose up to 5 kGy. The ESR signal intensity faded by 30 and 42% during 4 weeks at 0–3°C in hind leg and rib bones, respectively. The magnitude of ESR signal in hind leg bone decreased by a maximum of 30% upon pressure cooking (for 15 min), 10% with MW cooking (for 15 min), and 13% after boiling (for 30 min). In the case of rib bones, all cooking methods led to a drop in ESR signal of approximately 40%. Storage of irradiated freeze-dried bone powder samples resulted in reduction in ESR signal intensity, as shown in Figure 4.3.

Commercial Bouzigues oysters and mussels were bought in a supermarket in Marseille, France. Irradiations were performed, usually at room temperature, in a cesium-137 (^{137}Cs) irradiator in Cadarache, France, delivering a dose rate of approximately 50 Gy/min. After the flesh was separated from the shells, the latter were washed and dried and crushed in powder, and ESR spectra were recorded. The reported differences in ESR spectra of mussels and oysters were mainly due to composition differences; the mussel shell consists mostly of calcite, phosphate, and conchioline (organic matter), yet the spectra differ from those of oysters despite the similarity of ionizing treatments. This could be explained by the simplicity of the mussel shell structure compared to the oyster structure, which is more lamellar. The signal lifetime is greater than 4 years, even for fresh shells. However, it was also found that there is a systematic difference between the g values of samples irradiated

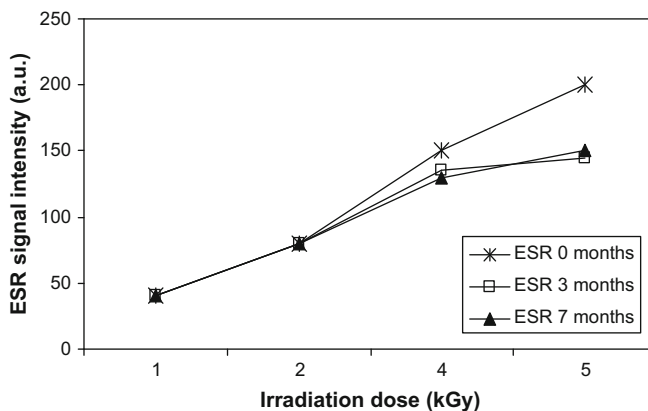


Figure 4.3: Effect of irradiation dose and storage (of freeze-dried powder at ambient temperature) on the intensity of radiation-induced ESR signals in irradiated lamb hind leg bone (1–5 kGy) (adapted from Chawla et al., 1999).

at low doses and those irradiated between 1 and 5 kGy because of the radicals induced in the organic part of the shell (conchioline) (Raffi et al., 1996).

Abdel-Rehim et al. (1997) determined the free radicals, produced in Spanish mackerel fish bone by ^{60}Co γ -rays, by means of ESR. The ESR spectra of the irradiated fish displayed an asymmetric absorption characterized by a major resonance at $g_1 = 2.0020$ and a minor resonance at $g_2 = 1.9980$. The intensity of the radiation-induced ESR signal was shown to be directly related to the absorbed dose. The results obtained after irradiation in the dose range 0.5–5.7 kGy gave a nonlinear relationship between the radiation dose and ESR signal height. The radiation-induced ESR signal of Spanish mackerel decayed most significantly within the first 15 days after irradiation, but it could still be detected after 60 days.

The suitability of TL and ESR measurements for the detection of mollusk shells was investigated by Ziegelman et al. (1999). They performed experiments on 18 samples of mollusks belonging to 10 different species. Unfortunately, significant TL signals of the irradiated samples were obtained for only 3 of the 10 species investigated, whereas the others did not show a higher signal than the unirradiated ones. The X-ray diffraction spectra revealed that all the radiation-sensitive samples contained calcite and in most cases aragonite as well. On the contrary, the nonsensitive samples contained only aragonite. The TL intensities of the sensitive samples were not the contents of calcite determined by X-ray diffraction. The ESR spectra revealed a correlation between relative content of Mn^{2+} ions and TL intensities. The ESR spectra of all samples displayed high-intensity signals that were very stable and dose-dependent signals. Experiments were carried out to characterize the signal stability under various commercial storage conditions and the dose response of both TL and ESR. ESR was more sensitive (detection limit lower than 0.05 kGy) than TL for detection of irradiated mollusk shells. The TL measurements confirmed the data obtained by ESR for food control purposes.

Goulas et al. (2008) employed ESR and PSL to detect e-beam radiation treatment (1.4 and 10 kGy) on stored fish samples (containing irradiated oregano). For fish samples, the detection of irradiation treatment was based on ESR or PSL signal of fish bones. The results revealed that PSL is a sensitive detection method for irradiated oregano samples, allowing verification of irradiation treatment for all absorbed doses, but this is not a sensitive detection method for irradiated herring-containing bones. In contrast, ESR allowed verification of the irradiation treatment of fish bone samples, but this is not a sensitive method for irradiated oregano samples. Daylight exposure of oregano samples (10 klux for 9 h) produced a strong effect on the PSL signal of all irradiated samples, decreasing the irradiation signal while the thermal treatment (100°C for 1 h) of fish bones decreased the ESR signal of irradiated samples. Although both PSL signals of oregano and herring bone ESR signals were strongly affected by storage time, the samples could still be identified as irradiated after several months of storage.

Cutrubinis and co-workers (2007) applied for the first time several food irradiation detection methods (DNA comet assay, TL, ESR, and PSL) in an attempt to detect irradiated spices, vegetables, and meat. The ESR spectra of five samples of imported foodstuffs (chicken, pork, and shrimp) revealed the typical symmetric signal of unirradiated food. The detection of irradiation treatment is not significantly influenced by heating the sample and storage times of up to 12 months. Twelve food samples were tested untreated and immediately after treatment using the TL method (European Standard EN 1788:2001). For all untreated samples, the glow ratio was lower than 0.1. After irradiation, glow ratios were greater than 0.1 for all samples. Usage of DNA comet assay correctly identified all the irradiation treated and untreated samples (European Standard EN 13784:2001).

Upon absorption of ionizing radiation, free radicals (molecules with unpaired electrons) were formed. Although free radicals exist as transient species, when formed in rigid, relatively dry matrices of food (e.g., bone, shell, and seeds), this results in the extension of the lifetime of radicals to near to or longer than the shelf life of the food. These long-lived free radicals are the basis for the EPR detection method (Desrosiers, 1996). ESR applications for detection of irradiation in food are summarized in Table 4.2.

4.2.1.2 PSL and TL

TL is a radiation-specific phenomenon that arises due to energy stored by trapped charge carriers following irradiation (Sanderson et al., 1996b). When foods are exposed to ionizing radiation, the mineral debris, which are present on many foodstuffs, store energy in charge carriers trapped at structural or interstitial sites. Optical stimulation of these minerals will release such stored energy as light that can be measured by a photon counter. This is the operating principle of PSL, which employs light at wavelength in the near infrared as stimulus for emission of detectable luminescence in the region $\lambda = 300\text{--}600$ nm from the mineral debris (Alberti et al., 2007).

Foods of plant origin

Jo et al. (2008) performed PSL and TL analyses to detect irradiated kiwifruit. Samples were irradiated with ^{60}Co γ -rays at 0–2 kGy. The freeze-dried kiwifruit peel had 309 photon counts (PCs) for non-irradiated samples that accounted for less than the lower threshold value (700 counts/60 s, negative) and had 9306 PCs for 1 and 2 kGy irradiated samples, which was higher than the upper threshold value (5000 counts/60 s, positive). PSL signals of irradiated samples decreased after 6 weeks of storage. The TL measurement using minerals isolated from the whole kiwifruit surface revealed a glow curve (TL_1) with a low intensity at 200–300°C in non-irradiated samples but with a higher intensity at approximately 180°C in irradiated samples at 1 kGy or more. The TL ratios, which integrated areas of TL_1/TL_2 that was measured after 1 kGy γ -irradiation for the TL_1 -tested minerals, were less than 0.1 in non-irradiated samples and more than 0.1 in irradiated samples and could verify TL_1 results.

TABLE 4.2 ESR Applications for Irradiation Detection in Foods

| Detection Method | Method Description/Modification | Target Compound | Irradiation Dose/Time | Food | References |
|-----------------------|---|---|---|---|--|
| Plant Products | | | | | |
| ESR | — | Free radicals | 5 and 8 kGy/6 months of storage | Vegetable (dried cabbage, carrot, chunggyungchae, garlic, onion, and green onion) | Kwon et al., 2000 |
| ESR | — | Cellulose radicals | — | Dried fruits, nutshells, spices, herbs | Helle et al., 1992 |
| EPR | Preservation treatment | Multicomponent signals | 0.6 and 2 kGy, 7 kGy/several months of storage | Seeds separated from fruits, mushrooms, dehydrated macaroni | Stachowicz et al., 1992; Stachowicz et al., 1993 |
| ESR | — | Cellulose radicals | 0.8, 1.0, 1.5. and 2.0 kGy/15 months of storage | Dry dates | Ghelawi et al., 1996 |
| ESR | Heating at annealing temperature | Mn ²⁺ ions and radiation induced radicals | 1.25 15 kGy | Ground broad deans | Polat and Korkmaz, 2003 |
| ESR | Heat treatment | Mn ²⁺ ions and radiation induced radicals, carbon centered radical | 10, 30, and 50 kGy | Wheat flour | Shimoyama et al., 2006 |
| ESR | Time stability and temperature dependence | Free radicals (hydroxyalkyl, aldehydalkyl, and unknown species) | 0.5 5.0 kGy/ 2 months of storage | Rice seeds | Polat and Korkmaz, 2003 |
| ESR and TL | Extraction of silicate minerals | — | 5 and 10 kGy | Spices | Marchioni et al., 2005 |
| ESR | Entrapment in KCl powder, mild heat temperature | Free radicals | 0.25 1 kGy | Monsooned coffee beans | Bhushan et al., 2003 |

(Continued)

TABLE 4.2 ESR Applications for Irradiation Detection in Foods—cont'd

| Detection Method | Method Description/Modification | Target Compound | Irradiation Dose/Time | Food | References |
|------------------|---|--|---|---|---|
| ESR | Capable of destroying the insects and the microorganism | Cellulose radicals | 5 kGy | Dried almonds, raisins, dates and pistachio, dried fruits | Esteves et al., 1999 |
| ESR | Paramagnetic probes introduced into the sample and transfer valuable information about the dynamic and structural changes | Free radicals | 1–20 kGy/24 h | Wheat seeds | Sunnetcioglu and Dadayli, 2000 |
| EPR | Abolishes the time limitation factor and irradiated factors | Free radicals | 1, 2.5, 5, 10, and 20 kGy/4 and 6 months of storage | Cereal grains, wheats | Sunnetcioglu et al., 1999; Dadayli et al., 1997 |
| ESR | Different relaxation behaviors | Free radicals | 10, 30, and 50 kGy | Black pepper | Ukai et al., 2006 |
| EPR and TL | Heating temperature | Cellulose radicals | 10 kGy/5–6 months of storage | Spices, aromatic herbs, fruits | Raffi et al., 2000 |
| EPR | Free radical investigation | Mn ²⁺ ions and radiation induced radicals | 1–15 kGy/7 months of storage | Soybeans | Oliveira and del Mastro, 2007 |
| EPR | — | Cellulose radicals | 1, 5, 10, 15, and 30 kGy | Black pepper and two kinds of chili and oregano, herbs and spices | Bortolin et al., 2006 |
| ESR | Different relaxation behaviors | Free radicals | 50 kGy | Black pepper | Ukai et al., 2006 |
| EPR | Heating temperature | Mn ²⁺ ions and radiation induced radicals | 10 kGy/3–5 months of storage | Dry plants | Yordanov et al., 2005 |

| | | | | | |
|------------------------|--|--|---|--|------------------------------|
| ESR | Entrapping small quantities of seed samples | Free radicals | 2.5, 5, 7.5, 10, 15, and 30 kGy | Seeds (<i>Mucuna pruriens</i>) | Bhat et al., 2007 |
| ESR | — | Free radicals | 2 kGy/8 weeks of storage | Paprika | Kispeter et al., 1999 |
| Animal Products | | | | | |
| ESR | Heating temperature | Free radicals | 5 kGy | Chicken, fish fillets, bones | Marchioni et al., 2005 |
| ESR | — | Hydroxyapatite, calcium carbonate, collagen, chitin, melanin | 0.05, 1 and 3 kGy | Meat and seafood samples (frog leg bone, wing tip bone of chicken, rib of black rockfish, and shells of clams) | Miyahara et al., 2004 |
| ESR | — | Free radicals | 0.25, 0.5, 1.0, 2.0, 4.0, 6.0, 8.0 and 10.0 kGy / 1 month storage | Chicken drumsticks | Duarte et al., 1995 |
| EPR | — | Crystalline hydroxyapatite, ion radicals | 1 to 2 kGy | Poultry carcass and bones dissected from raw fishes (carp, roach, trout, cod, sheatfish) | Stachowicz et al., 1995 |
| EPR | Processing of CaCO ₃ containing hard tissues is observed depending on their origin. | Mn ²⁺ ions and radiation induced radicals | 1, 3, 6 and 9 kGy | Sea snails and snails | Yordanov and Mladenova, 2001 |
| ESR | Cooking and boiling | Free radicals | 1, 2, 4 and 5 kGy / 4 weeks storage | Meat chunks containing bones | Chawla et al., 1999 |
| ESR | After the flesh was separated from the shells, the latter were washed and dried and crushed in powder. | Free radicals | 1 and 5 kGy | Mussel shells, oysters | Raffi et al., 1996 |
| ESR | — | Mn ²⁺ ions and radiation induced radicals | 0.5 5.7 kGy / 2 months storage | Mackerel fish bone | Abdel Rehim et al., 1997 |

(Continued)

TABLE 4.2 ESR Applications for Irradiation Detection in Foods—cont'd

| Detection Method | Method Description/Modification | Target Compound | Irradiation Dose/Time | Food | References |
|-----------------------------------|--|--|-----------------------------------|---|-------------------------|
| ESR and TL | Calcium carbonate modification | Mn ²⁺ ions and radiation induced radicals | 1 kGy | Mollusk shells | Ziegelman et al., 1999 |
| ESR or PSL | Verification of the irradiation treatment of fish bone samples | Free radicals | 1.4 and 10 kGy / 6 months storage | Fish bones | Goulas et al., 2008 |
| ESR, TL, PSL, and DNA comet assay | Heating temperature | Free radicals | 2 and 7 kGy / 12 months storage | Chicken, pork, shrimp, meat spices, vegetables | Cutrubinis et al., 2007 |
| EPR | — | Free radicals | | Meats bone, crustacean shells, spices, herbs, fruits, vegetables, seeds | Desrosiers, 1996 |

The PSL measurements were only applicable to the peel of the fruit for irradiation detection soon after irradiation. The TL ratios (TL_1/TL_2) calculated through the normalization step could enhance the reliability of TL_1 results (EN 1788:2001; Kwon et al., 2002). The inorganic dust minerals from the kiwifruit peel were mainly composed of feldspar and quartz, in which the former could be the predominant source of signals in PSL and TL analytes (Engin, 2007).

Several types of dried fruits (pistachio nut, dried apricot, almond, and raisin) were investigated for detection of their potential radiation treatment by γ -rays (1–3 kGy) or E-beam (0.75–3.9 kGy) using TL measurements. TL glow curves for the contaminating minerals separated from the dried fruits were recorded between the temperature range of 50 and 500°C. In all cases, the intensity of TL signal for the irradiated dried fruits was one to three orders of magnitude higher than that of the corresponding unirradiated control samples, thereby allowing clear distinction between them. The results were normalized by re-irradiating the mineral grains with a γ -ray dose of 1.0 kGy, and a second glow curve was recorded. The ratio of intensity of the first glow curve (TL_1) over that after the normalization dose (TL_2)—that is, TL_1/TL_2 —was determined and compared with the recommended threshold values. These parameters, together with comparison of the shape of the first glow curve, provided unequivocal results about the radiation treatment of the dried fruit samples (Khan et al., 2002a).

The results obtained by Sillano et al. (1994) suggested that the relatively inexpensive TL measurement of the adhered blown dust, naturally present on the surface of Chilean Thompson Seedless and Flame Seedless table grapes, can be a simple and reliable method to detect qualitatively γ -radiation treatment to doses as low as 0.5 kGy in this fruit (typically applied for quarantine purposes). Another advantage of this method is the TL response stability, because the irradiation treatment can be properly detected well beyond the shipping and marketing time for this Chilean export fruit (2–8 weeks).

An effort was made to identify the γ -irradiated sesame seeds even after they were roasted at 220°C for 10 min. Three classical irradiation identification methods—PSL, TL, and ESR—were applied to identify the irradiated samples. Following Lee et al. (2008), the photon counts of the irradiated samples (nonroasted and roasted) were higher than those of non-irradiated ones, making it possible to distinguish the two samples. The threshold values of nonroasted and roasted samples increased linearly with the irradiation dose, respectively. The TL for the non-irradiated nonroasted and roasted samples presented a lower peak at approximately 300°C, but irradiated samples showed a higher peak at approximately 150°C. The areas of TL glow curves were 15 times higher in nonroasted compared to roasted samples. TL ratio [integrated area of TL_1 (the first glow)/ TL_2 (the second glow)] obtained by the re-irradiation step was 0 in non-irradiated samples and more than 0.15 in irradiated samples. The radiation-induced ESR signals originating from cellulose were successfully determined in irradiated samples before and after roasting.

Cutrubinis et al. (2005) treated cereal grains with low-energy (<300 keV) or high-energy (1–10 MeV) electrons for decontamination of phytopathogenic and spoilage organisms. In this preliminary study, wheat and barley samples were treated with low-energy electrons of 145 keV or high-energy electrons of 10 MeV. To identify the electron treatment of cereal grains, the following detection methods have been investigated: PSL, TL, ESR, and DNA comet assay. These four methods have been standardized at a European level and have also been adopted as general Codex methods for detection of irradiated foodstuffs. The results suggest that the most suitable detection methods for electron-treated grains are PSL and TL. The results from the other two methods (ESR and comet assay) were not as promising because they seem to be applicable only in special cases. The PSL method has potential as a detection technique for wheat and barley samples treated with low- or high-energy electrons. Even months after irradiation, treated samples could be identified (Figure 4.4). The thresholds were very sensitive to the mineral content of each kind and variety of sample. The TL method also appeared to be suitable for wheat and barley samples treated with low- or high-energy electrons. An unknown sample can be correctly identified as treated or nontreated if sufficient minerals have been isolated. This can be achieved by increasing the amount of the sample from which the minerals are extracted.

Whenever foods are irradiated at a minimal dose, irradiation detection becomes very difficult. Sanyal et al. (2009) used EPR and TL to detect whether Basmati rice had been irradiated or not. EPR investigation of 0.5- to 2.0-kGy irradiated rice samples revealed a short-lived, asymmetric, dose-dependent spectrum ($g = 2.005$), characterized by the radicals of irradiated starch. However, this signal disappeared with time. This study reported for the first time that the different MW saturation behaviors of the signal ($g = 2.004$) in irradiated and non-irradiated rice samples provide an important clue to identify radiation treatment beyond the period when the radiation-specific EPR spectral lines have disappeared. TL

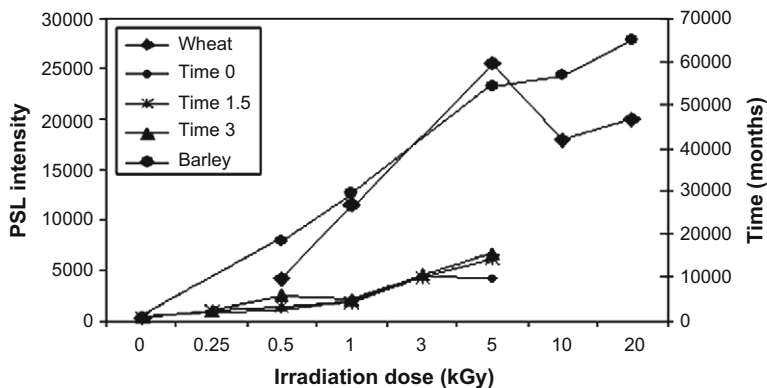


Figure 4.4: PSL mean signals for the grain samples of 1170 and 1267 kV treated with high-energy electrons (time 0, immediately after treatment; time 1.5, 1.5 months after treatment; and time 3, 3 months after treatment) (adapted from Cutrubinis et al., 2005).

investigation involving scanning electron microscopy/energy dispersive X-ray analysis of the polyminerals isolated from the rice samples allowed the clear discrimination between irradiated and non-irradiated samples even after a prolonged period of storage.

Both ESR and TL were first employed for identification of irradiated (1.5 and 10 kGy) lentils by [Kiyak \(1993\)](#). Twenty milligrams and 200 g of irradiated lentils were used for ESR and TL measurements, respectively. Both TL and ESR peak height increased with respect to the doses. They were also saturated above 10 kGy, thus covering the accepted dose range for irradiated foods.

[D'Oca et al. \(2007, 2009\)](#) reported on the employment of the additive dose method for dose estimation in irradiated oregano with TL based on EN 1788:2001. The experimentally obtained results revealed that at least up to the highest tested doses (2 kGy), it was possible to set up a procedure to estimate the actual dose in the irradiated oregano using TL in conjunction with the additive, even after months of storage.

The reliability of the PSL technique, as a screening method for irradiated food identification, has been tested with three kinds of herbs and spices (oregano, red pepper, and fennel), prepared in two different ways [granular (i.e., seeds and flakes) and powdered], over a long period of storage with different light exposures ([Alberti et al., 2007](#)). These authors found that:

the irradiated samples kept in the dark gave always a positive response (the sample was correctly classified as “irradiated”) for the entire examination period. The samples kept under ambient light conditions, in typical commercial glass containers, exhibited a reduction of the PSL signal, more or less pronounced depending on the type of food and packaging. The different PSL response of the irradiated samples was related to the quantity and quality of the mineral debris present in the individual food. It was also found that, for the same type of food, the light-induced fading was much stronger for the flaked and seed samples than for the corresponding powder samples, the penetrating capability of light being much more inhibited in powdered than in whole seeds or flaked form samples. The observed light bleaching of the PSL signal in irradiated herbs and spices was of practical relevance since it may lead to false-negative classifications.

According to [Engin \(2004, 2007\)](#), TL is the most acceptable method for detection of irradiated black peppers (and other spices). TL can be applied to all foodstuffs provided they have inorganic dust contaminants. Results revealed that all the investigated black peppers gave TL responses much greater than the background. It is usually possible to differentiate the irradiated samples from unirradiated ones if the measurements are carried out within 1 year after irradiation. All X-ray diffraction-characterized inorganic dust samples collected from black peppers disclosed the presence of at least three common minerals: quartz, feldspar, and clay minerals. The experimental and computerized deconvolution results of this study were consistent with the presence of four closely unseparable overlapping second-order TL peaks in the single glow curve around 240°C. Only quartz and feldspar minerals appear to

account for the TL signals detected in the γ -irradiated inorganic dust samples. Although the polymineral dust samples are mainly quartz mineral, the major part of the glow peak could be due to the feldspar minerals between 1- and 10-kGy dose intervals (Engin, 2005).

Bayram and Delincée (2004) irradiated spices, tea, dried fruits, and nuts at doses of 0.5, 1, 3, 5, and 10, kGy by 10 MeV electrons. The foodstuffs were analyzed with PSL. ESR spectroscopy and TL analysis were applied if silicate minerals could be isolated in an adequate amount. PSL intensity sign was shown to depend on the irradiation dose. The effect of irradiation dose on the intensity of PSL measurements of Turkish export foodstuffs is shown in Figure 4.5.

Elahi et al. (2008) noted that:

the analyses of third portion referee samples of chili powder and guarana powder demonstrated the capability of the techniques applied (PSL, TL) to produce analytical results of the quality necessary for formal food law enforcement action. The experience of expert laboratories in the techniques applied was combined with that of the Government Chemist in analytical quality assurance and other formal procedures to produce evidence in a way that complied with the requirements of the Food Safety Act 1990, as amended. It was clearly demonstrated that the TL method is suitable for blends of irradiated and non-irradiated material down to a concentration of 1%. However, it should be pointed out that in the case of low concentration blends, the results have to be interpreted with extreme care as contradictory results can arise, especially if there are issues with homogeneity, low mineral content, or low sensitivity.

TL is a method whereby heat is applied to release trapped energy; a plot of photons emitted versus temperature (the so-called glow curve) can be generated. This single photon counting procedure affords a high degree of selectivity as well as sensitivity. Another benefit of the TL method is that no reference standard is needed (Pinnioja, 1993).

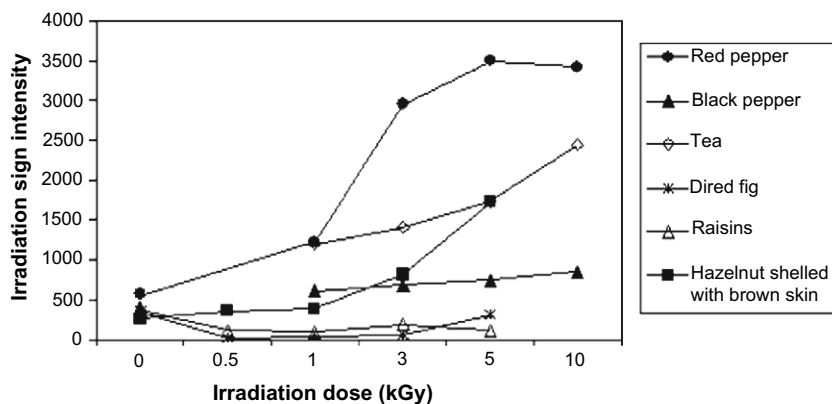


Figure 4.5: Impact of irradiation dose on the PSL measurements (counts/60 s) of Turkish export foodstuffs (spices, tea, dried fruits, and nuts) irradiated with 10 MeV electrons (adapted from Bayaram and Delincée, 2004).

Four date cultivars (Tunisian and Iranian origin) were investigated for the detection of irradiation treatment using TL from the mineral contaminants adhering to the dates. The results were normalized using a re-irradiation step to improve the identification method. These date samples were irradiated using ^{60}Co γ -rays to 1.0 kGy or electron accelerator to 0.75, 2.2, and 3.9 kGy. The difference in the intensity of the TL glow curve for minerals separated from the irradiated samples made possible their identification compared to non-irradiated samples. Application of normalization revealed that the ratio of first glow curve to the second glow curve was more than 1.0 for all irradiated samples and much less than 0.1 for non-irradiated samples, thereby making reliable the detection of irradiated dates (Khan and Delincée, 1995a).

Kwon et al. (1998) applied TL analysis to detect commercially irradiated traditional Korean condiments and soup mixes containing salt (NaCl). A consistent high correlation (R^2) between the absorbed doses and the corresponding TL responses was established. Table salt was found to play a role as an in-built indicator in TL measurements, and its concentration test samples were a correction factor for varying conditions of TL measurements. Pre-established threshold values were successfully adopted to identify 167 coded samples of ramen soup mixes, both non-irradiated and irradiated with γ -ray and E-beam energy. The TL intensity of irradiated soup mixes decreased with the lapse of time but was still distinguishable from that of the non-irradiated samples after 4 months of ambient storage. Expected estimates of absorbed doses, 2.85 and 4.75 kGy, were obtained using a quadratic equation with average values of 1.57 and 4.90 kGy, respectively. The effect of irradiation dose on TL intensity of irradiated Ramen is displayed in Figure 4.6.

Foods of animal origin

Stewart et al. (2000) investigated the applicability of the 2-ACBs as markers for irradiated Camembert cheese, salmon meat, mango, and papaya. These authors found that both 2-DCB

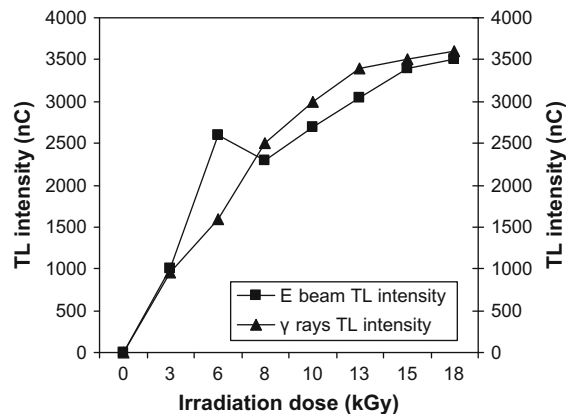


Figure 4.6: Dose-effect curves of Ramen soup mixes by γ -ray and e-beam irradiation (adapted from Kwon et al., 1998).

and 2-TCB were readily detected in Camembert cheese even after storage for 26 days at 10°C. A linear relationship was observed between irradiation dose (0.5–5 kGy) and the amount of cyclobutanone produced in the cheese. 2-DCB and 2-TCB were both identified in salmon meat irradiated in either the chilled (4°C) or the frozen state (−40°C), but the authors noted that less 2-DCB was determined in the frozen samples. A linear response to increasing irradiation dose was demonstrated for salmon over the experimental range of 1 ± 10 kGy. 2-TCB was identified as the main marker for irradiated mango and could be detected in samples following storage for 14 days at 10°C at doses as low as 0.1 kGy. Regarding the other products investigated, the concentration of this cyclobutanone increased linearly with increasing dose (0.1–2 kGy). 2-DCB was identified as the principal irradiation marker for papaya. However, the concentration of this cyclobutanone decreased significantly with time so that by day 21 of storage at 10°C it could only be detected at the 2-kGy dose level. 2-Tetradecenylcyclobutanone was also detected in irradiated mango and papaya.

A study was conducted by Yazici et al. (2008) to establish a detection method for irradiated legumes (chickpea and corn) by means of TL. The extracted samples from both legumes displayed good TL intensity after irradiation by γ -rays, and the TL intensity of glow curves of the legumes increased proportionally to irradiation doses. The TL signals of both irradiated leguminous showed a single broad glow peak below 400°C within the range of 150–350°C. TL glow curves of both samples displayed the presence of a very intense peak at approximately 260°C related to γ -irradiation. The TL kinetic (trapping) parameters of glow peaks of both samples were estimated by the additive dose (AD), $T_m(E_a) - T_{stop}$, and computerized glow curve deconvolution (CGCD) methods. The $T_m - T_{stop}$ procedure confirmed that the positions of glow peaks shift toward the high temperatures with increasing T_{stop} . These results clearly indicated that the glow peak of both samples was a superposition of a number of first-order glow peaks. Fading observations of TL after irradiation at 4 kGy displayed the same trend in all cases—that is, an initial rapid decay to maintain certain stability from 3 or 4 months onwards. The effects of irradiation dose (ID) and storage time on TL signal intensity of chickpea and corn samples are shown in Figures 4.7 and 4.8. Although the TL intensity increased with irradiation dosage, the effect of storage time resulted in exactly the opposite—that is, lower TL for higher irradiation dose.

Atta and co-workers (2001) analyzed chicken and fish for the detection of radiation treatment using TL. The samples were irradiated with ^{60}Co γ -source at doses of 1–5 kGy. TL response of treated and untreated samples in the temperature range of 50–300°C was measured using a TL reader with a temperature profile of 10°C/s. The results revealed that TL values increased with temperature and maximum signal was obtained at 195°C. It was also observed that the TL intensities increased with the absorbed doses (1–5 kGy) and that increase was dependent on the absorbed dose. It was therefore concluded that the TL technique is a rapid, simple, and promising method for identifying chicken and fish treated with γ -irradiation and for prediction of the absorbed dose as well.

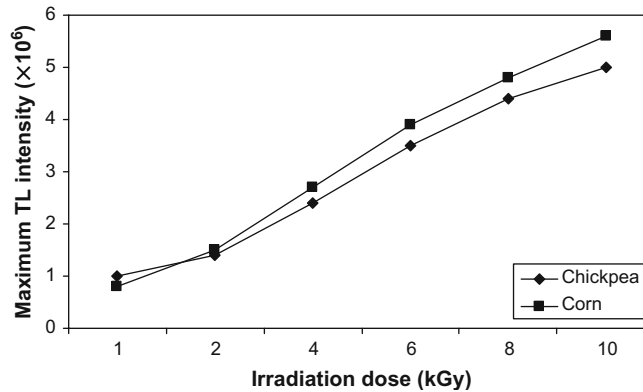


Figure 4.7: TL response curves of glow curves of chickpea and corn samples by the peak height method versus irradiation dose (adapted from Yazici et al., 2008).

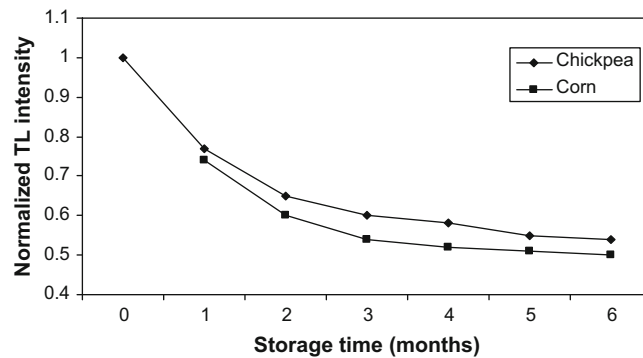


Figure 4.8: The obtained fading characteristics of glow peaks of corn and chickpea using the CGCD program (adapted from Yazici et al., 2008).

In a series of controlled experiments, silicate minerals were extracted from the intestines of six shellfish species (*Nerhrops norvegicus*, brown shrimp, Mediterranean crevettes, black tiger prawns, warm water shrimp, and king scallops) by means of acid hydrolysis in an attempt to compare the results of TL analysis of these extracts with those of minerals extracted by the conventional manual dissection method. In all cases, excellent discrimination between irradiated and unirradiated products was obtained using hydrolysis extracts. The method gave results that were comparable or better than conventional physical extraction and had some benefits in sample handling (Carmichael and Sanderson, 2000).

Chung et al. (2002) used PSL, ESR, and TL for the detection of dried anchovy and shrimp exposed to e-beam at 0–10 kGy. They noted that the PSL values for irradiated samples were more than 5000 photon counts/60 s (upper threshold, T_2), whereas those of non-irradiated samples were less than 700 counts (lower threshold, T_1) in anchovy and intermediate values of $T_1 - T_2$ in shrimp. ESR measurements using both the whole samples

did not show any signals specific to irradiation. In the case of anchovy, however, bone could be used for ESR detection, showing typical signals ($g = 2.002, 1.998$). Minerals separated from both the samples for TL measurement indicated that non-irradiated samples were characterized by glow curves situated at approximately 300°C with low intensity, whereas all irradiated samples exhibited glow peaked at approximately 200°C and its intensity was high enough to be discriminated from the non-irradiated ones. Furthermore, normalization with re-irradiation enhanced the reliability of detection results of TL.

Rahman et al. (1996) successfully employed both Soxtec and supercritical fluid extraction (SFE) methods as alternatives to the Soxhlet method for the isolation of cyclobutanones from irradiated foods. The main advantages of these two methods are the rapidity and simplicity for routine analysis (reduction of extraction time from 6 h to 45 and 20 min for Soxtec and SFE, respectively). However, a further comparison between Soxtec and SFE revealed that the former is lengthier because of the required cleanup procedure, similar to Soxhlet. Therefore, SFE–GC/MS was found to be very promising for extraction and quantitative determination, whereas SFE–thin layer chromatography could be employed as a rapid screening test for qualitative purposes such as the determination of 2-dodecylcyclobutanone because of its low cost, simplicity, and the fact that it can be performed quickly.

A concise description of PSL/TL on irradiated food is given in Table 4.3.

4.3.1.3 Viscosimetry

It is fairly well-established that γ -irradiation of certain foodstuffs leads to solutions of reduced viscosity (Anonymous, 1994; Glidewell et al., 1993; Polonia et al., 1995; Schreider et al., 1993; Stevenson and Stewart, 1995). Although this method is clearly one of the most facile, low-cost, and rapid methods to perform, it was suggested (Schreider et al., 1993) that positive results should be double-checked with ESR or TL analysis.

Foods of plant origin

Hayashi and Todoriki (1996) reported that the viscosity values determined at a high pH of 13.8 were significantly different between non-irradiated and irradiated peppers irrespective of planting locality and storage period. All the parameter values, viscosity/starch amount, of non-irradiated peppers were higher than 320, and those of irradiated pepper (5 kGy) were lower than 320. Peppers were usually irradiated at doses higher than 5 kGy for decontamination. They concluded that the viscosity measurement can differentiate irradiated black and white peppers from non-irradiated ones completely and can effectively be used as a method for detecting irradiated black and white peppers.

4.3.1.4 Pulsed flame photometry

Pulsed flame photometry (PFP) is a relatively new technique that offers several advantages over the other detectors for sulfur compounds, such as high sensitivity, selectivity, and

TABLE 4.3 PSL/TL Applications for Irradiation Detection in Food

| Detection Method | Method Description/Modification | Target Compound | Irradiation Dose/Time | Food | References |
|-----------------------------------|--|--|--|--|--------------------------|
| Plant Products | | | | | |
| PSL and TL | — | — | 1 and 2 kGy/6 weeks of storage | Kiwifruit | Jo et al., 2008 |
| TL | — | Silicate minerals | 1–3 kGy | Dried fruits (pistachio nut, dried apricot, almond, and raisins) | Khan et al., 2002 |
| TL | — | Silicate minerals | 0.5 and 1 kGy/125 days of storage | Grapes | Sillano et al., 1994 |
| PSL, TL, and ESR | Roasting treatment | Mn ²⁺ ions and radiation induced radicals, cellulose radicals | 0–4 kGy/10 min | Sesame seeds | Lee et al., 2008 |
| PSL, TL, ESR, and DNA comet assay | Isolated husks from barley sample | Cellulose radicals | 0.25, 0.5, 10, and 20 kGy/2 months of storage (barley), 10 months of storage (wheat) | Wheat and barley samples | Cutrubinis et al., 2005 |
| TL and EPR | Polyminerals isolated from the rice samples | Free radicals | 0.5–2.0 kGy | Rice | Sanyal et al., 2009 |
| TL and ESR | Covering the accepted dose range for irradiated foods | Free radicals | 1.5 and 10 kGy | Lentils | Kiyak, 1993 |
| TL | Distinguishes irradiated from non irradiated samples | Silicate minerals | 2 kGy/2 months of storage | Oregano | D'Oca et al., 2007, 2009 |
| PSL | The samples kept under ambient light conditions | — | 10 kGy/6 months of storage | Herbs and spices (oregano, red pepper, and fennel) | Alberti et al., 2007 |
| TL | The preparation and irradiation of samples took place at ambient temperature | Quartz, feldspar, clay minerals | 1, 3, 5, and 10 kGy/1 year of storage | Black peppers, herbs, and dried fruits | Engin, 2004, 2005 |

(Continued)

TABLE 4.3 PSL/TL Applications for Irradiation Detection in Food—cont'd

| Detection Method | Method Description/Modification | Target Compound | Irradiation Dose/Time | Food | References |
|------------------------|---|------------------------------|---|---|--------------------------------|
| PSL, ESR, and TL | — | Cellulose radicals, minerals | 0.5, 1, 3, 5, 10 kGy/ 3 weeks of storage | Spices, tea, dried fruits, and nuts | Bayaram and Delincée, 2004 |
| PSL and TL | — | Silicate minerals | 3, 5, and 10 kGy | Chili powder and guarana powder | Elahi et al., 2008 |
| TL | Detected using TL of mineral contaminants and normalization by a re irradiation | Silicate minerals | 0.75, 2.2, and 3.9 kGy | Dates | Khan and Delincée, 1995 |
| TL | Discriminates irradiated from not irradiated samples | NaCl | 2.85 and 4.75 kGy/ 4 months of storage | | Kwon et al., 1998 |
| Animal Products | | | | | |
| TL | Discriminates irradiated from not irradiated samples | Silicate minerals | 1, 4, 8, and 10 kGy/ 3 4 months of storage | Chickpea and corn | Yazici et al., 2008 |
| TL | Temperature increased with increasing absorbed doses. | Free radicals | 1 5 kGy | Chicken and fish | Atta et al., 2001 |
| TL | All preparation and handling of samples was carried out under subdued safelight | Silicate minerals | 1 kGy/68 days of storage | Shellfish (<i>Nerhrops norvegicus</i> , brown shrimp, Mediterranean crevettes, black tiger prawns, warm water shrimp, and king scallops) | Carmichael and Sanderson, 2000 |
| PSL, ESR, and TL | All preparation and handling of samples was carried out under subdued safelight | Hydroxyapatite radicals | 0 10 kGy | Dried anchovy and shrimp | Chung et al., 2002 |
| SFE | — | TCB, DCB | 5 and 10 kGy/h | Chicken | Rahman et al., 1996 |

repeatability. PFP has been used for analyzing volatile sulfur compounds in beer and for several other applications. The sulfur compounds were then separated and detected using GC/PFP (Amirav and Jing, 1995).

In a study by Fan et al. (2002), precooked turkey breast was exposed to 0–5 kGy of γ -radiation and stored for 14 days at 5°C. Volatile sulfur compounds were extracted using solid phase microextraction (SPME) followed by GC separation and PFP detection. Irradiation considerably increased the concentrations of hydrogen sulfide, sulfur dioxide, methanethiol, and dimethyl disulfide. The rate of increase was higher at low doses (0–2 kGy) than at higher doses of 3–5 kGy. Carbon disulfide was the only volatile sulfur compound reduced by irradiation. Concentrations of all volatile sulfur compounds decreased in both irradiated and non-irradiated samples stored at 5°C.

The advantages and disadvantages of physical methods employed for irradiation detection in food are summarized in Table 4.4.

4.3.2 Chemical

4.3.2.1 GC/MS

GC was introduced in 1952 by James and Martin, who attempted to separate 17 fatty acids; they designed and constructed the first equipment and described the theory. In this technique, the mobile phase is always an inert gas that transports the analytes through the stationary phase placed in a column. The separation process is mainly governed by the interaction of solutes with the stationary phase (Soria et al., 2008).

Foods of plant origin

Horvatovich et al. (2006) reported that the use of a column containing 60 g of silica gel for cleanup in conjunction with isobutane as a reactant reagent for chemical ionization–MS analysis of the saturated and monounsaturated alkyl side chain 2-ACBs improved both the sensibility and the selectivity of the method when applied for the detection of irradiated foods. It was possible to detect avocados irradiated at low doses (0.1 kGy) or irradiated ingredients included in low proportions (<5% w/w) in non-irradiated culinary foods. It was stated that these modifications for the detection of 2-ACBs on the official EN 1785 method will widen considerably the current field of application.

Vegetable oils, avocado pears, pilchards, and poultry meat were γ -irradiated with ^{137}Cs at room temperature and kept in a domestic freezer until analysis for triglycerides [GC with flame ionization detection (FID)] and volatile compounds (evaporation of volatiles, cryoconcentration on a Tenax trap, and injection in GC with flash heating). Although this method was rapid and reliable, its two main problems were the extraction of radiation-induced volatile hydrocarbons and the presence of interference in GC. Application of this

TABLE 4.4 Advantages and Disadvantages of Physical Methods Employed for Irradiation Detection in Food

| Method | Advantages | Disadvantages | References |
|--------------|--|---|--|
| ESR or EPR | Highly sensitive and selective technique Permits the observation of unpaired electrons Can be used as an identification test The signal strength is proportional to the amount of γ irradiation Free radicals present Spectra disclose the free radical's structure Microenvironment or motion Relatively noninvasive The sample is not destroyed and thus may be checked for changes with time | Instability of the relatively weak radiation specific signals Cost of the spectrometer and the special technical skills required to operate it | Haire et al., 1997; Raffi, 1992, 1998; Raffi and Benzaria, 1994; Swallow, 1990; Yordanov et al., 2005 |
| PSL and TL | TL is a rapid method TL is relatively inexpensive TL is a selective and sensitive technique No reference standard is needed Screening method for irradiated food identification In PSL the emission of trapped energy as light may be induced photochemically, thermally, or by solvation Nondestructive method Samples may be checked more than once PSL is less time consuming than TL and CL In PSL the γ irradiated samples may exhibit anti stokes luminescence | The TL response must be calibrated for each substance | Alberti et al., 2007; Anonymous 1994; Glidewell et al., 1993; Haire et al., 1997; Schreiber et al., 1993; Stevenson and Stewart, 1995 |
| Viscosimetry | Facile method Low cost and rapid performance Effective in detection of irradiated food | Positive results must be double checked with ESR or TL analysis | Glidewell et al., 1993; Hayashi and Todoriki, 1996; Schreiber et al., 1993; Stevenson and Stewart, 1995 |
| PFP | Several advantages over the other detectors for sulfur compounds Highly sensitive, selective, and repeatable method | | Amirav and Jing, 1995 |

detection method to avocado pears and poultry meat proved to be successful, whereas it was not possible to apply it to fresh pilchards because of the high number of volatile compounds already available prior to irradiation (Lesgards et al., 1993).

Application of SFE (CO_2 extraction, 152 bar or 15 200 kPa, 80°C, 4 ml/min, 60 min) on lipids previously extracted from irradiated plant foods allowed a selective extraction of 2-DCB and its detection with GC/MS in 50 Gy irradiated cowpeas and 100 Gy irradiated rice (Horvatovich et al., 2002). However, in view of the greater quantities of lipid impurities in these test samples

compared to those present in meat samples, a modification of the capillary column is required (longer and more polar) compared to the EN 1785 method in order to obtain satisfactory resolution.

In a study by Fan and Sokorai (2002), fresh cilantro leaves (*Coriandrum sativum* L.) were irradiated with 0–3 kGy γ -radiation and then stored at 3°C up to 14 days. Volatile compounds were extracted using SPME, followed by GC separation and mass spectra detection at 0, 3, 7, and 14 days after irradiation. Most of the volatile compounds identified were aldehydes. Decanal and (E)-2-decenal were the most abundant compounds, accounting for more than 80% of the total amount of identified compounds. The amounts of linalool, dodecanal, and (E)-2-dodecenal in irradiated samples were significantly lower than those in non-irradiated samples at day 14. However, the most abundant compounds [decanal and (E)-2-decenal] were not consistently affected by irradiation. During storage at 3°C, the amount of most aldehydes peaked at 3 days and decreased afterwards. The results suggest that irradiation of fresh cilantro for safety enhancement at doses up to 3 kGy had minimal effect on volatile compounds compared with the losses that occurred during storage.

Soybeans were irradiated; irradiated and roasted; roasted and irradiated; irradiated and powdered; and roasted, powdered, and irradiated. Oils were extracted using hexane and Na₂SO₄, and hydrocarbon fraction was separated through a Florisil column and analyzed using GC. All the post-treatments that the soybeans underwent (roasting and powdering) in conjunction with irradiation only minimally affected the detection levels of hydrocarbons due to irradiation, apart from the roasted, powdered, and irradiated treatment, which resulted in a different pattern (i.e., the 17:2 level was lower than the 16:3 level). The hydrocarbon detection patterns in the samples stored at room temperature for 30 weeks were similar to those of the initial and refrigerated samples with slight detection levels in the room-stored samples (Hwang et al., 2007).

Application of Fourier transform infrared spectroscopy and IT-Raman in conjunction with canonical analysis to irradiated starch samples revealed the presence of biochemical changes in irradiated samples (Kizil et al., 2002). The absorbances at O–H (3000–3600 cm⁻¹) stretch, C–H (2800–3000 cm⁻¹) stretch, the skeletal mode vibration of the glycosidic linkage (900–950 cm⁻¹) in both Raman and infrared spectra, and the infrared band of water adsorbed in the amorphous parts of starches (1550–1750 cm⁻¹) were employed in classification analysis of irradiated starches. Spectral data related to water adsorbed in the noncrystalline regions of starches provided a better classification of irradiated starches with five partial least-squares (PLS) factors in the multivariate model. Using the wave number range 1550–1750 cm⁻¹, five PLS factors were required in the CVA model for complete discrimination of irradiated starches from the non-irradiated starches. However, 10 PLS factors were required to create clusters of starches based on the extent of irradiation.

Foods of animal origin

SFE was used for the isolation of characteristic hydrocarbon patterns formed by irradiation of fat-containing foods. The method has the advantage of not requiring the use of organic solvents because analyte recovery is obtained simply by thermal desorption of the solutes previously retained in an adsorbent material, packed in the trap of the SF extractor. Based on results obtained from GC/MS, it was concluded that this method allowed cheese samples to be rapidly analyzed for irradiation treatment because the overall procedure (including SF extraction and GC/MS analysis) takes less than 2 h without demanding the use of organic solvents. Moreover, a purification step of the SF extract (e.g., using Florisil) is not required prior to the chromatographic analysis (Barba et al., 2009).

Irradiation detection of raw milk Camembert cheeses with GC analysis of radio-induced volatile hydrocarbons, formed by radiolysis of myristic, palmitic, and stearic acids, was suggested by Bergaentzle et al. (1994). The presence of tridecane, 1-dodecene, 1-tetradecene, and 1-hexadecane in conjunction with an increase in levels of pentadecane and heptadecane can be considered an indication of irradiation. Moreover, the quantity of radio-induced volatile hydrocarbons, formed from the same fatty acid precursor, was proportional to the fatty acid composition in the sample and the *I*-alkene/alkane ratio remained constant (~1.3) and independent of the fatty acid precursor. Since the quantity of each radio-induced hydrocarbon increased linearly with the irradiation dose and remained stable during ripening and storage, the determination of the irradiation dose should be possible if a reference Camembert cheese is available, thus allowing standardization.

Hydrocarbons were extracted (with hexane) from shell eggs irradiated at 0.5, 1, and 3 kGy and boiled, fried, or heated in ovens. The lipid extracts were analyzed for hydrocarbons 15:0, 14:1, 17:0, 16:1, 17:1, 16:2, 17:2, and 16:3 irradiated at 0.5 kGy or higher. Boiling non-irradiated or irradiated eggs for 40 min only slightly affected detection levels of hydrocarbons. Hydrocarbons 15:0, 17:0, 17:1, 17:2, 14:1, and 16:1 were detected in the egg yolk of the non-irradiated eggs while heating it in a cooking oven at 170°C for 60 min. In view of the considerable differences in hydrocarbons occurring in irradiated and non-irradiated eggs (Figure 4.9), it was easy to distinguish which eggs had been irradiated (Hwang et al., 2001).

An interlaboratory trial (among four European laboratories) was set up to assess the qualitative performance of a new rapid direct solvent extraction (DSE) method as a potential detection method to differentiate between irradiated and non-irradiated food samples. The compound 2-DCB was picked up as radiolytic marker for detection of irradiated minced chicken and liquid egg. Every laboratory received 12 blind coded “unknown” and four known coded samples for analysis. All four laboratories were able to correctly identify all 12 blind coded samples as either irradiated or non-irradiated samples. The tested DSE method is regarded as a rapid, low-cost, appropriate method and recommended for use in laboratories that are involved in routine screening of large numbers of food samples for irradiation (Tewfik, 2008).

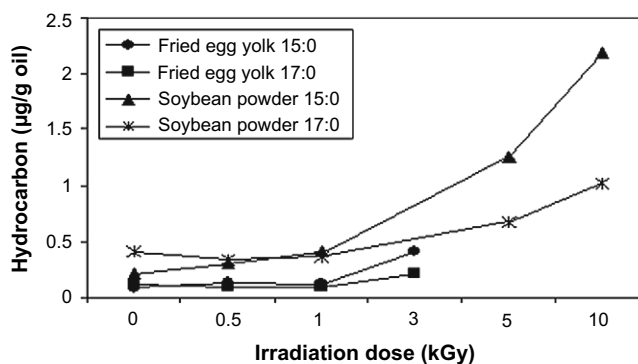


Figure 4.9: Hydrocarbons detected in irradiated soybean powder (Hwang et al., 2007) and fried egg yolk against irradiation dose (Hwang et al., 2001).

GC/MS (European Standard EN 1785:1996) was applied to irradiated muscle and skin chicken samples. The peaks of ions at 98 and 112 Da were recorded at a ratio of approximately 4:1, typical of radiation-induced 2-DCB. The results revealed that 1 month after irradiation at 3 kGy, the method was suitable for use with the skin but not the muscle, whereas the measured parameters were detectable in both samples irradiated at 5 kGy. The microbial population was substantially reduced even at 3 kGy (Parlato et al., 2007).

A simple and rapid (30 min) method for the isolation of these markers using carbon dioxide as a supercritical fluid was described for beef and chicken samples irradiated up to 8 kGy. Significant levels of both 2-DCB and 2-TCB were extracted from all irradiated samples using carbon dioxide as a supercritical fluid; the method is proposed as a promising Florisil chromatography. Tewfik and Ismail (1998) reported that the SFE method may be used as an alternative to the lengthy Florisil chromatography method in the detection of irradiated samples of beef and chicken. They noted that the Florisil method has long extraction times, large solvent volumes, and high running costs.

Horvatovich et al. (2005) described a detection method for the analysis of mono-unsaturated alkyl side chain 2-ACBs formed upon irradiation from mono-unsaturated fatty acids. The estimated radioproduction yields of the *cis*-2-(dodec-5'-enyl)-cyclobutanones (*cis*-2-dDeCB) and the *cis*-2-(tetradec-5'-enyl)-cyclobutanones (*cis*-2-tDeCB) were 1.0 ± 0.5 and 0.9 ± 0.2 nmol/mmol precursor fatty acid/kGy, respectively—equivalent to that of saturated 2-ACBs. The stability study of the *cis*-2-ACBs in poultry meat samples irradiated at 10 kGy and stored for 3 or 4 weeks at 4 and 25°C revealed that these compounds undergo some transformation, due to which their amounts were reduced by almost 50%. The detection of *cis*-2-tDeCB should only be preferred over 2-dDeCB when the concentration of its precursor oleic acid is at least three times higher than that of palmitic acid (e.g., liquid whole eggs, avocados, and papaya seeds).

Hwang (1999) analyzed the hydrocarbons produced by γ -radiation of pork, bacon, and ham to determine how irradiation affected the production of the hydrocarbons and whether the hydrocarbons could be successfully used for identifying post-irradiation of pork, bacon, and ham. Hydrocarbons were determined by means of a sequential procedure of lipid extraction by hexane, Florisil column chromatography (FCC), and GC. Hydrocarbons C17:1, C16:2, C17:2, and C16:3 were detected in pork, bacon, and ham irradiated at 0.5 kGy or higher but not in non-irradiated ones except C17:1. The detection levels in all the irradiated samples were in the order C16:2, C17:1, C17:2, and C16:3 from the highest to the lowest.

SPME was applied in an effort to detect the occurrence of the irradiation markers 2-DCB and 1,3-bis(1,1-dimethylethyl)benzene in irradiated ground beef. Beef samples were first irradiated with different irradiation doses and analyzed; both treated and untreated beef samples were used as control samples. The selected SPME conditions (fibers, extraction times, and temperatures) were the result of an optimization study. 2-DCB and 1,3-bis(1,1-dimethylethyl)benzene were identified in some of the samples by steam distillation-solvent extraction (SDE). Moreover, SPME confirmed the validity of 2-DCB as a useful marker to distinguish non-irradiated from irradiated ground beef. However, the occurrence of 1,3-bis(1,1-dimethylethyl)benzene was established in both types of samples by SPME and SDE (Caja et al., 2008). SPME may be an interesting alternative to the official method based on solvent extraction to detect 2-DCB in irradiated ground beef. Advantages of SPME are its rapidness (overall extraction time of 50 min), simplicity, low cost, accessibility, and the fact that there is no need for use of large amounts of organic solvents.

The hydrocarbons formed from beef, pork, and chicken irradiated with 0–10 kGy were determined with SPE and quantified with GC/MS. The limit of detection for the hydrocarbons in irradiated meats was 0.5 kGy, with the exception of C16:3 in beef and C17:0. The correlation between the irradiation dose and the concentrations of hydrocarbons in beef, pork, and chicken was high, and linear regression coefficients were 0.87–0.99. SPE can be used for the rapid detection of irradiated meats (Kim et al., 2004). The impact of irradiation dose on hydrocarbon concentration in beef determined with SPE is exhibited in Figure 4.10.

To develop a detection method for marker compounds from irradiated powdery foods, Kim et al. (2005) applied two different extraction methods such as the SPME and purge and trap (P&T) methods to detect radiolytic volatile compounds as marker compounds by testing beef extract powder. Beef extract powder was irradiated using a ^{60}Co source (c-irradiation) at 1, 3, 5, and 10 kGy and then divided into 0 and 30 days of storage (30°C). On 0 day of storage, each concentration of 1,3-bis(1,1-dimethylethyl)benzene as a marker compound detected simultaneously by the extraction methods increased linearly with irradiation dose and had the same trend after 30 days of storage. Four other compounds—tridecane, hexadecane, 2-octene, and 2-decanone—were excluded from possible marker compounds because these

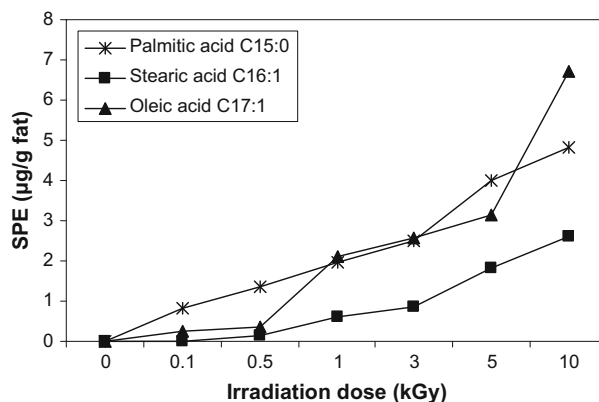


Figure 4.10: Effect of irradiation dose on hydrocarbon concentration in beef using the SPE method (adapted from Kim et al., 2004).

were detected initially but soon disappeared. Another reason these compounds were excluded was because they were detectable in non-irradiated samples. Therefore, 1,3-bis(1,1-dimethylethyl)benzene was selected as a marker compound in irradiated beef extract powder.

2-ACBs are routinely used as chemical markers for irradiated foods containing lipids. A simple and rapid method for the isolation of 2-ACB carbon dioxide as a supercritical fluid has been described for low lipid-content fish samples (fresh- and seawater) irradiated up to 8 kGy. The presence of 2-DCB was confirmed in all irradiated fish samples irrespective of irradiation dose, thereby confirming the irradiation of fish samples. SFE was proposed as an alternative extraction procedure to the Florisil chromatography method currently in use and has the added advantage of a considerably shorter extraction time (Tewfik et al., 1999). However, it is not always possible to identify two radiolytic markers (2-DCB and 2-TCB) unless one deals with high lipid-containing irradiated foods. When both palmitic and stearic levels are low, however, irradiation identification can proceed even with a single marker.

SFE was employed to carry out an effective and rapid extraction (30 min) of volatile hydrocarbons and 2-ACBs contained in radiated foods. After elimination of the traces of triglycerides still contained in the extracts on a silica column, the compounds were analyzed with GC/MS for 2-ACBs and GC/FID for volatile hydrocarbons (Horvatovich et al., 2000). This method was carried out effectively on freeze-dried samples of cheese, chicken, avocados, and various ingredients (chocolate and liquid whole eggs) and proved to be much more rapid than the corresponding reference methods EN 1784 (volatile hydrocarbons) and EN 1785 (2-ACBs). Another advantage of this method was that lower irradiation doses could be detected compared to those of the two reference EN methods.

A sensitive and reliable method for detection of irradiated chicken, pork, and mangoes was described by Sin et al. (2006). This method involved a derivatization treatment of

irradiation markers 2-dDCB and 2-tDCB with pentafluorophenyl hydrazine (PFPH) and detection with GC/MS. Samples were first subjected to Soxhlet extraction with *n*-hexane and purified by passing through Florisil columns following the EN 1785 method. The extracted 2-dDCB and 2-tDCB were derivatized with PFPH in acidic buffer for 60 min. Identification of the derivatives was confirmed by the presence of two characteristic and dominant ion fragments at *m/z* 249 and [M-54]. The limits of detection (LODs) were estimated to be 0.01 µg/g. This sensitive and reliable method was applicable to detect food samples exposed to irradiation doses at 1–5 kGy. The concentration of 2-dDCB and 2-tDCB in foods was proportional to the irradiated dose they were exposed to.

Spiegelberg and co-workers (1994) compared two methods for the isolation of radiation-induced hydrocarbons—high-vacuum “cold finger” distillation and FCC. The findings suggested that they were of similar sensitivity but the latter was more practical for routine application. In terms of parameters optimization, FCC was found to be more promising with regard to the degree of Florisil activation and hydrocarbon resolution (on polar and nonpolar GC columns). Furthermore, the effective application of FCC to various food containing fats revealed that this method can be effectively used in conjunction with GC/MS for detection of irradiated products.

The applications of GC/MS for detection of irradiated foods are summarized in [Table 4.5](#).

4.3.2.2 *Root morphology*

A simple and inexpensive method based on root numbers and root length to discriminate irradiated onions and shallots from non-irradiated and chemically (maleic hydrazide) sprout-inhibited bulb crops was put forward by [Selvan and Thomas \(1999\)](#). Irradiated bulbs, when placed in contact with water for a period of 24–72 h, underwent a drastic reduction in both number of roots and root length. In maleic hydrazide-treated onions, no inhibition in rooting efficiency was recorded. Irradiated bulbs placed on 0.2% agar exhibited drastic inhibition only in root length. Therefore, the inhibition of root number and root length is a salient feature of irradiated onions and shallots when placed in contact with water for root formation. Irradiated bulbs in contact with agar medium can easily be identified by the drastic reduction in root length; hence, there is no requirement for control specimens.

4.3.2.3 *H₂ (gas evolution)*

Eggshell irradiated above 0.1 kGy gave a significant reading, even after 6 months, and no false-positive results were observed. The precision of the observed signals was tested with repeated analysis of both irradiated NaCl and irradiated eggshell at different doses and on different occasions, and it was found to be satisfactory; relative standard deviations were 10% or less. Failure to detect hydrogen provided no absolute proof of a non-irradiated sample ([Hitchcock, 2000](#)).

TABLE 4.5 GC/MS Applications for Irradiation Detection in Food

| Detection Method | Method Description/Modification | Target Compound | Irradiation Dose/Time | Food | Reference |
|------------------------|--|--|------------------------------------|--|--------------------------|
| Plant Products | | | | | |
| MS | Usage of superficial fluid extraction fat High solvent volume | Pseudomolecular ions and (M+H) ⁺ and pseudomolecular ion minus 18 (M+H H ₂ O) ⁺ | 0.1 kGy | Avocados | Horvatovich et al., 2006 |
| GC with FID | Heating temperature | Hydrocarbons | 0.5 kGy | Vegetable oils, avocado pears, olive, peanut oils, pilchards, and poultry meat | Lesgards et al., 1993 |
| GC/MS | — | 2 Dodecylcyclobutanone | 50 and 100 Gy | Cowpeas and rice | Horvatovich et al., 2002 |
| SPME and GC | — | Decanal and (E) 2 decenal | 0, 1, 2, or 3 kGy/ 14 days | Fresh cilantro leaves | Fan and Sokorai, 2002 |
| GC | Roasted, powdered, and irradiated treatment | Hydrocarbons | 0.5, 1, 5, and 10 kGy/30 weeks | Soybeans | Hwang et al., 2007 |
| Animal Products | | | | | |
| GC/MS | — | <i>n</i> Pentadecane, 1 tetradecene, <i>n</i> heptadecane, and 1 hexadecene | 2–4 kGy | Cheese | Barba et al., 2009 |
| GC | — | Tridecane, 1 dodecene, 1 tetradecene, and 1 hexadecane | 0, 1.2, 1.91, and 3.97 kGy/43 days | Cheese (Camembert) | Bergaentzle et al., 1994 |
| GC/MS | Technique applicable only at higher doses | 2 DCB | 3 and 5 kGy/ 1 month | Chicken (muscle and skin) | Parlato et al., 2007 |

(Continued)

TABLE 4.5 GC/MS Applications for Irradiation Detection in Food—cont'd

| Detection Method | Method Description/Modification | Target Compound | Irradiation Dose/Time | Food | Reference |
|------------------|---|--|--|---|--------------------------|
| SFE | Usage of carbon dioxide as a supercritical fluid The method is an alternative to Florisil chromatography | 2 DCB and 2 TCB | 2, 4, 6, and 8 kGy | Chicken and beef | Tewfik and Ismail, 1998 |
| GC and FCC | — | Hydrocarbons | 0.5 kGy | Pork, bacon, and ham | Hwang, 1999 |
| SPME | Low amount of organic solvents is required | 2 DCB | 0, 2, 4, and 8 kGy | Ground beef | Caja et al., 2008 |
| GC/MS with SPE | Hydrocarbon identification with chromatography retention times and MS | Hydrocarbons | 0.1, 0.5, 1, 3, 5, and 10 kGy | Beef, chicken, and pork | Kim et al., 2004 |
| SPME and P&T | High positive correlation with irradiation dose | 1,3 bis(1,1 dimethylethyl) benzene | 1, 3, 5, and 10 kGy/ 1 month of storage | Beef | Kim et al., 2005 |
| GC/MS and SFE | SFE for 2 DCB extraction | 2 DCB, 2 TCB | 8 kGy | Fish (fresh and seawater) | Tewfik et al., 1999 |
| GC/MS and FID | Minimal dose detectable by this method, slightly lower than those of the reference methods | Hydrocarbons and 2 alkylcyclobutanones | 0.5, 3, 4, and 100 kGy | Freeze dried samples of cheese, eggs, chicken, and avocados | Horvatovich et al., 2000 |
| GC/MS and PFPH | — | (2 dDCB), (2 tDCB) | 1 5 kGy | Chicken, pork, and mangoes | Sin et al., 2006 |
| GC/MS | — | Hydrocarbons | 3 and 5 kGy | Chicken, pork, and beef | Spiegelberg et al., 1994 |
| FPF and GC | Irradiation can be used for pathogen inactivation without major loss of volatile compounds | Hydrogen sulfide, sulfur dioxide, methanethiol, and dimethyl disulfide | 0 5 kGy/14 days of storage | Turkey breast | Fan et al., 2002 |

The determination of hydrogen from thawed samples of frozen food offers a reliable, rapid, and robust method for the detection of prior irradiation. Because it is based on an electronic sensor incorporated into a simple headspace analyzer, it is particularly useful as a low-cost, on-site screening procedure. False-positive results were not observed (except after obvious gross microbial contamination), but failure to detect hydrogen provided no proof of a non-irradiated sample. The technique is limited to frozen foods (e.g., chicken) that can be thawed inside the analyzer (Hitchcock, 2000).

Hitchcock (1995, 2000) performed two studies on the determination of H₂ (radiolytic gas) as a robust method for irradiation detection of foods. In the first study (1995), in which the unmodified method was used, frozen chicken drumsticks, irradiated at 5 kGy, were identified after storage up to 15 weeks. The application of the modified method (Hitchcock, 2000) to frozen prawns showed that 10-g samples could be identified 2 days after irradiation at doses down to 0.8 kGy, but the hydrogen marker was not available after storage for 4 weeks. Therefore, this method cannot be applied on a routine basis because wholesale and retail storage of the prawns might exceed 1 month. However, incipient spoilage of a non-irradiated sample might result in a false-positive result for irradiation. Prethawing in water in a refrigerator at 4°C for up to 40 h solved the problem.

A concise description of applications of irradiation detection methods based on the determination of radiolytic gas (H₂) in foods is given in Table 4.6.

4.3.2.4 High-performance liquid chromatography

High-performance liquid chromatography (HPLC) is a separation method that can be applied to analyze compounds of different properties, from the low to very high molecular mass substances. The HPCL method is not suitable for highly volatile compounds. HPLC

TABLE 4.6 Applications of Radiolytic Gas (H₂) in Irradiated Food

| Detection Method | Method Description/Modification | Target Compound | Irradiation Dose/Time | Food | References |
|----------------------------------|--|-----------------|---|---|-----------------------|
| Animal Products | | | | | |
| Radiolytic gas (H ₂) | All samples analyzed on receipt and after storage at ambient temperature | Free radicals | 0.1 and 4 kGy/ 25 weeks | Eggshells | Hitchcock, 2000 |
| Radiolytic gas (H ₂) | Robust method for irradiation detection of foods | | 5 and 0.8 kGy/ storage for 15 weeks (chicken) and 4 weeks (prawns) | Frozen chicken drumsticks and frozen prawns | Hitchcock, 1995, 2000 |

techniques have been coupled with spectrometric or spectroscopic techniques, such as MS, nuclear magnetic resonance (NMR) spectroscopy, and Fourier transform Raman spectroscopy, to analyze complex mixtures of compounds through separation, identification, and quantification in a single step and in one place (Sass-Kiss, 2008).

Foods of animal origin

The radiation-induced products of tryptophan (TRP) were determined in γ -irradiated egg white, chicken meat, and shrimp using reverse-phase HPLC and electrochemical detection. A two-step hydrolysis with proteinase K and carboxypeptidase A was developed to release the radiation products from egg white and chicken meat and with proteinase K and proteinase E from shrimps. The four hydroxytryptophan isomers (OH-TRP) were identified and quantified as radiation products in all samples. The amounts determined ranged from 0.02 to 1.97 mg/kg protein. A significant difference between irradiated and non-irradiated samples was found for irradiation doses of more than 3 kGy for egg white and chicken meat. However, for shrimp no significant increase in OH-TRP isomers was recorded up to a radiation dose of 5 kGy (Kleeberg et al., 2000).

Irradiation of pasteurized liquid whole egg was performed with a ^{60}Co source at room temperature using γ -ray doses of approximately 1, 3, and 5 kGy. The sponge cakes were prepared with irradiated as well as non-irradiated liquid egg according to two different recipes. Baking was performed at 170–190°C for 20 min. After cooling, the products were vacuum-packed (VP) in PE bags. The fat was extracted from cake samples with hexane, the solvent was evaporated, and hydrocarbon analysis was carried out with GC and HPLC. The online LC-GC technique was shown to be very efficient because only a few milligrams of fat is injected into the LC column, which means that only one-tenth of the amount of fat (~100 mg) needed for FCC has to be extracted from food (Schulzki et al., 1995).

Krach et al. (1997, 1999) published two simple and rapid methods aimed at determining the irradiation in shrimp, liquid egg, and sausages (protein-rich foods). First, using HPLC with an RP C-18 column and trichloroacetic acid as ion-pairing agent in combination with an electrochemical dual-cell detector, *o*- and *m*-tyrosine were identified by relative retention times. Second, coulometric electron array detected *o*- and *m*-tyrosine levels and their peak height ratios at different potentials in comparison to those of a standard mixture and quantified by calibration curves. The latter were identified by relative retention times. The amount of *o*-tyrosine formed by irradiation depends on the concentration of free phenylalanine. The free phenylalanine content is considerably higher in egg yolk than in albumin, thereby leading in low *o*-tyrosine formation during irradiation in liquid egg whose composition is two-thirds albumin and one-third egg yolk.

Tyrosine isomers produced by γ -radiation of aqueous phenylalanine solutions at mid-dose levels (1–10 kGy) were analyzed for irradiated food detection using a new HPLC analytical procedure. The procedure was established by means of an automated precolumn

derivatization with 4-fluoro-7-nitro 2,1,3-benzoxadiazole (NBD-F) followed by reverse-phase HPLC and laser fluorometric detection. The LOD was 0.06 ng on-column, the linear range for calibration for the tyrosine derivatives was 0.06–50 ng, and the relative standard deviation was 10–12%. The amounts of the tyrosine isomers increased with levels of irradiation. Irradiation at low temperature with reduced oxygen decreased the isomer yields. Dose rates varying from 0.5 to 10 kGy/h had no significant effect on tyrosine isomer formation if a total of 10 kGy was used in each case (Miyahara et al., 2000).

Use of the capillary liquid chromatography–diode array detection (DAD) method by Rosales-Conrado et al. (2008), combined with the optimized extraction and sample cleanup procedure, has allowed the residue determination of MeIQx, norharman, and harman heterocyclic aromatic amines (HAs) in both irradiated and non-irradiated spiked cooked ham samples at their usual levels of occurrence in meat food, with constant and reproducible spiked recoveries. Rosales-Conrado and co-workers noted that the use of DAD could be a practical advantageous alternative to the more expensive HPLC-MS/MS systems for routine use. The target HAs were detected either in non-irradiated or irradiated cooked ham samples at ionizing radiation levels of 1–8 kGy. With regard to the formation of HAs, the application of accelerated electrons to packed cooked ham could be a suitable and effective treatment for sanitation purposes for this type of ready-to-eat food.

Pérez-Ruiz et al. (2004) developed an HPLC method for the determination of citric, lactic, malic, oxalic, and tartaric acids by chemiluminescent detection following online irradiation with visible light. The organic acids were irradiated with visible light in the presence of Fe^{3+} and UO_2^{2+} to generate Fe^{2+} , which was determined by measuring the chemiluminescence intensity in a luminol system in the absence of added oxidant. The chromatographic separation was performed on a C-18 column under isocratic reverse-phase conditions using 0.005 M H_2SO_4 mobile phase. The robustness of the method resides in its ability to remain unaffected by small deliberate variations in the method parameters. The analytical usefulness of the proposed reaction detection system was tested by determining these analytes in milk, wine, beer, fruit juices, and soft drinks. It was shown that the content of the organic acids, as measured by the proposed method, was in excellent agreement with that obtained by HPLC with absorbance detection at 210 nm.

Mörsel and Schmiedl (1994) used 2-DCB as a model substance, synthesized by means of the key substance 1-bromo-1-ethoxycyclopropane, usually determined in fact matrices. The determination was carried out by labeling the cyclic ketone with fluorescent dyes and subsequent HPLC separation. 1-Pyrenebutyrylhydrazide and 7-diethylamino-3-carbonylazide were used as labeling reagents. Labeling with 1-pyrenebutyrylhydrazide was unsuccessful because of its low reactivity. Medium- and short-chain aldehydes and ketones were easily labeled. After reduction to the corresponding alcohol, dodecylcyclobutanone, as well as aldehydes and ketones were successfully labeled with 7-diethylamino-3-carbonylazide.

TABLE 4.7 HPLC Applications for Detection in Irradiated Food

| Detection Method | Method Description/Modification | Target Compound | Irradiation Dose/Time | Food | Reference |
|------------------------|---|--|-------------------------|---|------------------------------|
| Animal Products | | | | | |
| HPLC and GC | Solvent evaporation and hydrocarbon analysis with GC and HPLC | Hexanal | 1.3 and 5 kGy | Liquid whole eggs | Schulzki et al., 1995 |
| HPLC | HPLC with a RP C 18 column and coulometric electron array | <i>o</i> and <i>m</i> tyrosine levels | 0.5, 1, 2, 4, and 6 kGy | Shrimp, liquid egg, and sausages | Krach et al., 1997, 1999 |
| HPLC MS/MS | Heating treatment | Synthetic compounds | 1 and 8 kGy | RTE cooked ham | Rosales Conrado et al., 2008 |
| HPLC | — | Fe ²⁺ , Fe ³⁺ , and UO ₂ ²⁺ ions | — | Milk, wine, beer, fruit juices, and soft drinks | Pérez Ruiz et al., 2004 |

Separation was carried out with good results on RP-18 reversed phases using methanol water mixtures as mobile phases in HPLC. The detection limit of DCB was approximately 5 ng.

Table 4.7 presents HPLC applications for irradiation detection in food.

4.3.2.5 Thiobarbituric acid/2-tetradecylcyclobutanone

Thiobarbituric acid (TBA) test for detecting the development of oxidation rancidity was measured with distillation methods from *Official Methods of Analysis of AOAC International*, 16th edition. Iodine value (IV), universally used to measure unsaturated halogenation of double bonds, and peroxide value of fat/oil, expressed in terms of milliequivalents of active oxygen per kilogram, were also determined by Yosuf et al. (2007).

Foods of plant origin

Yosuf and co-workers (2007) conducted a study in an attempt to determine the optimum decontamination dose for a locally manufactured coconut cream powder. Samples were γ -irradiated (0–15 kGy) and the aging process was achieved using a Geer oven at 60°C for 7 days (equivalent to 1 year of storage at room temperature). IVs ranging from 4.8 to 6.4 were not affected by radiation doses and storage. Although a 25-member sensory panel reported scores on odor, creamy taste, and overall acceptance for all irradiated samples at more than 5 kGy that were significantly lower than scores for the control, no significant differences among the applied irradiation doses were found. All stored products were significantly different in color, creamy taste, odor, and overall acceptance compared to the nonstored, non-irradiated control. Although the decontamination dose to be applied

(1–5 kGy) greatly depends on the coconut hygienic condition, application of good hygiene practices (GHPs) and good manufacturing practices (GMPs) is expected to improve it considerably and thereby avoid or at least limit the employment of irradiation.

Foods of animal origin

An investigation was undertaken to determine the potential radiation dose for treating liquid egg white (LEW) and liquid egg yolk (LEY) at room temperature to improve their microbial safety (Badr, 2006). Samples of LEW and LEY were subjected to γ -irradiation doses of 0–4 kGy at room temperature followed by storage at $4 \pm 1^\circ\text{C}$. Then, the effects of irradiation and cold storage on proximate composition, pH, soluble proteins, and free sulfhydryl content (SH) were determined for LEW and LEY in addition to the contents of total carotenoids in LEY. The effects of irradiation at a dose of 3 kGy, which was enough to improve the microbial safety of samples, on amino acid composition of LEW and LEY and fatty acid profiles of LEY lipids were studied. Moreover, sensory evaluation was carried out for liquid and scrambled egg white and egg yolk samples. The results revealed that the contents of total carotenoids significantly decreased in LEY samples. Furthermore, γ -irradiation had no significant effect on protein solubility and the contents of free SH in LEW, whereas it induced slight decreases in protein solubility and the contents of free SH in LEY. It was concluded that the 3-kGy dose of γ -irradiation can be used as an optimum dose for treating LEW and LEY at room temperature followed by refrigerated storage ($4 \pm 1^\circ\text{C}$) to improve their microbial safety without adverse chemical changes that may affect their sensory or functional properties. The sensory preferences were not altered for the liquid egg samples or for scrambled egg samples prepared from irradiated liquid egg products.

Tewfik and Tewfik (2008) reported that after storage for 1 year at 20°C , the amounts of 2-DCB and 2-TCB (detected with SFE and GC/MS) were significantly reduced at all doses. However, the relationship between the losses of the markers and dose remained linear for minced beef. Irrespective of the recorded decrease, it was still possible to detect irradiation in fatty foods even after 12 months of storage. It was surprising that although the irradiation dose was very low (2 Gy), 2-DCB and 2-TCB could still be detected in minced beef. Moreover, it was confirmed that both the storage period and the irradiation dose greatly affected the levels of 2-ACBs detected.

Gautam et al. (1998) suggested a simple and rapid method for detection of irradiated food. The method was based on the principle of microbial contribution to the development of turbidity. The A_{600} values of all the non-irradiated samples (fish, lamb meat, chicken, and mushroom) varied within the absorbency range of 1.2–1.4 after 4 h compared to less than 0.1 for all irradiated samples.

The applications of the TBA/TCB irradiation detection method in food are summarized in Table 4.8.

TABLE 4.8 TBA/TCB Applications for Irradiation Detection in Food

| Detection Method | Method Description/Modification | Target Compound | Irradiation Dose/Time | Food | Reference |
|------------------------|---|-----------------------|---|--|-------------------------|
| Plant Product | | | | | |
| TBA | Very little effect on flavor, texture, and other important sensory properties | Peroxide | 0, 5, 10, and 15 kGy/7 days of storage | Coconut cream powder | Yosuf et al., 2007 |
| Animal Products | | | | | |
| TCB with SFE and GC/MS | Despite low irradiation dose, 2 DCB and 2 TCD could be still detected | 2 DCB and 2 TCB | 2, 4, 6, and 8 kGy/12 months of storage | Minced beef | Tewfik and Tewfik, 2008 |
| Turbidimetric method | Distinguishes the irradiation treatment from other hygienization techniques | Turbidity measurement | 1 and 2 kGy/10 days | Fish, lamb meat, chicken, and mushroom | Gautam et al., 1998 |

4.3.2.6 Peroxidation

The level of peroxides in irradiated pork was shown to increase linearly with the increasing absorbed dose. The chemical yield of peroxides formed in the irradiated fat was approximately 4.2; it was independent of the sample temperature or absorbed dose rate but dependent on storage time of sample before γ -irradiation. The irradiated pork revealed some unusual features: (i) The peroxide content in irradiated pork was higher than that in non-irradiated pork; (ii) the peroxide content in irradiated pork increased gradually with storage time and was essentially constant in the non-irradiated pork; and (iii) UV radiation could potentially trigger further formation at peroxides (Qi et al., 1998).

The advantages and disadvantages of chemical methods employed for irradiation detection in food are given in Table 4.9.

4.3.3 Biological

4.3.3.1 Enzyme-linked immunosorbent assay

Catala and Puchades (2008) noted that:

immunochemical techniques are simple and powerful analytical methods applicable to all types of analytes, from low-molecular-weight substances (e.g., antibiotics) to highly complex entities such as enzymes, viruses, or microorganisms. The first immunoassay was developed by Yalow and Berson in 1960, for the determination of insulin in blood. Since then, immunoassays were extended

TABLE 4.9 Advantages and Disadvantages of Chemical Methods Used for Irradiation Detection in Food

| Method | Advantages | Disadvantages | References |
|-----------------|---|---|---|
| GC/MS | Effective on freeze dried samples More rapid than reference method EN 1784 Reduction of extraction time from 6 h to 30 min Larger sample can be used for analysis Extraction of low contents of radiolytic markers | High experimental error ($\pm 20\%$) Fluctuations of parameters of the ionization treatment (temperature and dose rate) | Horvatovich et al., 2000; Tewfik and Ismail, 1998 |
| Root morphology | A simple and low cost method based on root numbers and root length | — | Selvan and Thomas, 1999 |
| H ₂ | Reliable, rapid, and robust method Low cost on site screening procedure Use of activated carbon to purify recirculating headspace minimizes interference Reduces blanks and allows more rapid throughput Improved sensitivity allows detection of 1 kGy doses after 4 months of storage at 18°C | The technique is limited to frozen foods, samples of at least 100 g, and minimum detectable dose 1 kGy Failure to detect hydrogen provides no proof of an un irradiated sample | Hitchcock, 2000 |
| HPLC | Reliable and effective | High experimental cost due to consumables' high cost (solvents, column) | Sass Kiss, 2008 |
| TBA/TCB | Detects development of oxidation rancidity | — | Yosuf et al., 2007 |
| Peroxidation | Increases linearly with increasing absorbed dose Peroxide content in irradiated food is higher than in non irradiated food Peroxide in irradiated food increases gradually with storage time, whereas it is constant in non irradiated food | — | Qi et al., 1998 |

to a large number of fields, ranging from basic research to routine control (e.g., pregnancy test). Due to its sensitivity, selectivity, and versatility, immunoassay has become a very popular tool, including in authentication work, where discriminating between different animal species in meat, or detecting cow's milk adulteration in sheep's milk, is routine.

Tyreman et al. (2004) described the development and use of a competitive ELISA to detect prawns that had been irradiated. The ELISA utilizes a monoclonal antibody against a modified DNA base, dihydrothymidine. The ELISA was applied successfully to two prawn species—North Atlantic prawn (*Pandalus borealis*) and tiger prawn (*Penaeus monodon*). The ELISA had a working range of 0.5–2 kGy with CVs typically below 10%.

Storage of irradiated prawns for up to 12 months at 20°C was shown to have no effect on ELISA performance.

4.3.3.2 DNA

Comet assay

The first method involved DNA hybridization techniques on membrane-bound (nitrocellulose or nylon) media or in solution. This study illustrated that nonradioactive DNA probes could detect DNA from specific bacterial contaminants. Haine et al. (1995) proposed the development of a DNA hybridization test for nonspecific (i.e., normal) bacteria. The second technique, dubbed the comet assay, relied on the fact that irradiation induces DNA fragmentation. Leakage of these DNA subunits from the nuclei of lysed cells during electrophoresis produced the aforementioned characteristic “comet” feature, whereas non-irradiated samples did not exhibit this trait.

Foods of plant origin. Papaya, melon, and watermelon samples were treated in a ^{60}Co facility at dose levels of 0.0, 0.5, 0.75, and 1.0 kGy. The irradiated samples showed typical DNA fragmentation, whereas cells from non-irradiated ones appeared intact. In addition to the DNA comet assay, the half-embryo test was equally applied in melon and watermelon to detect the irradiation treatment. The tails of the comets of irradiated fruits up to 1.0 kGy increased in length but not in width. Although differentiation was sometimes difficult at the lowest radiation dose (0.5 kGy) applied, at higher doses the irradiated samples could be easily distinguished from the non-irradiated ones. With regard to root growth, clear differences between irradiated and non-irradiated samples were observed beginning on the second and third day after incubation for melon and watermelon, respectively, as illustrated in Figure 4.11. Roots of irradiated samples were markedly reduced, and very limited secondary root elongation was observed (Marín-Huachaca et al., 2004).

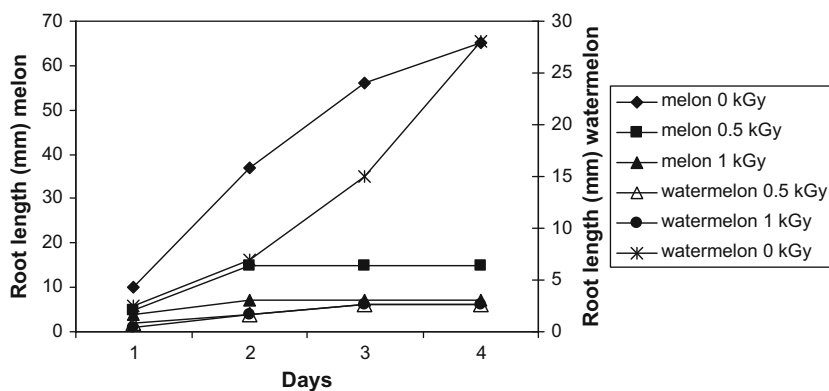


Figure 4.11: Effect of γ -irradiation on the root growth of half-embryos of melon and watermelon (0, 0.5, and 1 kGy) (adapted from Marín-Huachaca et al., 2004).

Application of the DNA comet assay enabled rapid detection of radiation treatment (0.5, 1, and 5 kGy) of several leguminous beans (azuki, black, black eye, mung, pinto, red kidney, and white beans). The cells or nuclei from beans were extracted and analyzed between 15 and 60 min in 2.5% SDS, and electrophoresis was carried out followed by silver staining. In irradiated samples, fragmented DNA stretched toward the anode and the damaged cells appeared as a comet. The density of DNA in the tails increased with increasing radiation dose. In non-irradiated samples, the large molecules of DNA remained relatively intact and the cells were almost round. Therefore, under appropriate experimental conditions, several cultivars of beans irradiated to insect disinfestation dose of at least 0.5 kGy can be detected for radiation treatment (Khan et al., 2002b).

Soybean harvest is of great importance in Brazil because this country is one of the major exporters worldwide. However, soybean is very susceptible to *Phakopsora pachyrhizi*, which is easy to disseminate, and e-beam irradiation (1–9 kGy) was used in an attempt to minimize soybean losses during storage. Satisfactory effect of e-beam treatment to control *P. pachyrhizi* growth was reached with doses higher than 6.0 kGy because there was no evidence of fungi colony in the samples analyzed by the microbiological viability test. The percentage of root growth with radiation doses of 1, 2, 5, 6, 7, 8, 9, and 10 kGy was 246.2, 150.8, 141.3, 114.7, 103.2, 99.7, 97.2, and 94.2%, respectively (Villavicencio et al., 2007). Application of the DNA comet assay resulted in the detection of DNA degradation due to the irradiation treatment.

Two cultivars of Brazilian beans, *Phaseolus vulgaris* L. (var. carioca) and *Vigna unguiculata* (L.) Walp (var. macacar), were irradiated using a ^{60}Co source with doses ranging from 0 to 10 kGy. The detection tests were conducted after 6 months of storage at room temperature. The germination test of these two bean cultivars showed that for roots (for a radiation dose at 1 kGy), the macacar cultivar exhibited a better germination response than the carioca cultivar [10 vs. 4 mm and 16 vs. 12 mm (root length) 6 months after irradiation for 24 and 72 h, respectively]. In the DNA comet assay, non-irradiated cells of the two varieties of beans exhibited only limited DNA migration out of the cells, whereas irradiation with 10 kGy caused extensive DNA fragmentation. The DNA fragments migrated toward the anode, which was confirmed by the presence of typical comets with long tails. However, application of ESR was not successful in identifying the irradiated beans, probably because of the decay that the signal underwent during the 6 months of storage. TL measurements of the isolated mineral debris from the beans made the identification of the radiation treatment feasible at both 1.0 and 10 kGy, even after 6 months of storage. The obtained TL results were in agreement with those obtained by other authors (Khan and Delincée, 1995a,b; Pinnioja, 1993; Sanderson et al., 1989, 1996a; Schreiber et al., 1995) that TL is a sensitive and reliable method to detect whether foods were irradiated.

Villavicencio et al. (2004) analyzed three soybean varieties to evaluate the irradiation effect on the detection of genetic modification. Samples were treated in a ^{60}Co facility at dose levels of

0, 0.5, 0.8, and 1 kGy. The seeds were first analyzed with the comet assay. Germination test was performed to detect the viability of irradiated soybeans. Finally, because of its high sensitivity, specificity, and rapidity, the polymerase chain reaction (PCR) was applied for genetic modified organism (GMO) detection. The analysis of DNA by microgel electrophoresis of single cells (DNA comet assay) showed that DNA damage increased with increasing radiation doses.

Microgel electrophoresis of single cells (DNA comet assay) was applied to detect irradiation treatment (e-beam, 1 or 2 kGy) in fresh and frozen rainbow trout, red lentil, and sliced almonds. Rainbow trout samples gave good results, with samples irradiated to 1 or 2 kGy showing fragmentation of DNA (long comets). Non-irradiated samples displayed shorter comets with a significant number of intact cells. For rainbow trout stored in a freezer for 11 days, the irradiated samples could still be identified with electrophoresis from non-irradiated samples. Radiation treatment of red lentils was equally detected with this method, whereas irradiated almonds could not be properly identified, probably due to incomplete lysis (Khan and Delincée, 1998).

Foods of animal origin. The DNA comet assay was applied by Villavicencio et al. (2000) to identify exotic meat (boar, jacaré, and capybara) irradiated with ^{60}Co γ -rays (0, 1.5, 3.0, and 4.5 kGy). Analysis of the DNA migration (comet assay) enabled rapid identification of the radiation treatment. In fact, the results revealed that the distance of DNA migration, “comet length,” increased with radiation dose for all samples. Furthermore, the size of the dose could be identified by the shape of the comet.

Delincée (1995) reported on the use of the comet assay (DNA fragmentation in irradiated foods) and determination of radiolytic-formed gases (CO and H₂) with electrochemical gas sensors. An increase in radiation comet greatly affected the shape of the comet, thereby indicating an existing relationship. Using this classification principle, an interlaboratory study with frozen chicken and pork cells irradiated with 0, 1, 3, and 5 kGy yielded a very high rate (>90%) of identification (Delincée, 1994). The gas evaluation method proved to be very successful because irradiated chicken breast chops and mechanically recovered poultry meat were closely related with increases in CO and H₂.

Refrigerated pork meat was irradiated with ^{60}Co γ -rays at 0, 1.5, 3.0, and 4.5 kGy for refrigerated samples. Samples were kept in the refrigerator after irradiation. Pork meat was analyzed 1, 8, and 10 days after irradiation using the DNA comet assay. The results revealed that an increase in irradiation dose led to an increase in migration distance of DNA fragments. Depending on the structure of DNA fragments formed, an approximate estimation of the applied dose could be made. A long storage time and other factors such as frozen/heat cycles also induced DNA degradation (Araújo et al., 2004).

To detect the treatment of beef meat pieces either by γ -rays or by e-beam, the method EN 13784 was applied. The dose levels were 2.5, 4.5, and 7.0 kGy for chilled samples and 2.5, 4.5, 7.0, and 8.5 kGy for frozen samples. All analyses were carried out 15 and 30 days after irradiation for the chilled and frozen samples, respectively. No difference was observed in the effect of γ -rays and e-beam on DNA migration. It was shown that the DNA comet assay, at neutral pH, could easily discriminate between irradiated and non-irradiated beef (Huachaca et al., 2005).

Delincée (2002) analyzed frozen ready-prepared hamburgers from the marketplace that were “electron irradiated” with doses of 0, 1.3, 2.7, 4.5, and 7.2 kGy covering the range of potential commercial irradiation. DNA fragmentation in hamburgers was visible within a few hours using the comet assay, and non-irradiated hamburgers were easily distinguished from the irradiated ones. Even after 9 months of frozen storage, irradiated hamburgers could be identified. Delincée noted that because DNA fragmentation may also occur with other food processes (e.g., temperature abuse), positive screening tests should be confirmed using a validated method, such as EN 1784 or EN 1785, to specifically prove an irradiation treatment.

The DNA comet assay is a rapid, simple, sensitive, reliable, and fairly inexpensive method for measuring DNA strand break. An analysis of DNA damage following γ -radiation (^{60}Co) treatments at a dose of 0.5 and 1 kGy was carried out on cells obtained from the larvae, pupae, and adults of *Sitophilus zeamais* (Hansan et al., 2008). Gamma radiation induced considerable damage at the DNA level in larvae, pupae, and adults, as shown by increased strand breaks compared to intact cells from non-irradiated ones. Comet assay revealed that tail length and percentage tail DNA varied greatly for all developmental stages of *S. zeamais* and may be a promising tool for detecting the effectiveness (DNA damage) in insect pest strategies.

In a study by Khan et al. (2005), cereals and nuts were exposed to radiation doses of 0.5, 1, and 3 or 5 kGy covering the range for insect/pest disinfestation or for microbial control. After electrophoresis, irradiated cells from buckwheat, maize, millet, oat, almonds, peanuts, walnuts, and hazelnuts gave dose-dependent comets, indicating stretching of fragmented DNA toward the anode. Non-irradiated samples of all cereals exhibited intact cells/nuclei in the form of round stains or with short faint tails; except for wheat, which showed only comets also in non-irradiated samples. In addition, qualitative differentiation between non-irradiated and irradiated nut samples, a rough dose estimate, was also possible. However, detection of radiation treatment was not possible for nuts such as Brazil, cashew, and pistachio because an appropriate amount of DNA material could not be isolated from the samples of these foods. The assay disclosed several limitations because a number of foods could not be screened for irradiation using this technique. In applying the comet assay for detection of irradiated foods, therefore, preliminary tests per type of foodstuff are recommended prior to the analysis of unknown samples. It should also be recognized that the assay is not radiation specific, and

a positive result needs to be confirmed by another validated method to specifically prove the radiation treatment. The DNA comet assay, therefore, has its restraints, but for several cereals and nuts it serves as a rapid and inexpensive screening test.

A description of DNA comet assay applications for irradiation detection in food is given in [Table 4.10](#).

Polymerase chain reaction

Foods of animal origin. [Lee and Levin \(2008\)](#) examined the effects of γ -irradiation on the destruction of *Vibrio vulnificus* by real-time PCR. They found that γ -irradiation induced an extensive reduction in the molecular size of DNA. Irradiation of viable cells (1×10^6 CFU/ml) at 1.08 kGy resulted in 100% destruction determined by plate counts, with most of the DNA from the irradiated cells having a base pair (bp) length of less than 1000. The use of a pair of primers to amplify a 1000-bp sequence of DNA from cells exposed to 1.08 kGy did not yield any amplification. In contrast, primers designed to amplify sequences of 700, 300, and 70 bp yielded amplification with C_t values resulting in 13.4, 27.6, and 45.4% detection of genomic targets. When viable cells of *V. vulnificus* were exposed to 1.08, 3.0, and 5.0 kGy, the average molecular size of genomic DNA visualized in an agarose gel decreased with increasing dose, corresponding to an increased probability of amplification with primers targeting sequences of decreasing size.

[Lim et al. \(2008\)](#) investigated the effect of irradiation treatment (1, 3, 6, and 10 kGy) on the detection of *Salmonella* using real-time PCR. They tested three commercially available kits, of which the InstaGene Matrix procedure was most effective in preparing template DNA from *Salmonella* exposed to radiation in broth culture. The minimum level of detection by real-time PCR combined with InstaGene Matrix was 3 log units of *Salmonella* per milliliter. When pure cultures of *Salmonella* were irradiated at 3 and 5 kGy, however, the cycle threshold (C_t) increased 1- to 1.5-fold compared to irradiation at 0 and 1 kGy, indicating that irradiation treatment may result in an underestimation of bacterial counts due to radiation-induced DNA lesions. The sensitivity of detection of *Salmonella typhimurium* in pure culture without enrichment was 10^3 CFU/ml, regardless of the procedure for recovering template DNA, because specific PCR products with a distinct melting point of 85°C were not observed at the concentration of 10^2 CFU/ml. However, the C_t values for the PCR reaction using template purified with InstaGene Matrix were lower than those observed with the DNeasy Tissue kit.

[Table 4.11](#) presents applications of PCR for irradiation detection in irradiated food.

Half-embryo test

A collaborative study on the use of the half-embryo test for the detection of irradiated citrus fruit was undertaken by [Kawamura et al. \(1996\)](#). Samples of seeds removed from citrus fruit were irradiated with doses of 0, 0.2, and 0.5 kGy and examined by 12 participating laboratories.

TABLE 4.10 DNA Comet Assay Applications for Irradiation Detection in Food

| Detection Method | Method Description/Modification | Target Compound | Irradiation Dose/Time | Food | Reference |
|------------------------|--|------------------|--|---|-----------------------------|
| Plant Products | | | | | |
| DNA comet assay | Irradiated cells show an increased extension of DNA | — | 0, 0.5, 0.75, and 1.0 kGy | Papaya, melon and watermelon | Marin Huachaca et al., 2004 |
| DNA comet assay | The unavailability of sufficient DNA precluded the use of the comet test for these samples | Polyethylene | 0.5, 1, and 5 kGy | Beans (azuki, black, black eye, mung, pinto, red kidney, and white beans) | Khan et al., 2002 |
| DNA comet assay | Indicates possible modifications caused by treatment | Sodium chloride | 0, 1, 2, 5, 6, 7, 8, 9, and 10 kGy | Soybeans | Villavicencio et al., 2007 |
| DNA comet assay | — | Agarose gel | 0, 0.5, 0.8, and 1 kGy | Soybeans | Villavicencio et al., 2004 |
| DNA comet assay | Microgel electrophoresis | Agarose gel | 1 and 2 kGy/11 days of storage | Fresh and frozen rainbow trout, red lentil, and gram and sliced almonds | Khan and Delincée, 1998 |
| DNA comet assay | Stretching of fragmented DNA | — | 0.5, 1, and 3 or 5 kGy | Cereals and nuts, buckwheat, maize, millet and oat, and also from almonds, peanuts, walnuts and hazelnuts | Khan et al., 2005 |
| Animal Products | | | | | |
| DNA comet assay | DNA migration increased with radiation dose | — | 0, 1.5, 3.0, and 4.5 kGy/1 day | Exotic meat (boar, jacareá, and capybara) | Villavicencio et al., 2000 |
| DNA comet assay | Increase of irradiation dose led to increase of migration distance of DNA fragments | — | 0, 1.5, 3.0, and 4.5 kGy | Pork meat | Araújo et al., 2004 |
| DNA comet assay | Gradual increase of radiation induced DNA damage in beef samples | Agarose | 2.5, 4.5, 7.0, and 8.5 kGy/1 month | Beef meat | Huachaca et al., 2005 |
| DNA comet assay | Identification of food radiation treatment | — | 0, 1.3, 2.7, 4.5, and 7.2 kGy/9 months | Frozen ready prepared hamburgers | Delincée, 2002 |
| ELISA | No effect on ELISA performance Utilizes a monoclonal antibody against a modified DNA base | Thymidine glycol | 0.5 2 kGy/12 months of storage | Prawns | Tyreman et al., 2004 |

TABLE 4.11 PCR Applications for Detection of Irradiated Food

| Detection Method | Method Description/Modification | Target Compound | Irradiation Dose/Time | Food | Reference |
|------------------------|---|-----------------|------------------------|------------------------|---------------------|
| Animal Products | | | | | |
| PCR | Quantify bacteria from any source | — | 1.08, 3.0, and 5.0 kGy | Seafood | Lee and Levin, 2008 |
| PCR | The PCR based detection of bacteria exposed to irradiation depends on the efficiency of the DNA extraction procedure used to prepare the template DNA | — | 1, 3, 6, and 10 kGy | Chicken breast fillets | Lim et al., 2008 |

The percentage of correct identifications, whether irradiated or unirradiated, amounted to 92% of 48 samples after 4 days of incubation and 98% after 7 days of incubation. Only one sample, irradiated with 0.2 kGy, was incorrectly identified. This collaborative study revealed that irradiated citrus fruit can be identified using the half-embryo test and that the test can be effectively applied in practice. The main advantages of the half-embryo test are that: (i) the detection limit of the irradiation dose is 0.15 kGy or less so that it is sufficiently sensitive for the identification of irradiated fruit; and (ii) the method is simple, inexpensive, and environment friendly and no specialized equipment is required.

DEFT/APC

Foods of plant origin. The DEFT/APC method has been used for screening irradiated spices (Boisen, 1993; Hammerton and Benos, 1996). Oh et al. (2003) found that for imported spices (whole black pepper, powdered white pepper, marjoram, and thyme) except powdered black pepper and marjoram, a logDEFT/APC ratio of 2.5 was indicative of irradiation treatment with a dose level of at least 3 kGy or higher. The Korean red pepper powder and garlic powder gave 2.5 or more logarithmic units in the irradiated samples with 5 kGy or higher, whereas the onion and ginger powder gave 2.5 or more units in the irradiated samples with 3 kGy or higher. Spices irradiated with a dose of 5 kGy were clearly identified in all samples. This method revealed the microbiological characteristics of the product at the time of analysis (APC count) and also provided information about the product history (DEFT count). The combined DEFT/APC method can be effectively used for screening purposes.

Foods of animal origin. DEFT/APC was devised to monitor the amount of microorganisms in food products. Typically, the food sample is treated with a proteolytic enzyme and surfactant and heated (50°C). The microorganisms are then caught by a membrane filter, stained with a fluorescent nucleic acid dye (e.g., acridine orange), and then viewed with an epifluorescent

microscope. In the late 1980s, [Betts et al. \(1988\)](#) reported that DEFT might be employed to detect irradiated foods by comparison with the APC, a method to evaluate the amount of aerobic mesophyllic microorganisms. The DEFT microorganism count is generally unaffected by irradiation technique. It is also noteworthy that sample storage may affect the DEFT/APC results ([Jones et al., 1995](#)).

In 2003, Leth and co-workers carried out a survey for irradiation detection (using DEFT/APC, PSL, and TL) of 106 herbal food supplements in Denmark. Although 40 samples were screened positive with the DEFT/APC method, the TL method could only confirm irradiation of 15 samples. The DEFT/APC method gave a large number of false-positive results, although the number of false-negative results was probably very low. Furthermore, 7 of the 15 confirmed irradiated samples screened positive with the PSL screening method because the samples with low photon counts were not detected.

The advantages and disadvantages of biological methods applied for irradiation detection in food are given in [Table 4.12](#). A summary of DEFT/APC applications for irradiation detection in food is given in [Table 4.13](#).

TABLE 4.12 Advantages and Disadvantages of Biological Methods Employed for Irradiation Detection in Food

| Method | Advantages | Disadvantages | References |
|-----------------|--|---|---|
| ELISA | Highly sensitive, selective, and versatile technique High working capacity Little sample treatment Minimum sample size (microliter volumes) Reduced wasting chemicals Work from batch to full automation Simple and powerful analytical method Immunoassays can provide information to validate new sampling test Cost effective method Immunoagents developed to respond specifically to the target of interest ELISA is a specific, rapid, and low cost technique that is easy to perform The investment in equipment is smaller than that for other techniques | Difficulty in producing an antibody specific to a particular target Heat lability of proteins is the main obstacle to the general application Availability of adequate immunoreagents Immunoreagent stability Qualitative information some times difficult to interpret Sometimes need confirmation of screening results Methodology still not well accepted in food area High cost of commercial kits | Catala and Puchades, 2008 |
| DNA comet assay | Qualitative differentiation between non irradiated and irradiated samples Rough dose estimate is also possible Rapid and inexpensive screening test | A number of foods could not be screened for irradiation using this technique Preliminary tests per new type of foodstuff are recommended The assay is not radiation specific and a positive result needs to be confirmed by another validated method | Khan et al., 2005 |

(Continued)

TABLE 4.12 Advantages and Disadvantages of Biological Methods Employed for Irradiation Detection in Food—cont'd

| Method | Advantages | Disadvantages | References |
|------------------|---|---|--|
| PCR | Extremely powerful biochemical tool Large copy numbers (800–1000) per cell Variety of complementary molecular techniques A number of unique matrix based assay systems | Allergic reactions to the presence of small amounts of specific species Life threatening anaphylactic symptoms Allows only a short amplicon | Levin, 2008 |
| Half embryo test | Sensitive for irradiated fruits identification Detection limit of the irradiation dose is 0.15 kGy or less Method is simple, inexpensive, and friendly to the environment No specialized equipment is required | — | Kawamura et al., 1996 |
| DEFT/APC | Controls the amount of microorganisms in food products The method can be effectively used for screening purposes | Sample storage may affect the DEFT/APC results Large number of false positive results No detection in samples with low photon counts | Jones et al., 1995; Leth et al., 2006; Oh et al., 2003 |

TABLE 4.13 DEFT/APC Applications for Irradiated Detection in Food

| Detection Method | Method Description/ Modification | Target Compound | Irradiation Dose/Time | Food | Reference |
|-----------------------|---|------------------------|--------------------------|--|-------------------|
| Plant Products | | | | | |
| DEFT/APC | Screening purposes Provides information on the microbiological characteristics | Colored microorganisms | 1, 3, 5, and 7 kGy | Black pepper and marjoram, red pepper and garlic powder, onion and ginger powder | Oh et al., 2003 |
| DEFT/APC, PSL, and TL | — | Colored microorganisms | 1 kGy | Herbal food supplements | Leth et al., 2006 |

4.4 Conclusions

New methods of detection continue to be devised; unfortunately, however, several of these have not been described in detail in the widely available scientific literature. It seems likely that regulatory systems will require a combination of a rapid low-cost screening assay that may be applied in a number of inspection stations or laboratories (e.g., comet or ELISA

tests) and a specific, official, and, ideally, quantitative assay at a centralized location (e.g., ESR). ESR spectroscopy has proven to be one of the most powerful methodologies to differentiate irradiated from unirradiated foodstuffs (Anonymous, 1996; McMurray et al., 1996).

With respect to the irradiation of food with doses of 10 kGy, studies on radiation chemistry have shown that under the technological conditions necessary for obtaining chemistry foods of an acceptable organoleptic quality, chemiclearance, commonality of radiolytic reaction products, and predictability of radiation chemical reaction mechanisms can continue to be used in the assessment of the safety of food (WHO, 1994).

Although few laboratories specialize in irradiation detection, in a Polish laboratory, the following detection methods have been accredited:

1. Detection of irradiation in bone containing foods by EPR spectroscopy
2. Detection of irradiation in foods containing cellulose by EPR spectroscopy
3. Detection of irradiation by TL technique in foods from which silicate minerals can be separated (four detection methods were tested in addition and were validated to be implemented as routine detection methods)
4. Detection of irradiation in foods containing sugars by EPR spectroscopy
5. Detection of irradiation by the DNA comet assay test (screening method) (Kruszewski et al., 1998)
6. Detection of irradiation in seeds by germination power test (Malec-Czechowska et al., 1999)
7. Detection of irradiation by determination of volatile hydrocarbons in fat-containing foods.

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Risk Assessment of Irradiated Foods

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5.1 Introduction

Risk assessment and its twin, risk perception, began at least as early as the 1300s when insurance rates, proportional to the risk, on merchant shipping were established. Throughout the years, the basis for risk assessment and perception changed as they were used, in addition to marine insurance, for actuarial tables and life insurance rates, for safety factors on engineering projects, for public safety when threatened by natural hazards such as floods and hurricanes, for environmental and health risks, and for chronic risks (Sharlin, 1989).

For some time now, risk analysts have dealt with both sides of risk in an additive manner. At times when risk management has been under serious pressure to demonstrate effectiveness and cost-efficiency, the parallel approach of pleasing the technical elite and the public alike has lost legitimacy. Risk assessment is the scientific process of defining the components of risk in precise, usually quantitative, terms. In technical risk assessments, this means specifying what is at stake, calculating the probabilities for (un)wanted consequences, and aggregating both components (Kolluru and Brooks, 1996).

A definition of risk can be found in Regulation (EC) No. 178/2002: Risk assessment means a scientifically based process consisting of four steps—hazard identification, hazard characterization, exposure assessment, and risk characterization. Risk also includes nutritional risk, resulting from both deficient and excessive intake. Regarding a definition of benefit, it was proposed to either convert the definition of risk into positive wording or to include any identifiable potential positive effect in connection with food. This would also include reduction of risk (European Food Safety Authority, 2006).

The term “risk communication” was first coined and used in the United States in the 1980s. The need for risk communication has arisen from the fact that modern life is increasingly surrounded by such hazards as pollutants in the air and in drinking water; pesticide residues in food and milk; threats from radiation and toxic chemicals; and global climatic anomalies such as the greenhouse effect, acid rain, and the ozone hole. Risk communication is

therefore considered as a rational step to enhance the accurate knowledge of the risks (National Research Council, 1989).

The analytical tools of risk assessment, as applied to chemicals and radiation, have assumed a critical role in decision making in the United States. Although risk assessment might appear to be an arcane subject, every day the nation's public health, environmental resources, and economic well-being are affected by the outcomes of risk assessment. However, risk assessment is not necessarily the solution for all of the problems in policy making. For example, it is the responsibility of the risk manager to establish a process that engenders public trust and credibility (Graham, 1995).

Estimation and, hence, control of microbiological hazards presented by foods, though compounded by biological diversity and variability, are nonetheless less beset by the problems of inaccuracy that exist in relation to adverse effects from chemical in foods. The impacts of the hazards posed by microbiological contamination of foods are generally better defined. Unfortunately, incidents are rather common, in sharp contrast to those resulting from exposure to chemical food additives, allowing better risk assessment (Bernard and Scott, 1995).

Risk can be defined in different ways. Conheren and Covello (1989) define risk as the possibility of suffering harm from a risk agent (i.e., chemical substance, organism, radioactive material, or other potential hazard). The analysis of risk involves the description of the discharge of the risk agent, its transport and fate in an environmental media (i.e., air, soil, food, and water), and any associated human exposure. Human health risks are then calculated based on data and models that relate exposures to risk (Till and Meyer, 1983).

Becker (1965) explored whether information about health hazards affected the perception of an attribute (rating), its importance weight (marginal utility from the attribute), or both. He was interested in exploring the effect of information on the structure of the demanded formation. His theoretical model was based on the household production function framework, into which he integrated information about health hazards through consumers' perceptions of a certain food's role in the production of health.

Slovic et al. (1982) noted that:

the probability of adverse health effects, psychological concerns, socially influenced aspects, and political, economic, and ethical characteristics. Risk should be recognized as a multidimensional concept incorporating physical, psychological, social/cultural, political, economic, and ethical dimensions. The risk perceptions and attitudes include control, voluntariness, dread, knowledge, immediacy, catastrophic potential, severity, equity, and others.

The probabilistic risk assessment is related to public risk because, for example, by definition a reactor that was truly "inherently safe" would have zero probability of creating a hazard. However, on closer examination, most inherently safe reactors are based on inherent features, the failure of which could lead to severe core damage and possibly to a release of radioactivity.

Furthermore, the analyses used to show that, in specified conditions, the reactor is inherently safe, require the use of parameters and assumptions that are subject to uncertainty (Cave and Kastenber, 1991).

Palou et al. (2009) noted that although absolute safety or benefit cannot be guaranteed, the risk–benefit equation has to be judged based on the scientific evidence available at the time of evaluation. The following are uncertainties involved in the assessment of scientific evidence:

1. Although benefits should be guaranteed, risks should absolutely be excluded.
2. Strategies used to prove a benefit are substantially different from those used to prove a risk.
3. An important consideration in the assessment for risks and benefits.
4. Unintended effects are a risk issue and not a benefit issue.

Within the frame of an ecological risk assessment perspective, the ecosystem approach was viewed through a thermodynamics perspective, thereby providing remarkable new findings. In the ecological risk assessment approach, it is recommended that several target indicators be selected at various hierarchical levels of the ecological organization (Mauriello, 1993).

During the past few decades, emphasis has been on the risk of genetically modified organisms (GMOs) and pesticide residues, food and potable water, and irradiated foods. A book by Thomas and Fuchs (2002) on biotechnology and safety assessment provides insight into many topics, including animals, plants, and safety assessment of GMOs and insect-protected cotton. The issue of pesticide residues in foods and potable water is addressed in Hamilton and Crossley (2004).

Food irradiation is a thoroughly tested technique, and the results of numerous studies have led to the conclusion that irradiated food produced in accordance with established good manufacturing practice (GMP) can be considered safe because the process of irradiation does not lead to changes in the composition of the food that, from a toxicological standpoint, would have an adverse effect on human health. It is well-known that some radiolytic products are formed in very low quantities, which may cause some health hazards only if consumed in amounts much higher than actually present in irradiated food (World Health Organization, 1994).

5.2 Risk Assessment Methodology

High doses of irradiation sterilize food, killing all microorganisms except for viruses. This process produced similar results for pathogen elimination as for food treated with high heat for commercial canning. However, radiation-sterilized meat and poultry products produced by current methods were rated by experts as superior to their canned counterparts in texture, appearance, and, in some instances, vitamin retention and taste (Steele and Engel, 1992).

Dugan and Bedford (2003) showed that instability could be induced in transformed human cells by high and low linear energy transfer radiations but not in normal human cells. This contrast needs to be studied further because of the implications for a possible role of induced instability in tumor development. Another form of delayed effect potentially affecting the levels of various toxicities following a radiation exposure is that of an adaptive response, although this type of delayed effect is of a much shorter duration than that of genomic instability (Rigaud and Moustacchi, 1996).

Kersten et al. (1999) used the fluoroquinolones BAYy3118 and lomefloxacin as standards to demonstrate the performance of the following tests: photo-induced interaction with supercoiled circular DNA, photomutagenicity in the yeast *Saccharomyces cerevisiae*, induction of DNA photo damage in cultured human skin cells as revealed by comet assay, and induction of specific phototoxic stress responses such as p53 activation or melanogenesis stimulation. The aim of the *in vitro* photogenotoxicity testing was to provide clear data to evaluate the biological impact of a compound when exposed to artificial UV light simulating natural light reaching skin cells.

The Hazard Analysis Critical Control Point (HACCP) system is applicable to the entire food chain as a food safety management tool for the identification of measures for the prevention of foodborne illness. Application of the HACCP system allows identification of hazards and assessment of the risk of such hazards (Codex Alimentarius Commission, 1997), which, it is hoped, leads to the establishment of control measures that are essential for achieving food safety. At the processing level, in particular, and properly applied, HACCP may offer the best means to enhance the safety of raw foods of animal origin, fresh produce, and certain prepared foods by minimizing the incidence and levels of pathogenic microorganisms (Bauman, 1995).

Risk analysis plays a role alongside other decision tools for risk management. Not all risks require detailed analysis to be managed. In many industries, there are accepted standards of performance and codes of practice. These are applied where uncertainties and system vulnerabilities are well understood (UK Offshore Oil Operators Association, 1999).

The approval of irradiated red meat in the United States has led to an increased interest in modern packaging materials for use in food irradiation because most of the materials currently listed in 21 Code of Federal Regulations 179.45 were approved in the 1960s. Despite decades of radiation chemical research, there is still a considerable lack of information on low-molecular-weight degradation products that can potentially migrate into food. For example, it has been found that even polystyrene, a material extremely radiation resistant in terms of mechanical strength, forms detectable amounts of such radiolysis products (Buchalla et al., 1999).

The analysis of gram amounts of 2-alkylcyclobutanones (2-ACBs) of radiolytic compounds in various irradiated foods made it possible to clearly highlight the linear relation between the formation of 2-ACBs and the absorbed radiation dose even for very high absorbed doses.

Concerning the toxic potential, it was shown that the 2-ACBs have cyto- and genotoxic properties under precise experimental (*in vitro*) conditions, that they inhibit bacterial growth, and that these compounds have a promoter effect (*in vivo* studies) for the development of tumors in the colon of rats (Marchioni et al., 2004).

The development of genetically modified crops prompted widespread debate regarding both human safety and environmental issues. Food crops produced by modern biotechnology using recombinant techniques usually differ from their conventional counterparts only with respect to one or a few desirable genes, as opposed to the use of traditional breeding methods that mix thousands of genes and require considerable effort to select acceptable and robust hybrid offspring. The difficulties of applying traditional toxicological testing and risk assessment procedures to whole foods are discussed by Atherton (2002).

Preventive measures such as GMP, supplemented by the HACCP system, have been introduced as a means of ensuring the production of safe food. Quantitative risk analysis can be defined as a stepwise analysis of hazards that may be associated with a particular type of food product, permitting an estimation of the probability of occurrence of adverse effects on health from consuming the product in question. It also includes a characterization of unacceptable risks. Starting from this definition, the first step to be taken is to identify the potential hazards (Notermans and Mead, 1996).

The increasing frequency and scale of recalls raise questions regarding whether sufficient attention is placed on these events. Three measures of recall effectiveness are introduced to evaluate this public–private crisis management process. Results from regression models suggest that recalls carried out by small-size plants, those that took place after pathogen reduction/HACCP implementation, and recalls involving processed products are more effective (Hooker et al., 2005).

Impact and risk assessments associated with radioactive contamination are usually based on information on the source term or contamination density (Bq/m^2) of selected radionuclides, transport in soils, transport to vegetation or to animals, and biological uptake and accumulation (e.g., for fish, the concentration ratio is the Bq/kg tissue per Bq/l water). Thus, measurements of environmental radioactivity and associated assessments are often based on the average bulk mass or surface concentration, assuming that radionuclides in sample matrices are homogeneously distributed as simple atomic, molecular, or ionic species (Salbu, 2007).

Szerbin and Popov (1988) determined the concentrations of radium-228, thorium-228, and radium-226 in different natural forage materials and in feed supplements. The activity concentrations of these nuclides were then determined in the bones of domestic farm animals, with emphasis on their distributions within the skeleton and humerus, using a method for calculation of nuclide retention coefficients by means of a new approach that simplified their assessment and provided important information on radium metabolism.

The influence of mutational breeding on the contents of nutritionally relevant minerals in low phytic acid (LPA) mutants compared to their wild types has been studied. Three LPA rice mutants (Os-LPA-XQZ-1, Os-LPA-XS110-1, and Os-LPA-XS110-2) and two LPA soybean mutants (Gm-LPA-TW75-1 and Gm-LPA-ZC-2) were analyzed regarding their contents of phytic acid, lower inositol phosphates, and the minerals calcium, iron, and zinc. The phytic acid reduction in LPA rice was consistently more pronounced in Os-LPA-XS110-1 than in Os-LPA-XQZ-1 and Os-LPA-XS110-2 (Frank et al., 2009).

Scientists and decision makers from all sectors agree that risk assessments should be based on the best available science. Some time ago, the Health and Environmental Sciences Institute, a global branch of the International Life Sciences Institute, identified the need for better scientific understanding of dose-dependent transitions in mechanisms of toxicity as one avenue by which the best and latest science could be integrated into the decision-making process (Slikker et al., 2004).

Using numerous nuclide-specific measurement results of activity concentrations in air, soil, vegetation, and foodstuffs and outdoor dose rates, it was possible by means of radio-ecological models to assess the upper level of current and future absorbed radiation doses for populations in different regions of the Federal Republic of Germany (Kaul, 1988).

Gadgil and Smith (2004) evaluated the mutagenicity and acute toxicity of 2-dodecyl-cyclobutanone (2-DCB), a unique radiolytic product. Mutagenicity was evaluated by the Ames assay using five standard *Salmonella* tester strains with S3 enzyme activation and five concentrations of 2-DCB. Sodium azide (NaN_3), fenaminosulf, and 2-aminofluorene (AF-2) served as positive controls. The results indicated that 2-DCB does not produce point or frameshift mutations in *Salmonella* and is not activated by S9. The maximum percentage of cells affected by 2-DCB was 65%, whereas 30–100% of the other two compounds were affected.

Laser–tissue interaction may, by energy absorption, generate a complex mixture of gaseous, volatile, semivolatile, and particular substances. The laser–tissue interaction process is thereby dominated by heating processes, which is confirmed by the similarity of formed chemical products in comparison with conventional cooking processes for food preparation. The main route of intake of pyrolysis products is through inhalation, which results from the fine aerosols formed and the high spreading energy emanating out of the irradiated source (Weber and Meier, 1996).

The final food and environmental safety assessment of agriculture product irradiation can only be determined by product history. Field product monitoring begins when food irradiation progresses from the pilot/demonstration phase to the commercial phase. Therefore, it is important to have a monitoring system in place to collect and analyze field data (Butterweck, 1990).

5.3 Risk Assessment Applications

5.3.1 Humans

Murthy and Sankaranarayanan (1978) established dose–effect relationships for the induction of gene conversion by AF-2 in diploid yeast. On the basis of these, the rec value for AF-2 for induction of gene conversion was calculated to be 0.085 pg/ml/h. The genetic burden to the Japanese population due to consumption of AF-2 was estimated to be equivalent to 55 millirec. However, uncertainties regarding the consumption of AF-2 per person and its metabolic detoxication tended to lower this value to, probably, a small fraction of that due to natural background ionizing radiation.

The risk assessment of di(2-ethylhexyl) phthalate (DEHP) migration from polyvinyl chloride (PVC) medical devices is an important issue for patients. The method for the simultaneous determination of DEHP and its breakdown products [(mono(2-ethylhexyl)phthalate (MEHP) and phthalic acid (PA)] was improved. The migration levels of PVC sheets irradiated from 0 to 50 kGy were determined. DEHP migration level decreased in proportion to the dose of γ -ray irradiation, whereas MEHP and PA migration levels increased (Ito et al., 2009).

David et al. (1991) determined the relevance of rodent cancer bioassay data to humans in relation to the needs of regulatory agencies. The usefulness of *in vivo* and *in vitro* genotoxicity testing in this connection was also discussed. In the case of rodent carcinogens that do not elicit genotoxicity, it was suggested that homeostatic imbalance, cell proliferation, and other processes may play a major role in tumor development and its importance to the possible ability of the test agent to induce human cancer.

The toxicological potential of 2-ACBs, radiolytic derivatives of triglycerides, is formed uniquely upon irradiation of fat-containing food. In irradiated food, they are generated proportionally to fat content and absorbed radiation dose. The cyto- and genotoxic potentials of various highly pure synthetic 2-ACBs were studied in bacteria and human cell lines. Although pronounced cytotoxicity was evident in bacteria, no mutagenic activity was revealed by the Ames test in *Salmonella* strains TA 97, TA 98, and TA 100 (Hartwig et al., 2007).

5.3.2 Animals (Mice, Rats, Rabbits, and Pigs)

Zinc oxide (ZnO), a widely used ingredient in dermatological preparations and sunscreens, is clastogenic *in vitro* but not *in vivo*. To clarify whether this increased potency is a genuine photo-genotoxic effect, the clastogenicity of ZnO in Chinese hamster ovary (CHO) cells of mice in the dark, in pre-irradiated, and in simultaneously irradiated CHO cells at UV doses of 350 and 700 mJ/cm² was investigated. In pre-irradiated or simultaneously irradiated CHO cells, ZnO was clastogenic at significantly lower concentrations compared with effective

concentrations in the dark, indicating an increased susceptibility of CHO cells to ZnO-mediated clastogenic effects due to UV irradiation *per se* (Dufour et al., 2006).

Benkovic et al. (2008) investigated the radioprotective effects of ethanolic extract of propolis (EEP) and quercetin on the white blood cells of whole-body irradiated CBA mice. Irradiation was performed using a γ -ray source (^{60}Co), and the absorbed dose was 9 Gy. The results suggested that propolis and quercetin given to mice before irradiation protect their white blood cells from lethal effects of irradiation and diminish primary DNA damage as confirmed by the alkaline comet assay.

Three groups of Swiss male mice were fed a stock ration or a non-irradiated or irradiated (2.5 mrad) test diet for 8 weeks. After the feeding period, the males were mated with groups of untreated female mice for 4 consecutive weeks. The females were autopsied at midterm pregnancy for evaluation of dominant lethal mutations including deciduomas and dead embryos. Consumption of irradiated diet did not affect the fertility of mice. Total pre- and post-implantation loss, as indicated by the numbers of live implantations, were comparable among all the groups of mice (Chauhan et al., 1975).

The mutagenic potency of the common mushroom *Agaricus bisporus* and crude agaritine extracted from mushrooms was determined *in vivo* using a mutagenesis assay with *lacl* transgenic mice (Big Blue mice). Pairs of female *lacl* mice were fed one of three diets for 15 weeks. Of the mushroom diets, significant effects were seen only with the crude agaritine extract: It induced an increase in mutant frequency of 100% in the kidney and 50% in the forestomach (Shephard et al., 1995).

C3H/HeJ mice were irradiated (100 kVp X-rays) with nine fractions of 3.1 Gy over 30 days (approximately equivalent to 10 Gy single dose) and were maintained on a genistein diet (~10 mg/kg). Damage was assessed over 28 weeks in lung cells by a cytokinesis block micronucleus (MN) assay and by changes in breathing rate and histology. Genistein caused an approximately 50% reduction in MN damage observed during the fractionated radiation treatment, and this damage continued to decrease at later times to background levels by 16 weeks. In mice not receiving genistein, the MN levels remained well above background 28 weeks after irradiation (Para et al., 2009).

Sixty Wistar albino rats were divided into four groups, and their hearts were given 15 Gy/fraction with ^{60}Co . In groups 1 and 2, the rats were killed after 24 h to detect early effects; in groups 3 and 4, the rats were killed 100 days after irradiation to detect late effects. Before irradiation, groups 1 and 3 received 0.9% saline solution, whereas groups 2 and 4 received amifostine (200 mg/kg). Twenty rats were used as a control group (Tokatli et al., 2004).

Rats were fed for 4 or 90 days either with 70% freshly irradiated wheat (0.25, 0.75, or 2.25 kGy) and 30% complementary feed or with a control diet. None of the parameters examined (food consumption, body weight, hematological analysis, and histopathological inspection of

thymus) showed any statistically significant association with the feeding regimen. Minor changes in ploidy of liver cells and cell cycling of bone marrow cells were detectable (wheat-irradiation dose-dependent increase in G₂/M phase bone marrow cells up to 0.6% and decrease of 8C nuclei up to 1.1% in liver cells) (Maier et al., 1993).

Lovell and Sanders (1992) applied solutions of test chemicals to the skin of guinea pigs, and after 30 min the animals were irradiated with near-ultraviolet radiation. Skin reactions were assessed between 3 and 72 h after the start of treatment. Acridine and anthracene caused immediate photoirritation, whereas reaction to 8-methoxypsoralen (8-MOP) was delayed; acridine was weakly active compared with the strong photoirritancy of anthracene and 8-MOP. Ethanol and a mixture of dimethylacetamide acetone ethanol (DAE) were satisfactory solvents, and the optimal interval between application and irradiation was 15–30 min.

Guinea pig tests do not generally include dose–response assessment and are therefore not designed for the assessment of potency, defined as the relative ability of a chemical to induce sensitization in a previously naive individual. Epidemiological evidence can be used only in certain circumstances for the evaluation of the sensitizing potency of chemicals because it reflects a degree of exposure as well as intrinsic potency. Nevertheless, human diagnostic patch test data and quantitative elicitation data have provided very important information for reducing allergic contact dermatitis risk and sensitization in the general population (Loveren et al., 2008).

Todoriki et al. (2006) assessed the effect of electron (e)-beam treatment on DNA damage in mature larvae of chestnut weevil *Curculio sikkimensis* (Heller) using single-cell gel electrophoresis (DNA comet assay). Electrons at acceleration voltages of 0 (control), 300, 750, 1000, and 1500 kV at radiation doses of 1 and 4 kGy were employed. Investigations using the comet assay showed that the parameters including tail length, tail moment, olive tail moment, as well as the quota of DNA damage at both the doses were significantly larger than the control batch larvae.

Table 5.1 presents the effect of irradiation on animals and risk assessment applications.

5.3.3 Foods

5.3.3.1 Products of plant origin

Fruits and vegetables

Utilization of *Fusarium*-infected (FI) barley for malting may lead to mycotoxin production during malting and decreased malt quality. E-beam irradiation may prevent safety and quality defects and allow use of otherwise good-quality barley. E-beam irradiation was evaluated for preventing *Fusarium* growth and mycotoxin production while maintaining barley malt quality characteristics. Four barley lots with varying deoxynivalenol (DON) concentrations were

TABLE 5.1 Effect of Irradiation on Animals and Risk Assessment Applications

| Animal | Irradiation Type/Dose | Effect on Animal | Active Compounds | Reference |
|--------------------|--|--|---|-----------------------|
| Chinese hamster | UV: 350 and 700 mJ/cm ² | Mycoplasma contamination | 8 Methoxy psoralen (photo genotoxicity testing, 3 min 41 s and 7 min 22 s for the 350 and 700 mJ/cm ² UV doses, respectively) | Dufour et al., 2006 |
| Mice | γ Irradiation/ 9 Gy | Leukocyte counts in mice treated prophylactically with EEP and quercetin were not significantly disturbed | The radioprotective effects of EEP and quercetin on the white blood cells of the whole body irradiated CBA mice (a dose of 100 mg/kg for 3 consecutive days) | Benkovic et al., 2008 |
| Mice | γ Irradiation/ 2 and 5 mrad | Consumption of irradiated diet did not affect the fertility of mice | Direct irradiated diet for 8 weeks [three groups of Swiss male mice were fed a stock ration (protein content 16%) or an unirradiated or irradiated test diet (2.5 Mrad)] | Chauhan et al., 1975 |
| Mice | γ Irradiation/ 100 kVp | The fibrosis developing in mouse lung, lung cancer, breast cancer, and various lymphomas was reduced | Direct genistein diet (~10 mg/kg) over 30 days and irradiation in lung cells | Para et al., 2009 |
| Rats | γ Irradiation/ 0.25, 0.75, or 2.25 kGy | Minor changes in ploidy of liver cells and cell cycling of bone marrow cells were detectable | Direct cell cycle and ploidy analysis in bone marrow and liver cells of rats after long term consumption of irradiated wheat for 4–90 days | Maier et al., 1993 |
| Wistar albino rats | γ Irradiation/15 Gy | High cure rates of disease and irradiation of the heart caused chronic impairment of cardiac pump function and cardiac disease | Direct radiotherapy on source skin distance of 80 cm. Single doses of 15 Gy were given at a dose rate of 0.76 Gy/min to the whole heart, and tissue equivalent backscatter material (solid phantom of 10 cm) was used | Tokatli et al., 2004 |

TABLE 5.1 Effect of Irradiation on Animals and Risk Assessment Applications—cont'd

| Animal | Irradiation Type/Dose | Effect on Animal | Active Compounds | Reference |
|-----------------------------------|-----------------------|--|--|--------------------------|
| Guinea pigs | UV/300 400 nm | The skin reaction occurred during or soon after irradiation | Direct phototoxicity testing. Ethanol and a mixture of DAE were satisfactory solvents and a time interval of 15–30 min between application and irradiation was optimal | Lovell and Sanders, 1992 |
| Curculio sikkimensis (Coleoptera) | E beam/1 and 4 kGy | Tail length as well as the quota of DNA damaged at both doses were significantly larger than those of the control batch larvae | Direct single cell electrophoresis gel (liquid nitrogen) at 26 V for 10 min (radiotherapy) | Todoriki et al., 2006 |

irradiated at 0, 2, 4, 6, 8, and 10 kGy. FI, aerobic plate counts, and mold and yeast counts decreased in barley with an increase in dosage (Kottapalli et al., 2006).

Ochratoxin A (OTA) is one of the most important mycotoxins of worldwide concern for human health. Irradiated corn grains were rehydrated to 0.910–0.995 of water activity with sterile distilled water at 15, 25, and 30°C. Growth assessment was made every day during the incubation period (21 days) to calculate the growth rate, lag phase, and the OTA production at 7, 14, and 21 days. The results obtained suggested that the storage of corn grains at water activities lower than 0.951 and 15°C should prevent the growth and OTA production of these fungal species during approximately 21 days (Astoreca et al., 2009).

Three ready-to-use vegetables—cucumber, blanched and seasoned spinach, and seasoned burdock—were selected to study the effects of an irradiation treatment for eliminating pathogens. The pathogens tested were *Salmonella typhimurium*, *Escherichia coli*, *Staphylococcus aureus*, and *Listeria ivanovii*. It was found that a low-dose irradiation (3 kGy or less) can improve the microbial safety of ready-to-use vegetables (Lee et al., 2006).

Bidawid et al. (2000) applied doses of γ -irradiation ranging between 1 and 10 kGy to investigate the inactivation of hepatitis A virus (HAV) inoculated onto lettuce and strawberries at ambient temperature. Data analysis with a linear model indicated that *D* values of 2.7260.05 and 2.9760.18 kGy were required to achieve a 1-log reduction in HAV titer in lettuce and strawberries, respectively. These data indicated that γ -irradiation doses between 2.7 and 3.0 kGy would be required to achieve greater than 90% kill in HAV populations on fruits and vegetables.

Pezzutti et al. (2005) investigated the contaminating microflora of 12 dehydrated garlic and onion products. The products were in the form of powder, chop, and flake, both packed and unpacked, as sold in the Argentinean retail market. Moreover, the efficacy of γ -ray doses between 5 and 25 kGy to reduce the microbial population was investigated. A dose of 10 kGy for onion was required to reduce the spore counts to nondetectable levels. Regarding public health, the treatment with γ -rays was suggested for garlic and onion products used by Argentinean consumers.

The presence of flavored colorants (peach and raspberry), flavors (caramel, citric acid, and vanilla), and food preservatives (sodium nitrite, sodium nitrate, sodium benzoate, benzoic acid, potassium sorbate, and sodium chloride) in *E. coli* suspension during exposure to sunlight did not change the extent of cell survival. No effect on viability and mutation induction (kanamycin resistant) was observed when cells were kept in contact with any of the additives for 80 min in the dark. Raspberry and peach produced mutations in a dose-dependent manner, whereas vanilla produced mutations in an additive manner (Salih, 2006).

Waje et al. (2009) evaluated the microbiological quality of fresh sprouts and their seeds and the potential use of e-beam and γ -irradiation for inactivating inoculated pathogens in both samples. Red radish and broccoli sprouts and their seeds were inoculated with *E. coli* O157:H7, *S. typhimurium*, *Listeria monocytogenes*, and *Bacillus cereus* and irradiated up to 3.0 kGy. The D_{10} values of the inoculated pathogens were lower in both broccoli and red radish samples treated with γ -ray than in those treated with e-beam, whereas the D_{10} values obtained in seeds were relatively higher compared with those obtained in sprouts.

Cereals and spices

OTA is a secondary metabolite of *Aspergillus* and *Penicillium* species, including *Aspergillus ochraceus*, a species found in stored cereal grains such as barley. The effects of water activity (a_w , 0.80–0.99), temperature (10, 20, and 30°C), and *A. ochraceus* isolate differences on radial growth and OTA production in irradiated barley grains were studied. The three isolates showed optimal conditions for growth and OTA production at 0.99 a_w and 30°C, with a marked decrease in growth rates and OTA production at the lowest levels of a_w and temperature assayed. The minimum a_w level for growth was 0.85 and 0.90 a_w for OTA production (Pardo et al., 2004).

The 9.50-GHz electron paramagnetic resonance (EPR) spectra of non-irradiated and ^{60}Co -irradiated cardamom (*Elettaria cardamomum* L. Maton, Zingiberaceae), ginger (*Zingiber officinale* Rosc., Zingiberaceae), and saffron (*Crocus sativus* L., Iridaceae) were recorded by Dului et al. (2007) at room temperature. After γ -irradiation at an absorbed dose of up to 11.3 kGy, the presence of EPR spectra whose amplitude increased monotonously with the absorbed dose was evident with all spices.

Rice

The effect of γ -irradiation for inactivating the pathogens inoculated into the ready-to-eat Kimbab, steamed rice rolled by dried laver, was investigated by Chung et al. (2007).

The pathogens used were *S. typhimurium*, *E. coli*, *Staphylococcus aureus*, and *L. ivanovii*, which are important for public health. Growth of four test organisms inoculated (approximately 10^6 – 10^7 CFU/g) into the Kimbab was sustained by an irradiation treatment during 24 h of storage regardless of the temperature at 10, 20, and 30°C. The four pathogens inoculated into Kimbab decreased 2 or 3 log CFU/g by 1 kGy treatment and were not detected after 3 kGy.

5.3.3.2 Products of animal origin

Dairy products

Cheese. Feta, a white brine cheese, was produced and contaminated with *L. monocytogenes*. Contaminated feta samples were vacuum packaged and exposed to irradiation doses of 1.0, 2.5, and 4.7 kGy and stored at 4°C for 1 month. Irradiation had no effect on the texture of feta. Irradiation at 4.7 kGy increased feta's redness and decreased its yellowness and lightness. Sensorial analyses revealed that at the 4.7-kGy dose, the aroma profile of feta was temporarily affected; it was restored after 30 days of cold storage (Konteles et al., 2009).

Eggs

Irradiated eggshells exhibited a paramagnetic center at $g = 2.0018$. The center is stable up to temperatures of 150°C and against UV light. The center concentration, as determined with EPR spectroscopy, increased with absorbed dose. A dose range between 3 and 10 kGy was examined in which eggshells can serve as a dosimeter. Precision of measurement was found to be better than 10% at a 95% confidence level for absorbed doses above 10Gy. Eggshells were shown to be applicable for retrospective dosimetry after radiation accidents (Regulla et al., 1994).

Food irradiation is an alternative to free *Salmonella* spp. and *Campylobacter* spp. eggs as a low-dose point to safety assurance. After irradiation at 5 kGy, both yolk color dye (pale yellow) and white egg were turned into a turbid yellow. Irradiation effects on nutritional properties were evaluated by means of egg protein patterns that were assessed by polyacrylamide gel electrophoresis. Lipids were identified by means of thin-layer chromatography. Based on the obtained results, the sanitation dose was lower than the limit dose for the decrease in the main properties of the eggs (Pinto et al., 2004).

Two major microbial groups were characterized in the egg's natural microbiota; no *Salmonella* or *Campylobacter* were detected. Whole eggs were artificially contaminated with reference strains of *S. typhimurium*, *Salmonella enteritidis*, *Campylobacter coli*, and *Campylobacter jejuni* and irradiated in the γ -facility at sublethal doses (0.2–1 kGy) with a dose rate of 1.0 kGy/h. *D* value varied between 0.31–0.26 kGy and 0.20–0.19 kGy in *S. typhimurium* and *S. enteritidis* and between 0.21–0.18 kGy and 0.07–0.09 in *C. coli* and *C. jejuni* for shell and

yolk white, respectively. The results revealed that low irradiation doses could guarantee egg sanitation (Verde et al., 2004).

Meat

Meat contains approximately 75% water and is clearly an excellent substrate to support the growth of all types of parasites and microorganisms. The pathogens of greatest concern in fresh and frozen meat are *E. coli*, *Salmonella*, and *Clostridium perfringens*. Cured meat concerns include *Salmonella*, *Staphylococcus*, and the potential for *Clostridium botulinum* in sausages. Food irradiation cannot be used to destroy microbial toxins, nor will viruses and spores be killed at the low doses employed to kill vegetative pathogens (<10 kGy). This is why irradiation treatments below 10 kGy are regarded similarly to heat pasteurization (Satin, 2002).

Beef

Research was performed to extend ground beef retail display life using antioxidants, reductants, and/or total aerobic plate count (TSP) treatments combined with e-beam irradiation. Half of the treated samples were irradiated at 2.0 kGy absorbed dose under a nitrogen atmosphere, and half remained non-irradiated. Samples were displayed under atmospheric oxygen and evaluated for TPC, thiobarbituric acid reactive substances (TBARS), and instrumental color during 9 days of simulated retail display (SRD). Treated irradiated samples were just as red and vivid on SRD Day 9 as the non-irradiated untreated control at Day 0 (Duong et al., 2008).

Escherichia coli O157:H7 can contaminate raw ground beef and cause serious human food-borne illness. Although lag phase duration decreased from 10.5 to 45°C, no lag phase was observed at 6, 8, or 10°C. The specific growth rate increased from 6 to 42°C and then declined up to 45°C. In contrast to these profiles, the maximum population density declined with increasing temperature, from approximately 9.7 to 8.2 log CFU/g (Tamplin et al., 2005).

The inactivation kinetics in the death of *Listeria innocua* NTC 11288 (more radioresistant than five different strains of *L. monocytogenes*) and *Salmonella enterica* serovar Enteritidis and *S. enterica* serovar Typhimurium by e-beam irradiation has been studied in two types of vacuum-packed RTE dry fermented sausages (“salchichon” and “chorizo”) in order to optimize the sanitation treatment of these products. Therefore, this treatment produces safe, dry fermented sausages with similar sensory properties to the non-irradiated product (Cabeza et al., 2009).

Moist beef biltong (mean moisture content, 46.7%; a_w , 0.919) was vacuum packaged and irradiated to target doses of 0, 2, 4, 6, and 8 kGy. TBARS measurements and sensory difference and hedonic tests were performed to determine the effect of γ -irradiation on the sensory quality of the biltong. Although lean moist beef biltong can thus be irradiated to doses up to 8 kGy without adversely affecting the sensory acceptability, low-dose irradiation (64 kGy) is most feasible to optimize the sensory quality (Nortjé et al., 2005).

E-beam and X-ray irradiation (2 kGy) inactivated *E. coli* O157:H7 below the limit of detection, whereas hydrostatic pressure treatment (300 mPa for 5 min at 4°C) did not inactivate this pathogen. Solid-phase microextraction was used to extract volatile compounds from treated ground beef patties. Irradiation and hydrostatic pressure altered the volatile composition of the ground beef patties with respect to radiolytic products. However, results were inconclusive regarding whether these differences were great enough to use this method to differentiate between irradiated and non-irradiated samples in a commercial setting (Schilling et al., 2009).

The effect of γ -irradiation (4 and 9 kGy) and packaging on the lipolytic and oxidative processes in lipid fraction of Bulgarian fermented salami during storage at 5°C was evaluated (1, 15, and 30 days). No significant differences were observed in the amounts of total lipids, total phospholipids, and acid number within the vacuum-packed samples of salami treated with 4 and 9 kGy during storage. The changes in TBARS depended mainly on the irradiation dose applied and did not exceed 1.37 mg/kg in all groups (Bakalivanova et al., 2009).

Pork

Zanardi et al. (2009) determined the effect of irradiation (2, 5, and 8 kGy) and vacuum storage for 60 days on fatty acid and cholesterol oxidation in three Italian cured pork products (salame Milano, coppa, and pancetta). A significant increase in the degree of fatty acid oxidation was observed starting from the 8-kGy irradiation dose. Unlike the non-irradiated samples, the vacuum storage was not sufficient enough to curb fatty acid oxidation in the irradiated pork products. The cholesterol oxide molecules were qualitatively similar in both irradiated and non-irradiated pork products, and the levels detected were approximately 100 times lower than the toxic level for *in vitro* and *in vivo* experiments.

Food safety can be improved using ionizing radiation to reduce food spoilage and to extend its shelf life. Gas chromatography–mass spectrometry has been validated by the European Community as a powerful method to identify irradiated food containing fat. Results revealed that the microbial population was substantially reduced even at 2 kGy and that a clear identification of irradiated samples can be achieved 1 month after irradiation at 2 kGy in frozen stored samples (D'Oca et al., 2009).

The effect of an irradiation dose (0, 5, and 10 kGy) of vacuum-packaged Iberian dry cured ham slices from pigs fed on concentrate or free-range reared was studied in relation to TBARS, hexanal content, and instrumental color changes. Irradiation produced statistically significant increases in vacuum-packed dry cured ham slices for lightness, yellowness, and chroma. Irradiation resulted in significantly lower hue angle (h8) values and higher redness values in both sets of hams, indicating a redder color of irradiated samples than non-irradiated samples, and these changes were greater in free-range-reared samples than in concentrate samples (Cava et al., 2005).

Fish

Medina et al. (2009) compared the effectiveness of e-beam irradiation and high-pressure treatment for the sanitation of cold smoked salmon with respect to microbial safety and shelf-life extension. From the response of *L. monocytogenes* INIA H66a to irradiation, a *D* value of 0.51 kGy was calculated. For samples stored at 5°C, 1.5 kGy would be sufficient to attain a food safety objective of 2 log₁₀CFU/g *L. monocytogenes* for a 35-day shelf life, whereas 3 kGy would be needed in the case of a temperature abuse (5 + 8°C).

Song et al. (2009) determined the efficacy of γ -irradiation and e-beam irradiation of the foodborne pathogens, including a three-strain cocktail of *L. monocytogenes* (ATCC 19114, 19115, and 19111), *Staphylococcus aureus* (ATCC 6538, 25923, and 29213), and *Vibrio parahaemolyticus* (ATCC 17802, 33844, and 27969), in *Bajirak jeotkal* (Korean traditional seafood; 8% salt), which is a salted, seasoned, and fermented short-necked clam commercially available in the market. Irradiation (0.5, 1, 2, and 5 kGy) significantly reduced the initial microbial level not only immediately after irradiation but also during storage at 10°C for 4 weeks. Gamma irradiation was more effective than e-beam irradiation and yielded *D*₁₀ values of 0.64, 0.63, and 0.29 kGy for *L. monocytogenes*, *Staphylococcus aureus*, and *V. parahaemolyticus*, respectively, and those for e-beam irradiation were 0.79, 0.81, and 0.36 kGy, respectively. The obtained results suggested that low-dose irradiation can improve the microbial quality and reduce the risk by the foodborne pathogens of *B. jeotkal*, which has limited alternative sterilization methods due to the temperature characteristics of the products.

Uncertainties associated with the effects from chronic low-level exposures to radiation prompted the construction of a low-dose rate irradiation facility. A description of the facility is included along with results from a pilot study in which Japanese medaka (a small fish native to Asia) were chronically irradiated at the highest dose rate possible within the facility (150–350 mGy/day). Irradiated fish produced fewer eggs per day, had a lower percentage of viable eggs, and produced a lower percentage of hatchlings (Hinton et al., 2004).

Crab exoskeleton was divided into six parts: dactyl, cheliped, carapace, apron, swimming legs, and walking legs. Samples of the exoskeleton were prepared and irradiated to ¹³⁷Cs γ -radiation in the range 1.156–5.365 kGy. EPR spectra of unirradiated as well as irradiated samples were recorded and analyzed. Response to γ -radiation was plotted for each part of the exoskeleton; dactyl was found to be the most sensitive part, followed by the apron (38%), cheliped (37%), walking legs (30%), swimming legs (24%), and carapace (21%), relative to the dactyl response (Maghraby, 2007).

Patagonian toothfish were captured in the southwestern Atlantic Ocean (FAO Zone N° 41). The fatty acid profile of total lipids and the triacylglycerol and phospholipid content of control and irradiated samples (1 and 5 kGy) stored at 18°C were analyzed at 0 and 293 days post-irradiation. The fatty acids are mainly monounsaturated acids (47 g/100 g total fatty acids), the most abundant one being oleic acid. It was therefore concluded that the species exhibits

a marked stability when subjected to irradiation and prolonged storage in the frozen state (Príncipe et al., 2009).

The effect of irradiation on foods (plant and animal origin) and risk assessment applications are shown in Table 5.2.

5.3.4 Environment

UV disinfection technology is of growing interest in the water industry because it has been demonstrated that UV radiation is very effective against oocysts of *Cryptosporidium* and *Giardia*, two pathogenic microorganisms of major importance for the safety of drinking water. The obtained results revealed that UV is effective against all waterborne pathogens. The most UV-resistant organisms are viruses, specifically adenoviruses, and bacterial spores. The protozoon *Acanthamoeba* is also highly UV resistant. Bacteria and oocysts of *Cryptosporidium* and *Giardia* are more susceptible with a fluence requirement of $<20 \text{ mJ/cm}^2$ for a minimal inhibitory concentration of 3 log (Hijnen et al., 2006).

5.4 Risk Assessment of Irradiated Foods

Risk assessment is a systematic process used to identify risks posed by certain activities to human health or to the environment (National Research Council, 1989, 1993). Performing a risk analysis, either at the logical or physical levels in and around the information technology enterprise, is a complex and often confusing endeavor. Risk analysis is simply a process of identifying the potential for possible harm to occur to a particular set of assets or processes and determining the impact. The two primary types of risk analysis processes are: (i) qualitative, which is a simplified process of identifying the major threats to which an enterprise is exposed; and (ii) quantitative, which provides a direct correlation to the value of the assets that require protection (Schreider, 2003).

In general, risk assessment covers a very wide range of activities, including engineering (e.g., construction and automobile manufacturing), pest control, GMOs, and preservation technologies (i.e., migration in packaging and irradiation).

According to the risk–benefit analysis of food published by the European Food Safety Authority (2006), the following require consideration:

- Minimally processed foods, such as fresh fruits and vegetables (responsible for 20–25% of foodborne outbreaks).
- Nitrite in meat products (nitrosamine formation vs. preservation).
- Reduction of pathogenic bacteria by salt versus increase of other health risks, such as the risk of cardiovascular disease, from ingestion of too much salt.

TABLE 5.2 Effect of Irradiation on Foods (Plant and Animal Origin) and Risk Assessment Applications

| Food | Irradiation Type/Dose | Effect on Sensory Property | Physicochemical/Biological Properties | Reference |
|---------------------------|--|--|--|-----------------------|
| Ready to use vegetables | γ Irradiation: 0, 1, 2, and 3 kGy | No significant change in nutritional or sensory quality | Bacteria contents were reduced | Lee et al., 2006 |
| Fruits and vegetables | γ Irradiation: 1–10 kGy | — | — | Bidawid et al., 2000 |
| Corn grains | γ Irradiation: 8–10 kGy | Minor changes in sensory quality after irradiation | Water activity and temperature declined | Astoreca et al., 2009 |
| Spices | γ Irradiation: 1.06 and 11.3 kGy | — | Cardamon and saffron almost reduced to their initial shape and amplitudes | Duliu et al., 2007 |
| Garlic and onion products | γ Irradiation: 0, 5, 10, 15, 20, and 25 kGy | Similar sensory properties to the non irradiated product | Microbial population was reduced | Pezzutti et al., 2005 |
| Steamed rice | γ Irradiation: 0, 1, 2, and 3 kGy | Appearance, texture, flavor, and overall acceptance were negatively correlated with irradiation dose | Temperature and microorganisms decreased | Chung et al., 2007 |
| Feta cheese | γ Irradiation: 0, 1, 2.5, and 4.7 kGy | The aroma of Feta was temporarily affected | Irradiation at 4.7 kGy increased Feta's redness and decreased its yellowness and lightness. No significant difference for moisture, fat, salt, and pH of Feta cheese | Konteles et al., 2009 |
| Chicken eggs | γ Irradiation: 0, 1, 2, 3, 4, and 5 kGy | — | The yolk color (pale yellow) and the white egg were changed to a turbid yellow | Pinto et al., 2004 |
| Eggshells | γ Irradiation: 3–10 kGy | — | — | Regulla et al., 1994 |
| Meat | γ Irradiation: 10 kGy | The flavor was effected by irradiation | — | Satin, 2002 |
| Dry fermented sausages | E beam: 0, 1, 2, and 3 kGy | The taste, odor, texture, and appearance had minimal changes | pH, a_w , color, and temperature were reduced | Cabeza et al., 2009 |

| | | | | |
|---|--|---|--|---------------------------|
| Bulgarian salami | γ Irradiation: 4 and 9 kGy | The flavor, texture, and taste were altered after irradiation | Color was affected by irradiation | Bakalivanova et al., 2009 |
| Dry cured ham | γ Irradiation: 0, 5, and 10 kGy | — | TBA RS values increased after irradiation. Hexanal content, lightness, yellowness, chroma, and lipid oxidation increased | Cava et al., 2005 |
| Pork | γ Irradiation: 0, 2, 5, and 8 kGy | Appearance and flavor were altered | Cholesterol content increased. The oxidation levels of fatty acids were much lower after irradiation | Zanardi et al., 2009 |
| Pork | γ Irradiation: 1, 2, 4, 5, 6, 7, 8, 9, 10 kGy | — | Strong reduction in contaminating microbiological flora | D'Oca et al., 2009 |
| Ground beef | E beam: 2 kGy | Effect on flavor and odor after irradiation | Treated irradiated samples were just as red and vivid. Oxidation of the lipids caused unpleasant odor | Duong et al., 2008 |
| Ground beef | γ Irradiation: 42 kGy | Minimal effect on flavor | Temperature reduction | Tamplin et al., 2005 |
| Ground beef | E beam and γ irradiation: 2 kGy | Appearance, flavor, texture, and overall acceptability were not meaningful | Hydrostatic pressure decreased | Schilling et al., 2009 |
| Moist beef biltong | γ Irradiation: 0, 2, 4, 6, and 8 kGy | Irradiation caused noticeable flavor changes in moist beef biltong | Thiobarbituric acid and moisture content increased significantly | Nortjé et al., 2005 |
| Cold smoked salmon | E beam: 0, 1, 2, 3, and 4 kGy | No change in odor, but the visual aspect of smoked salmon was negatively affected | No significant changes were detected after e beam irradiation or high pressure treatment | Medina et al., 2009 |
| <i>Bajirak jeotkal</i> (seafood) | γ Irradiation and e beam: 0, 0.5, 1, 2, and 5 kGy | Strong odor and flavor. The texture was altered after irradiation | The color was altered after irradiation | Song et al., 2009 |
| <i>Medaka</i> (a small fish native to Asia) | γ Irradiation: 0.74, 7.4, or 74.0 MBq | — | — | Hinton et al., 2004 |

(Continued)

TABLE 5.2 Effect of Irradiation on Foods (Plant and Animal Origin) and Risk Assessment Applications—cont'd

| Food | Irradiation Type/Dose | Effect on Sensory Property | Physicochemical/Biological Properties | Reference |
|---|--|--|---|-----------------------|
| Crab | γ Irradiation: 1.156–5.365 kGy | — | Reduction in microbiological contamination | Maghraby, 2007 |
| Oyster (<i>Crassostrea gigas</i>) | γ Irradiation: 0.46, 2.84, and 2.94 kGy | The sensory and nutritional qualities were altered | Radiation resistance of poliovirus increased at frozen state. pH and salt contents were not affected by irradiation | Jung et al., 2009 |
| Toothfish (<i>Dissostichus eleginoides</i>) | γ Irradiation: 0, 1, and 5 kGy | — | The fatty acid profile or triacylglycerol and phospholipid content of toothfish were not altered | Príncipe et al., 2009 |

- Preservation technologies, inclusive of packaging, are generally regarded as having beneficial effects, but it is important to also assess potential risks from the process of preservation (migration and irradiation).

The process of safety evaluation of whole foods and other complex mixtures is considerably more complex than that of single chemical substances or simple mixtures. Evaluation of new products must embody the notion that analytical studies and biological evaluation proceed in a coordinated manner, integrating the results of these various studies in a comprehensive and reasoned program of safety assessment ([International Food Biotechnology Council, 1990](#)).

The provision of wholesome, affordable, and safe drinking water that has the trust of customers is the goal of the international water utility sector. Risk management, in terms of protecting the public health from pathogenic and chemical hazards, has driven and continues to drive developments within the sector. In common with much of industry, the water sector is formalizing and making explicit approaches to risk management and decision making that have formerly been implicit ([Pollard et al., 2004](#)).

5.5 Conclusions

The social science perspective on risk broadens the scope of undesirable effects, includes other ways to express possibilities and likelihood, and expands the horizon of risk outcomes by referring to “socially constructed” realities. The social experience of risk includes the perception of actual damage, but it is more focused on the evaluation of the risk context, the nonphysical impacts, and the associations between the risk and social or cultural artifacts ([Renn, 1998](#)).

Risk assessment and the perception of risk have their roots in history. The understanding and meaning of the two terms have evolved, but the change in meaning is not always taken into account in debates concerning risk assessment and perception. Any intelligent debate should begin with a common definition of terms so as to clarify the basis of disagreement ([Sharlin, 1989](#)).

Risk assessment in the nuclear domain involves wide areas of disciplines, ranging from nuclear sciences to the social and behavioral sciences. Although further studies are needed in this respect, it is still important to note that the key to the contemporary nuclear problems seems to rest mainly on the social and behavioral sciences rather than on the nuclear sciences *per se* ([Tanaka, 1998](#)).

Organizations with a serious commitment to an information security program should have one of these products incorporated within their risk management methodology to facilitate a uniform approach to identifying, reducing, and managing risk. The time savings in baseline ALE

calculations can easily justify the cost of one of these products alone. However, one must remember that these products have their limitations and cannot replace sound risk management judgment or experience (Schreider, 2003).

It must be emphasized that all of the available evidence supports the notion that the following are important in one's tolerance of any risk, whether food related or not: the process by which tolerable risk decisions are made; the equity and fairness of the distribution of risks and benefits; the competence, trustworthiness, and accountability of those creating and controlling said risk; the ability to control exposure and the effects of exposure; and the probability of death or illness (Soby et al., 1994).

Regarding the risk assessment of irradiation (X-rays, e-beam, γ -irradiation, and microwave), it is important to stress that few studies have been performed in this field and their validity is limited. Therefore, there is a prioritized necessity for conducting epidemiological studies with regard to risk assessment of the consumption of irradiated food both for animals and for humans. Such studies are envisioned to provide better insight into the risk involved in exposure to irradiation and consumption of irradiated feed and food.

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Applications of Irradiation on Meat and Meat Products

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6.1 Introduction

Food irradiation is considered as an important tool not only for ensuring safety but also for extending the shelf life of fresh meat (Giroux et al., 2001; Yoon, 2003). Food irradiation has been shown to eliminate pathogenic and spoilage microorganisms, providing a safer longer lasting food supply for human consumption (Bruhn, 1995; Monk et al., 1995; Murano, 1995). It is one of the best emerging technologies to ensure the microbiological safety of meat (Kannat et al., 2006). Irradiation has been viewed by most food safety officials and scientists, as an effective critical control point in a hazard analysis and critical control points system established for meat processing (Badr, 2004; Farkas, 1998; Rao et al., 1998; Satin, 2002). Ionizing radiation includes gamma rays, electron beams, and X-rays. Gamma irradiation uses high-energy gamma rays from cobalt 60 or cesium 137, which have long half-lives (5.27 and 30.1 years, respectively) and high penetration power and thus can treat bulk foods on shipping pallets. Electron beam (E-beam) irradiation uses a stream of high-energy electrons, known as beta rays, which can penetrate only approximately 5 cm. X-Irradiation, which has intermediate properties of the two previously discussed irradiation methods, penetrates foods more shallowly than gamma irradiation but much more deeply than electron beams (Sadler et al., 2001). The Food and Drug Administration has approved irradiation of red meat at low dose levels to improve food safety in response to a petition from industry sources (Hollingsworth, 1998). Furthermore, the use of irradiation had previously been permitted in pork (1 kGy) and chicken (3 kGy) (Hampson et al., 1996). Meat and meat products pasteurized by radiation have been successfully marketed in Belgium, France, China, Indonesia, The Netherlands, South Africa, and Thailand for a number of years (Diehl, 1995).

6.2 Beef

6.2.1 Effect of Irradiation on the Quality and Sensory Properties of Beef

Nam et al. (2003) treated aged beef loins with e-beam irradiation (2.5 kGy) for different lengths of time post-slaughter. Irradiation increased 2-thiobarbituric acid reactive substances (TBARS) values of pre-aged and aged ground beef, but the difference between irradiated and non-irradiated long-term aged beef was not significantly different. During aerobic storage (4°C), the volatile sulfur compounds disappeared, whereas volatile aldehydes drastically increased in irradiated beef.

Yilmaz and Gecgel (2007) conducted an experiment to evaluate the combined effects of irradiation (0, 1, 3, 5, and 7 kGy) of ground beef on fatty and *trans* fatty acids. These results showed that irradiation induces the formation of *trans* fatty acids. Although the ratio of total unsaturated fatty acids to total saturated fatty acids was 0.85, 0.86, 0.87, and 0.89 in irradiated ground beef samples (1, 3, 5, and 7 kGy, respectively), it was 0.85 for the control samples. Giroux et al. (2001), with the use of a trained panel, concluded that there was no significant difference in odor and taste between irradiated (4 kGy) and non-irradiated ground beef patties (23% fat) during 7 days of storage at 4°C.

Sensory properties of irradiated ground beef specified for the National School Lunch Program were evaluated by Fan et al. (2004). Frozen ground beef patties with 15% fat content were either not irradiated or irradiated at doses of 1.35 and 3 kGy. Cooked patties after 0 and 6 months of storage were evaluated using nontrained panels. Results showed that irradiation had no significant impact on the ratings of any of the sensory attributes either at 0 or after 6 months of storage. Average ratings of liking of aroma, taste, aftertaste, and overall were higher at 6 months than at 0 months.

Zienkewicz and Penner (2004) irradiated ground beef (25% fat) at a dose of 1.5 kGy. They found that a consumer panel could not differentiate between irradiated and non-irradiated samples. For both the initial and the 3-month sensory tests, it was found that irradiated and non-irradiated ground beef were judged to be the same in terms of sensory properties. Using a consumer panel, Lorenzen and Heymann (2003) found that irradiation of frozen ground beef patties at 1 kGy had little effect on overall liking, tenderness, juiciness, and flavor of cooked patties.

Effects of irradiation (2 kGy) of ground beef patties from trimmings stored aerobically for 0 or 6 days on lean color, odor, and sensory attributes were investigated by Montgomery et al. (2003). Beef trimmings were coarse ground and split into two different groups. Group 1 was fine ground, pattied, and packaged immediately. Group 2 was stored for 6 days and then fine ground, pattied, and packaged. Irradiated beef patties had greater off-odors and off-flavors, lower CIE L^* (lightness), a^* (redness), and b^* (yellowness), and lower saturation indices after 4

days of storage at $0 \pm 1^\circ\text{C}$. Irradiation of patties produced from trimmings aged an extra 6 days resulted in increased saturation indices and b^* values but no off-odors compared to non-aged and irradiated patties.

Vickers and Wang (2002) conducted an experiment to determine the relative acceptability of irradiated (1.5 kGy) and non-irradiated ground beef patties and whether the acceptability is affected by informing consumers about the benefits of irradiating beef or by identifying whether the samples they tasted had been irradiated. Subjects rated the irradiated beef patties juicier than the non-irradiated samples. Ratings of overall liking, toughness, and flavor and texture liking were equal for both. Benefit information and sample identification increased the liking ratings of the patties because the group with no benefit information and no sample identification generally rated all samples lower.

Table 6.1 summarizes the effect of irradiation dose on quality and sensory properties of beef.

6.2.2 Effect of Irradiation and Hurdle Technology on Beef

According to Wheeler et al. (1999), boxes (4.5 kg) of frozen (-28°C) VP ground beef patties (113.4 g/patty, 19% fat) were γ -irradiated at one of three levels (0, 3, or 4.5 kGy). All boxes were stored at 28°C for 27–29 days after irradiation before evaluation by a trained panel and for 62–104 days after irradiation before consumer evaluation. Control patties had more intense ground beef aroma, less off-aroma, and more intense ground beef flavor than irradiated patties. However, there were no differences in any sensory trait between frozen ground beef patties treated with 3 or 4.5 kGy of γ -irradiation. There were no differences among treatments for tenderness or juiciness ratings, respectively, for 0, 3, and 4.5 kGy. Hamburgers made with patties treated with 4.5 kGy were rated lower in taste than hamburgers made with either control patties or those treated with 3 kGy; however, all doses were rated at some level of “fair.” These results imply that hamburgers made from ground beef patties irradiated under the conditions of this experiment would encounter little, if any, consumer acceptance problems at the 3-kGy dose and only slightly greater problems at the 4.5-kGy dose.

Millar et al. (2000b) investigated the effect of irradiation (0 and 5 kGy) of beef portions in retail overwrap packs and subsequent storage at 4°C in relation to color changes. The color of the exterior surface of beef was measured on the same samples on each day of storage for up to 7 days post-irradiation. On Day 7, the color of a freshly cut surface was measured. L^* values of irradiated beef increased significantly with storage, and a^* values for non-irradiated samples decreased significantly with storage. Irradiation resulted in significantly higher hue angle (h_0) values, and a^* , b^* , and C^* values were significantly higher on the exterior than on the freshly cut surface.

TABLE 6.1 Effect of Irradiation on Quality and Sensory Properties of Beef

| Food Type | Irradiation Type/Dose | Temperature | Effect on Sensory Quality | Reference |
|--------------------------------------|--|------------------------|---|-----------------------------|
| Frozen ground beef patties (15% fat) | 1.35 and 3 kGy γ irradiation | — | Results showed that irradiation had no significant effect on the ratings of any of the sensory attributes either at 0 or after 6 months of storage. Average ratings of liking of aroma, taste and aftertaste, and overall were higher at 6 months than at 0 months | Fan et al., 2004 |
| Ground beef patties | 2 kGy E beam | 0 \pm 1°C for 4 days | Irradiated beef patties had greater off odors, and off flavors, lower CIE L^* , a^* , and b^* ; after storage | Montgomery et al., 2003 |
| Ground beef patties | 1.5 kGy γ irradiation | — | Irradiated samples were juicier than the non irradiated samples. Ratings of overall liking, toughness, and flavor and texture liking were equal for both irradiated and non irradiated | Vickers and Wang, 2002 |
| Ground beef patties (23% fat) | — | 4°C for 7 days | No significant differences in odor and taste between irradiated (4 kGy) and not irradiated (23% fat) during 7 days of storage at 4°C | Giroux et al., 2001 |
| Ground beef patties (23% fat) | 4 kGy | 4°C for 7 days | | |
| Ground beef (25% fat) | 1.5 kGy | — | A consumer panel could not differentiate between irradiated and non irradiated samples. For both the initial and the 3 month sensory tests, it was found that irradiated and non irradiated ground beef were judged to be the same in terms of sensory properties | Zienkewicz and Penner, 2004 |
| Cooked beef patties | 1 kGy | — | Little effect on overall liking, tenderness, juiciness, and flavor. | Lorenzen and Heymann, 2003 |
| Beef loins | 2.5 kGy | 4°C | During aerobic storage (4°C), the volatile sulfur compounds disappeared, whereas volatile aldehydes drastically increased. Irradiation increased TBARS values of pre aged and aged ground beef | Nam et al., 2003 |
| Ground beef | 0, 1, 3, 5, and 7 kGy | — | Results showed that irradiation induces the formation of <i>trans</i> fatty acids. The ratio of total unsaturated fatty acids to total saturated fatty acids was 0.85, 0.86, 0.87, and 0.89 in irradiated ground beef samples (1, 3, 5, and 7 kGy, respectively); it was 0.85 for the control samples | Yilmaz and Gecgel, 2007 |

The effects of two doses (2.0 and 3.5 kGy) of irradiation on color and oxidative properties were determined for frozen and chilled VP boneless beef steaks. The chilled steaks were repackaged in oxygen-permeable film 14 days ($1 \pm 1^\circ\text{C}$) after irradiation. Irradiation up to 3.5 kGy had minimal effects on color and oxidative rancidity and significantly reduced bacterial counts of frozen and chilled, vacuum-packaged, beef steaks stored and/or displayed for up to 28 days. Irradiated steaks that were rewrapped in permeable film were microbially acceptable at 5 days of display and had more color stability than the controls (Luchsinger et al., 1997a).

Ground beef patties (irradiated with 2 kGy and non-irradiated) were packaged under air and vacuum using oxygen-permeable (polyolefin) or oxygen-impermeable material (PE). Immediately after irradiation of ground beef patties, there was a 2- to 3-log reduction in total microbial counts, regardless of whether they were irradiated under air or vacuum. Non-irradiated patties, which had an initial microbial load of 10^6 cells/g, reached levels indicative of spoilage (10^8 cells/g) after 8 days, whereas irradiated samples reached 10^6 cells/g after 55 days of storage at 4°C (Murano et al., 1998).

Moist beef biltong (mean moisture content, 46.7%; a_w , 0.919) was VP and irradiated to target doses of 0, 2, 4, 6, and 8 kGy and stored at 4°C . TBARS analysis indicated that irradiation did not induce a great deal of lipid oxidation in moist beef biltong. Although an expected dose-dependent increase in TBARS values was observed, only biltong irradiated at 8 kGy (actual dose 10.05 kGy) had significantly higher levels of oxidation products than untreated biltong. Biltong irradiated at 2 and 4 kGy, however, was liked significantly more than other samples, indicating that slight, nonoxidative irradiation-induced flavor changes may contribute to flavor development in the usually more bland moist beef biltong (Nortje et al., 2005).

Chen et al. (2007) irradiated eight Chinese yellow cattle using a γ -irradiation source (with doses of 1.13, 2.09, or 3.17 kGy) and stored (0 or 10 days at 7°C) to assess the effect of irradiation. Total saturated fatty acid and monounsaturated fatty acid increased with irradiation. The efficiency of irradiation on bacterial destruction was immediate (0 days), and the importance of the reduction of total bacterial counts was proportional to the irradiation doses (1.13, 2.09, and 3.17 kGy). At 0 days after γ -irradiation, total bacterial counts were reduced by 1.05, 1.44, and 1.66 log units for beef samples irradiated with doses of 1.13, 2.09, and 3.17 kGy, respectively, comparing with non-irradiated control (0 kGy, 0 day) of 5.39 log (CFU/g).

The effects of packaging atmosphere (aerobic, vacuum, or modified atmosphere with carbon monoxide) on ground beef treated with ionizing radiation were investigated by Kusmider et al. (2002). Incorporation of low levels of carbon monoxide (<1%) into modified atmosphere packaging greatly improved color and odor quality of irradiated fresh ground beef, thus countering potentially negative color effects of irradiation. Carbon monoxide reduced

lipid oxidation compared to other packaging treatments at the 4.5-kGy irradiation dose and provided a very stable, cherry-red product color, as indicated by instrumental and sensory analysis.

Wong et al. (2005) studied the effects of fat content and post-slaughter ascorbic acid (AA) infusion on microbial and physicochemical qualities of beef patties processed by e-beam irradiation (5 and 10 kGy) in a 4°C storage trial. Beef muscles from AA-infused or control animals were ground and mixed with tallow to achieve final fat contents of 4, 17, and 30%. The addition of fat significantly increased aerobic, total coliform, *Escherichia coli*, and psychrotrophic bacteria counts in beef patties during storage. No viable aerobic, total coliform, or *E. coli* bacteria were detected in any irradiated beef patties during storage. Physicochemical changes caused by lipid oxidation and surface discoloration of beef patties were significantly increased by both the addition of fat and irradiation processing. Moreover, irradiation-induced lipid oxidation was exacerbated by the presence of fat and the prior post-slaughter infusing of AA to animals that contributed to the beef muscle.

Figure 6.1 shows the impact of e-beam irradiation (2.5 kGy) on the TBARS values of ground beef and beef patties stored at 4°C, and Figure 6.2 displays the impact of different doses of irradiation on pH of Cornish game hen and beef patties.

Montgomery et al. (2000) examined the effects of irradiation (2 kGy) of ground beef made from trimmings aged 3, 6, or 9 days *postmortem* (PM) and packaged aerobically or anaerobically on lean color and aroma. Irradiation increased off-odors and reduced color scores and Hunter a^* and b^* values. Aerobic packaging increased off-odors and Hunter L^* and b^* values while reducing color scores and a^* values. Irradiated patties made from trimmings of

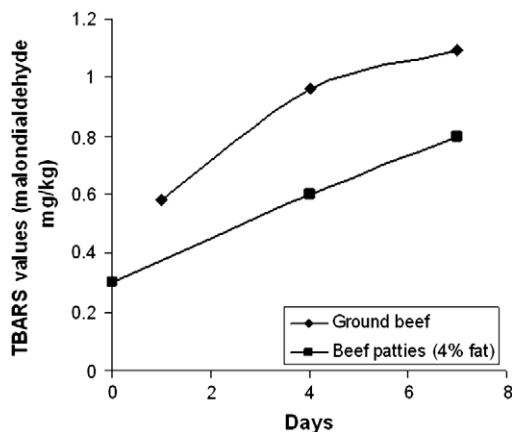


Figure 6.1: Effect of e-beam irradiation (2.5 kGy) on the TBARS values of ground beef and beef patties stored at 4°C (Nam et al., 2003; Wong et al., 2005).

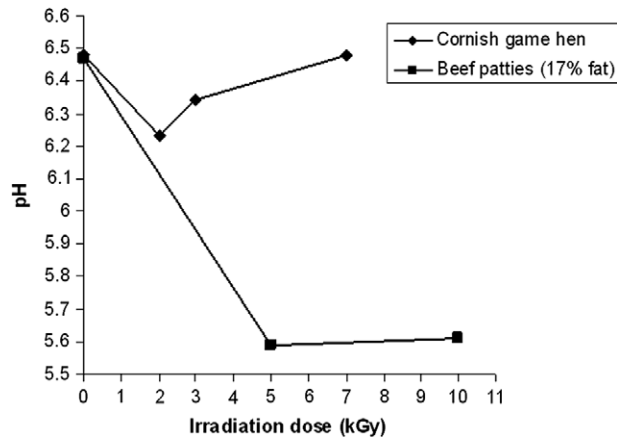


Figure 6.2: Effect of different doses of irradiation on pH of Cornish game hen (vacuum packaged) and beef patties (packaged in polyethylene bags) (Gomes et al., 2006; Wong et al., 2005).

the shortest aged meat, 3 days, had higher color scores and a^* values compared to irradiated samples aged 6 and 9 days PM. Irradiated patties packaged aerobically had more off-odors, hue angle, and L^* and b^* values and lower color scores and a^* values compared to irradiated anaerobic patties.

Wong and Kitts (2002) examined the effects of e-beam irradiation, with and without pre-seasoning with ginseng and garlic herbs, on microbial growth and oxidative stability of beef sirloin steaks. E-beam irradiation of sirloin steaks at all dosages (2, 3, and 4 kGy) tested was effective at reducing the number of psychrotrophic bacteria to a maximum of 2 log cycles. A further reduction in psychrotroph count was observed with the pre-seasoning of garlic, in both non-irradiated and irradiated steaks. The use of 3- and 4-kGy irradiation dosages, however, increased lipid oxidation during 4 weeks of storage. Ginseng decreased malondialdehyde concentrations in sirloin steaks more than garlic after e-beam irradiation of meats but had no effect on psychrotroph count. Inhibition of lipid oxidation by ginseng also minimized the discoloration of surface redness on sirloin steaks. Hardness value of sirloin steaks was minimized in the presence of garlic.

Badr (2007) investigated the activity of carnosine as a natural antioxidant in γ -irradiated ground beef and beef patties. Samples of ground beef, as well as raw and cooked beef patties prepared with 1.5% salt (NaCl), in the absence and presence of 0.5 or 1.0% carnosine were γ -irradiated at doses of 0, 2, and 4 kGy. The extent of oxidation in irradiated and non-irradiated samples of ground beef and raw beef patties was then determined during refrigerated ($4 \pm 1^\circ\text{C}$) and frozen (-18°C) storage, and it was determined for cooked beef patties during refrigerated storage only. Carnosine significantly reduced the acceleration of oxidation due to irradiation and storage of ground beef and raw or cooked beef patties, and

it slowed the formation of metmyoglobin post-irradiation and during storage of raw meat samples.

Aziz et al. (2002) examined the effect of γ -radiation and microwave treatments of different beef products. When beef samples with an initial bacterial count of 4.9×10^6 CFU/g were exposed to γ -rays at a dose level of 5 kGy, counts of bacteria were reduced by 2 or 3 log cycles, and when heated in a microwave oven, bacterial counts were reduced by 1 log cycle in 20-s and by 2 log cycles in 30-s exposure. Untreated samples had a shelf life of less than 7 days, whereas samples that were irradiated at a dose level of 3 kGy and then heated in a microwave oven for 20 s had a shelf life of at least 2 weeks at 5°C. Gamma-ray treatment had very little effect on the odor and flavor of the pretreated sample. The combined treatment exhibited either no change or loss of thiamine levels and free fatty acids but increased the peroxide values during storage at 5°C.

Nam and Ahn (2003a) studied the effects of AA and antioxidants on the color of irradiated (e-beam irradiation with dose range between 2.449 and 2.734) ground beef. Irradiation significantly decreased the redness of ground beef, and the visible color of beef changed from a bright red to a green/brown, depending on the age of the meat. Addition of AA (0.1%, wt/wt) in ground beef prior to irradiation prevented color changes in irradiated beef, and the effect of AA became greater as the age of the meat or storage time after irradiation increased. Ground beef with added AA had significantly lower oxidation-reduction potential than the control, and the low oxidation-reduction potential of meat helped maintain the heme pigments in reduced form.

The effects of irradiation (2 and 2.5 kGy) on flavor, texture, and aroma were compared to non-irradiated controls for: (i) frozen raw and precooked ground beef patties with 10 and 22% fat packaged in vacuum or aerobically; (ii) frozen, vacuum-packaged, boneless beef steaks; and (iii) chilled, VP, boneless, beef steaks that were repackaged in an oxygen-permeable film after 14 days of storage. Irradiation at doses up to 3.5 kGy had minimal effects, as evaluated by a trained descriptive panel, on flavor, texture, and aroma of frozen, raw, and precooked ground beef patties; frozen, boneless, beef steaks; and aged, VP, chilled, boneless, beef steaks. Package type was the most critical factor affecting beef sensory attributes (Luchsinger et al., 1997).

Ground beef patties were packaged in air with nylon/PE, Saran/polyester/PE, or Saran film overwrap plus a Styrofoam tray and stored at 5°C. Samples were irradiated at 2 kGy by either γ -rays or e-beam. The only difference observed between irradiated and non-irradiated samples was that the latter had a more pronounced beef/brothy flavor than irradiated patties. No differences were detected with regard to packaging material used. Comparing the two sources of irradiation, patties irradiated by γ -rays had more intense cardboardy and soured flavors and more salty and sour tastes than patties irradiated by e-beam (Lopez-Gonzalez et al., 2000).

Kim et al. (2002) found that irradiated (3 kGy) beef loins, packaged aerobically and stored at 4°C, produced new volatiles not found in non-irradiated meats, and the amounts of total volatiles and TBARS were higher than those of non-irradiated samples. The amounts of volatiles in aerobically packaged irradiated samples decreased with storage, whereas those of non-irradiated meats increased. Nanke et al. (1998) investigated the color changes in aerobically packaged beef irradiated with e-beam irradiation (1.5, 3, 4.5, 7.5, and 10.5 kGy). Irradiated beef became less red as a result of irradiation and display time. Beef exhibited a considerable increase in brownness. Reflectance spectra indicated that irradiation induced a metmyoglobin-like pigment in beef.

Ahn et al. (2001) determined the effect of irradiation and packaging conditions on the content of cholesterol oxidation products (COPs) and lipid oxidation in cooked beef during storage. Beef samples were cooked, packaged either in oxygen-permeable or in oxygen-impermeable bags, and irradiated at 0 or 4.5 kGy. Lipid oxidation and COPs were determined after 0 and 7 days of storage at 4°C. Irradiation had no significant effect on the amounts of any of the COPs found in cooked beef. The amounts of COPs and lipid oxidation products were closely related to the proportion of polyunsaturated fatty acids in meat.

Formanek et al. (2003) irradiated five batches of aerobically packaged minced beef from Friesian cattle at 0, 1, 2, 3, or 4 kGy using a ⁶⁰Co irradiation source. Dietary vitamin E supplementation and its combination with a commercial rosemary extract as a natural antioxidant additive resulted in a color-stabilizing and lipid-protecting effect in minced beef muscle. All antioxidant treatments were effective at inhibiting lipid peroxidation even at the highest irradiation dose applied. Irradiation caused a significant reduction in the polyunsaturated fatty acid content, mainly in C18:2, after storage at 40°C under fluorescent light for 8 days.

The impact of irradiation and hurdle technology on beef quality and the physical and sensory properties of beef are presented in Table 6.2.

6.3 Pork

6.3.1 Effect of Irradiation and Hurdle Technology on Pork

In cooked pork chops and hams inoculated with *Listeria monocytogenes*, low-dose (0.75–0.90 kGy) irradiation reduced *L. monocytogenes* by more than 2 log (Fu et al., 1995). Kamat et al. (1997) studied the γ -irradiation response of *Yersinia enterocolitica* 5692 and 152 at 0 and -40°C in phosphate buffer (pH 7) as well as in 10% raw meat/salami homogenate. They reported that, irrespective of the suspending medium or irradiation temperature, the survival curves were observed to be exponential up to 1-kGy dose. Although the tailing effect in meat was due to additional irradiation observed after 5-log cycle reduction, in buffer it was observed

TABLE 6.2 Effect of Irradiation and Hurdle Technology on Beef

| Food Type | Irradiation Type/Dose | Other Technology | Temperature | Shelf Life | Effect on Sensory Quality | Effect on Quality | Reference |
|--|---------------------------------------|----------------------|-------------|------------|---------------------------|---|--|
| Ground beef patties (113.4 g/patty, 19% fat) | 0, 3, or 4.5 kGy γ irradiation | Vacuum packaged | 28°C | — | — | There were no differences among treatments for tenderness or juiciness ratings, respectively, for 0, 3, and 4.5 kGy. Hamburgers made with patties treated with 4.5 kGy were rated lower in taste than hamburgers made with either control patties or those treated with 3 kGy; however, all doses were rated at some level of “fair.” Control patties had more intense ground beef aroma, less off aroma, and more intense ground beef flavor than irradiated patties | Wheeler et al., 1999 |
| Chilled boneless beef steaks | 3.5 kGy γ irradiation | Vacuum packaged | 1 \pm 1°C | — | — | Minimal effects on color and oxidative rancidity and significantly reduced bacterial counts | Luchsinger et al., 1997a |
| Ground beef patties | 2 kGy γ irradiation | Under vacuum and air | 4°C | — | — | Immediately after irradiation there was a 2 to 3 log reduction in total microbial counts, regardless of whether they were irradiated under air or vacuum | Murano et al., 1998 |

| | | | | | | | |
|-----------------------|---|--|-----|---|---|--|---------------------------------------|
| Moist beef biltong | 0, 2, 4, 6, and 8 kGy | Vacuum packaged | 4°C | — | Biltong irradiated at 2 and 4 kGy was, however, liked significantly more than other samples | TBARS analysis indicated that irradiation did not induce a great deal of lipid oxidation. A dose dependent increase in TBARS values was observed | Nortje et al., 2005 |
| Chinese yellow cattle | 1.13, 2.09, or 3.17 kGy γ irradiation | | 7°C | — | — | Total saturated fatty acid and monounsaturated fatty acid increased with irradiation. At 0 days after γ irradiation, total bacterial counts were reduced by 1.05, 1.44, and 1.66 log units for beef samples irradiated with doses of 1.13, 2.09, and 3.17 kGy, respectively, compared with non irradiated control of 5.39 log CFU/g | Chen et al., 2007 |
| Ground beef | 4.5 kGy | Aerobic, vacuum, or modified atmosphere with carbon monoxide (<1%) | 2°C | — | Carbon monoxide provided a very stable, cherry red product color, as indicated by instrumental and sensory analysis | Carbon monoxide reduced lipid oxidation when compared to other packaging treatments at the 4.5 kGy irradiation dose and provided a very stable, cherry red product color, as indicated by instrumental and sensory analysis | Kusmider et al., 2002 |

(Continued)

TABLE 6.2 Effect of Irradiation and Hurdle Technology on Beef—cont'd

| Food Type | Irradiation Type/Dose | Other Technology | Temperature | Shelf Life | Effect on Sensory Quality | Effect on Quality | Reference |
|---|------------------------|---------------------------------------|-------------|------------|--|--|-------------------------|
| Beef muscles with fat content of 4, 17, and 30% | 5 and 10 kGy E beam | Ascorbic acid infusion | 4°C | — | | The addition of fat significantly increased aerobic, total coliform, <i>E. coli</i> , and psychrotrophic bacteria counts in beef patties during storage. No viable aerobic, total coliform, or <i>E. coli</i> bacteria were detected in any irradiated beef patties during storage. Irradiation induced lipid oxidation was exacerbated by the presence of fat and the prior post slaughter infusing of ascorbic acid to animals that contributed to the beef muscle | Wong et al., 2005 |
| Ground beef | 2 kGy | Packaged aerobically or anaerobically | 0°C | — | Irradiated patties packaged aerobically had more off odors, hue angle, and L^* and b^* values and lower color scores and a^* values compared to irradiated anaerobic patties | — | Montgomery et al., 2000 |

| | | | | | | | | |
|------------------------------|---|---|--------------------|---|---|---|---|----------------------|
| Beef sirloin steaks | 2, 3, and 4 kGy E beam | Pre seasoning with ginseng and garlic herbs | 4°C | — | — | Ginseng also minimized the discoloration of surface redness on sirloin steaks. The hardness value of sirloin steaks was minimized in the presence of garlic | E beam irradiation at all dosages tested was effective at reducing the number of psychrotrophic bacteria to a maximum of 2 log cycles. A further reduction in psychrotroph count was observed with the pre seasoning of garlic, in both non irradiated and irradiated steaks. The use of 3 and 4 kGy irradiation dosages, however, increased lipid oxidation during 4 weeks of storage. Ginseng decreased malondialdehyde concentrations in sirloin steaks more than garlic after E beam irradiation of meats but had no effect on psychrotroph count | Wong and Kitts, 2002 |
| Ground beef and beef patties | 0, 2, and 4 kGy γ irradiation | Carnosine 0.5 or 1.0% | 4 \pm 1 and 18°C | — | — | Carnosine significantly reduced the acceleration of oxidation due to irradiation and storage of ground beef and raw or cooked beef patties, and it slowed the formation of metmyoglobin post irradiation and during storage of raw meat samples | | Badr et al., 2007 |

(Continued)

TABLE 6.2 Effect of Irradiation and Hurdle Technology on Beef—cont'd

| Food Type | Irradiation Type/Dose | Other Technology | Temperature | Shelf Life | Effect on Sensory Quality | Effect on Quality | Reference |
|---------------|---|-----------------------------------|-------------|------------|--|---|------------------------------------|
| Beef products | — | — | 5°C | 7 days | — | — | Aziz et al., 2002 |
| Beef products | 5 kGy γ irradiation | Heated in microwave oven for 20 s | 5°C | — | — | γ Rays reduced counts of bacteria by 2 or 3 log cycles, and when heated in a microwave oven, bacterial counts were reduced by 1 log cycle in 20 s and by 2 log cycles in 30 s exposure. | |
| Beef products | 3 kGy γ irradiation | Heated in microwave oven for 20 s | 5°C | 2 weeks | — | The combined treatment shows either no change or loss of thiamine levels and free fatty acids but increased the peroxide values during storage | |
| Ground beef | Dose range absorbed at meat samples was 2.449–2.734 kGy E beam | Ascorbic acid (0.1%, wt/wt) | 4°C | — | Irradiation significantly decreased the redness of ground beef, and the visible color of beef changed from a bright red to a green/brown, depending on the age of the meat | The addition of ascorbic acid resulted in significantly lower oxidation reduction potential than the control | Nam and Ahn, 2003a |

| | | | | | | | |
|---------------------|--|---|-----|---|---|--|-----------------------------|
| Beef loins | 3 kGy γ irradiation | Packaged aerobically | 4°C | — | — | The amounts of total volatiles and TBARS were higher than those of non irradiated samples. The amounts of volatiles in aerobically packaged irradiated samples decreased with storage, whereas those of non irradiated meats increased | Kim et al., 2002 |
| Ground beef patties | 2 kGy γ irradiation and E beam irradiation | Packaged in air with nylon/polyethylene, Saran/polyester/polyethylene, or Saran film overwrap plus a Styrofoam tray | 5°C | — | Non irradiated samples had a more pronounced beef/brothy flavor than irradiated patties. No differences were detected according to packaging material used. Comparing the two sources of irradiation, samples irradiated by γ rays had more intense cardboardy and soured flavors, and salty and sour tastes than patties irradiated by e beam | — | Lopez Gonzalez et al., 2000 |

(Continued)

TABLE 6.2 Effect of Irradiation and Hurdle Technology on Beef—cont'd

| Food Type | Irradiation Type/Dose | Other Technology | Temperature | Shelf Life | Effect on Sensory Quality | Effect on Quality | Reference |
|-------------|---------------------------------------|--|----------------|------------|---|--|--------------------|
| Beef | 1.5, 3, 4.5, 7.5, and 10.5 kGy E beam | Aerobically packaged | — | — | Irradiated beef became less red as a result of irradiation and display time. Beef showed an increase in brownness. Reflectance spectra indicated that irradiation induced a metmyoglobin like pigment in beef | — | Nanke et al., 1998 |
| Cooked beef | 0 or 4.5 cagy | Packaged in either oxygen permeable or oxygen impermeable bags | 4°C for 7 days | — | — | Irradiation had no significant effect on the amounts of any of the COPs found in cooked beef. The amounts of COPs and lipid oxidation products were closely related to the proportion of polyunsaturated fatty acids in meat | Ahn et al., 2001 |

after 8-log cycle reduction. This phenomenon was not affected by temperature of irradiation. The protection in 10% meat pork homogenate was also observed in terms of D_{10} values. The D_{10} value in homogenate was 0.25 kGy compared to 0.15 kGy (0°C) and 0.2 kGy (frozen) in buffer. The resistance of these cells in homogenate was not influenced by irradiation temperature.

The effect of irradiation and organic acid treatment in controlling the growth of microorganisms (*Bacillus cereus*, *Enterobacter cloacae*, and *Alcaligenes faecalis*) and the formation of biogenic amines (BAs) in pork was studied by [Min et al. \(2007\)](#). γ -Irradiation was used with absorbed doses of 0, 0.5, 1, and 2 kGy as irradiation treatment, and 2 M solutions of acetic, citric, and lactic acid were used as organic acid treatment. Irradiation was effective in reducing the inoculated bacteria and achieved approximately three decimal reductions by 2 kGy. The levels of putrescine, tyramine, spermine, and the total amount of biogenic amines were significantly reduced by irradiation of pork inoculated with different microorganisms tested. Organic acid treatment showed only two decimal reductions or less from the original inoculation level. Aerobically packaged irradiated (3 kGy) pork loins produced new volatiles not found in non-irradiated meats, and the amounts of total volatiles and TBARS were higher than those of non-irradiated samples. The amount of volatiles in aerobically packaged irradiated samples decreased with storage (at 4°C for 7 days), whereas those of non-irradiated meats increased ([Kim et al., 2002](#)).

[Du et al. \(2001\)](#) found that irradiation (4.5 kGy) had no effect on the content of cholesterol oxidation products in cooked pork patties at 0 day. After 7 days of storage (4°C), there were only small increases in cholesterol oxidation products for the VP patties. However, an approximately 10-fold increase in cholesterol oxidation products was observed in the cooked pork patties with aerobic packaging. [Nanke et al. \(1998\)](#) studied color changes in irradiated pork (1.5, 3, 4.5, 7.5, and 10.5 kGy, e-beam). Irradiated pork became less red as a result of irradiation and display time. Visual evaluation of irradiated pork indicated an increase in brownness, whereas turkey increased in redness as dose increased. The surface color of irradiated pork became less uniform than that of non-irradiated pork. Reflectance spectra indicated that irradiation induced a metmyoglobin-like pigment in pork.

[Ahn et al. \(2001\)](#) studied the effect of e-beam irradiation and packaging conditions on cooked pork during storage (4°C). Beef samples were cooked, packaged either in oxygen-permeable or in oxygen-impermeable bags, and irradiated at 0 or 4.5 kGy. Irradiation increased the amounts of α - plus 7β -hydroxycholesterol, β -epoxide, 7-ketocholesterol, and total COPs in aerobically packaged cooked pork. Moreover, they found that the amounts of COPs and lipid oxidation products closely related to the proportion of polyunsaturated fatty acids in meat.

[Nam et al. \(2001\)](#) found that irradiation and storage increased lipid oxidation of normal and pale soft exudative (PSE) muscles, whereas dark firm dry (DFD) muscle was very stable and resistant to oxidative changes. Irradiation increased redness regardless of pork quality type, and

the increases were dose dependent. Irradiation increased the production of sulfur-containing volatiles but not lipid oxidation products. The total volatiles produced in normal and PSE pork were higher than those of the DFD pork. Non-irradiated normal and DFD pork had higher odor preference scores than the non-irradiated PSE, but irradiation reduced the preference scores of all three pork quality types.

Luchsinger et al. (1996) investigated color and oxidative rancidity for chilled ($3 \pm 2^\circ\text{C}$) and frozen ($17 \pm 3^\circ\text{C}$) boneless pork chops packaged in vacuum or air and irradiated to an absorbed dose of 0, 1.5, or 2.5 kGy (chilled) or 0, 2.5, or 3.85 kGy (frozen) of e-beam or γ -irradiation. Irradiation of VP chops produced a redder, more stable (color and rancidity) product. More pronounced oxidative rancidity and less stable display color were noted for samples irradiated in aerobic packaging. Irradiation source had varying but limited effects on color and rancidity.

Zhao and Sebranek (1996) performed a study in which fresh pork chops were dipped for a target absorption of 0.5% sodium tripolyphosphate (STPP), 550 ppm sodium ascorbate (SA), or 0.1% potassium sorbate (PS) prior to irradiation (1.0 kGy). Untreated pork chops, both irradiated and non-irradiated, were used as controls. Dipping with STPP decreased drip loss and improved color and lipid stability of irradiated chops, and it resulted in better tenderness and juiciness scores than those of non-dipped, irradiated samples. STPP-treated chops had similar or better physicochemical and sensory properties than untreated (no irradiation, no dipping) controls. Furthermore, dipping with SA or PS had little effect compared with STPP but improved some sensory qualities.

Ahn et al. (2000b) analyzed the volatile components and the sensory characteristics of irradiated raw pork. Pork muscle strips were randomly placed in a single layer into labeled bags and packaged either aerobically or under vacuum. Samples were irradiated at 0, 5, or 10 kGy and stored at 4°C for 5 days. Irradiation had no effect on the production of volatiles related to lipid oxidation but produced a few sulfur-containing compounds not found in non-irradiated meat. Irradiated muscle strips produced more TBARS than non-irradiated only in aerobic packaging during storage.

The effects of packaging and irradiation combinations on lipid oxidation, off-flavor, and color changes of raw patties prepared from three pork muscles were studied by Ahn et al. (1998). Patties were prepared from each of the ground L. dorsi (L. thoracis and L. lumborum), psoas, and R. femoris muscles of pig, packaged either in oxygen-permeable PE bags or in impermeable nylon/PE bags, irradiated with an e-beam at 0 or 4.5 kGy, and then stored up to 2 weeks at 4°C . Oxygen availability during storage, however, was more important than irradiation on the lipid oxidation and color values of raw patties. Irradiated meat produced more volatiles than did non-irradiated patties, and the proportion of volatiles varied by the packaging irradiation conditions of patties. Irradiation produced many unidentified volatiles that could be responsible for the off-odor in irradiated raw meat.

Nam et al. (2007) studied the effects of oleoresin–tocopherol combinations on lipid oxidation, off-odor, and color of double-packaged irradiated raw and cooked pork patties. Rosemary and α -tocopherol combination at 0.05 and 0.02% of meat weight, respectively, showed the most potent antioxidant effects in reducing both TBARS values and the amounts of volatile aldehydes in irradiated raw and cooked pork loins. The antioxidant combination, however, did not affect the production of sulfur volatiles responsible for irradiation off-odor and showed little effect on color changes in irradiated raw and cooked pork loins. Double-packaging methods, exposing the irradiated meats to aerobic conditions for 3 days and then keeping them under vacuum conditions for the remaining 7 days of storage, effectively reduced the sulfur volatiles in irradiated pork loins.

The effect of γ -irradiation on pork loins was investigated by Lacroix et al. (2000) during 43 days of storage at $4 \pm 1^\circ\text{C}$. Irradiation treatments were carried out under air or VP on fresh pork loins at a dose of 6 kGy at two different dose rates: 2 and 20 kGy/h. Regardless of the type of packaging and dose rate of irradiation, all irradiated pork samples were effectively prevented from bacterial spoilage for at least 43 days. No marked difference in the intensity or red color or in the meat texture was found in samples during the first 20 days of storage. However, between 20 and 40 days of storage, the red color was more intense in samples packed under air. By the end of the experiment, a more intense red color was observed in samples treated at 20 kGy/h compared to samples treated at 2 kGy/h. A marked difference in the meat texture was also found between the air- and vacuum-packed pork throughout the storage. No marked changes in emulsifying capacity and protein sulfhydryl content of proteins were noted throughout the storage period. However, the hydrophobicity was reduced both by the faster dose rate of irradiation and by longer storage.

A comparison of e-beam irradiation effects on the quality of injected and non-injected fresh pork loin, stored at $0\text{--}2^\circ\text{C}$, was conducted by Davis et al. (2004). Thirty loins were injected with brine composed of 2.17% salt/3.04% phosphate/20.8% lactate brine, and another 30 were not injected. Ten loins of each group of 30 were not irradiated, whereas 10 loins from each group were irradiated at 2.2 kGy and the final 10 loins from each group were irradiated at 4.4 kGy. Lipid oxidation, as measured by thiobarbituric acid (TBA) values, increased with irradiation dosage, but the change in TBA value with irradiation did not seem to be affected by injection treatment. Color changes were observed with irradiation treatment, but injection did not appear to have an effect on irradiation-induced color changes. Purge was significantly lower for the non-injected loins irradiated at 2.2 kGy than for those irradiated at 0 and 4.4 kGy.

Ohene-Adjei et al. (2004) studied the effect of supplemental vitamin E (0, 100, 200, and 300 mg/kg feed), irradiation, and days in display on quality characteristics of aerobically packaged ground pork and VP loin chops. Samples held in display for 3 days were used for sensory evaluation. In the ground pork, irradiation (1.9 kGy) increased “wet dog” flavor, increased a^* values, and decreased L^* and b^* values. However, as display time (0, 4, and 8 days) increased,

the differences in a^* values diminished and putrefying and fishy odors were higher in non-irradiated than in irradiated samples. Supplemented vitamin E had no effect on odor and color measures but increased the juiciness of ground pork regardless of irradiation. Similarly, in the loin chops, irradiation (1.5 kGy) increased a^* values and wet dog flavor but decreased b^* values regardless of vitamin E supplementation. Furthermore, irradiation reduced putrefying and fishy odors during longer display times. TBARS increased with increased display time but was not affected by vitamin E supplementation. Vitamin E did not affect TBARS in the loin chops or in the ground pork.

The impact of different doses of irradiation on TBARS values of pork patties and cooked pork sausages stored aerobically at 4°C is displayed in Figure 6.3.

Dogbevi et al. (1999) investigated physicochemical and microbiological changes in fresh pork loins, packaged in plastic bags, after treatment with γ -irradiation (2, 4, and 8 kGy). Results show a significant increase in deamidation with the irradiation dose. At a dose of 8 kGy, deamidation is almost complete, reaching a level of more than 98%. However, the effect of γ -irradiation on sulfhydryl groups was quite different. Their results showed that γ -irradiation had little effect on SH groups. A small but significant improvement of the solubility was noted in all the irradiated samples compared to the non-irradiated control samples. In addition, it was shown that following irradiation (Day 0), the number of psychrotrophs decreased by 2.5 log cycles (log CFU/g decreased from 3.3 to 0.7). After only 6 days of storage at 4°C, the number of CFU/g of meat was approximately 10^8 , rendering the meat unacceptable. γ -Irradiation considerably decreased the number of *Pseudomonas* and mesophiles. Following a dose of 1 kGy, the number of colonies decreased from 2.8 to 0.7 (log CFU/g) for *Pseudomonas* and from 2.3 to 1.8 (log CFU/g) for mesophiles, which represents a decrease of 2 log cycles for *Pseudomonas* and half a cycle for the mesophiles.

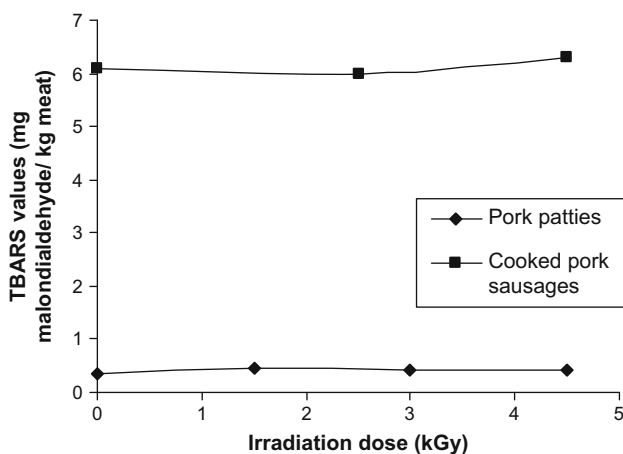


Figure 6.3: Effect of different doses of irradiation on TBARS values of pork patties and cooked pork sausages stored aerobically at 4°C (Ahn et al., 2000a; Jo et al., 2002).

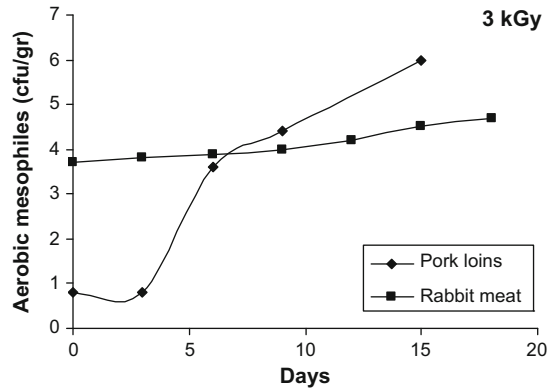


Figure 6.4: Effect of irradiation (3 kGy) on aerobic mesophilic bacteria in pork loins and rabbit meat aerobically packaged and stored at $4 \pm 1^\circ\text{C}$ (Badr, 2004; Dogbevi et al., 1999).

Figure 6.4 displays the effect of irradiation (3 kGy) on aerobic mesophilic bacteria in pork loins and rabbit meat aerobically packaged.

Patties were made from pork loin, individually vacuum or aerobic packaged, and stored at either 4 or 40°C . Refrigerated patties were irradiated at 0, 1.5, 3, or 4.5 kGy absorbed dose, and frozen ones were irradiated at 0, 2.5, 5, or 7.5 kGy. Refrigerated samples were analyzed at 0, 1, and 2 weeks, and frozen ones were examined after 0, 1.5, and 3 months of storage. Pork patties irradiated at 4.5 kGy and refrigerated for 1 week produced higher *n*-hexanal than other irradiation doses with vacuum packaging, but the amount of *n*-hexanal in non-irradiated or irradiated patties at 1.5 kGy increased at 1 and 2 weeks of storage. Irradiation had no effect on the production of *n*-hexanal in refrigerated, aerobic-packaged pork patties. Storage in aerobic conditions, however, significantly increased the production of *n*-hexanal in all irradiated pork patties. The TBARS of vacuum-packaged patties irradiated at 1.5, 3.0, or 4.5 kGy and stored at 4°C were not much different from those of the non-irradiated control at each storage time. However, the TBARS value of pork patties stored at 4°C for 1 week was the highest among all storage periods. The patties that were aerobic packaged and irradiated at 4.5 kGy had higher TBARS values than those irradiated at 1.5 kGy or the non-irradiated control at Day 0. The TBARS values increased sharply during refrigerated storage in aerobic packaging, but the effect of irradiation was not found at 2 weeks of storage. The TBARS of aerobic-packaged patties irradiated at 7.5 kGy was higher than that of the non-irradiated control at Day 0, but the TBARS value of the irradiated samples remained unchanged after 1.5 and 3 months of storage. Non-irradiated patties had higher preference scores than the irradiated ones for 1.5 months in frozen storage. Sulfur-containing compounds were responsible for most of the irradiation off-odor, but these volatilized quickly during storage under aerobic conditions (Ahn et al., 2000a).

Nam and Ahn (2003b) studied the use of antioxidants to reduce lipid oxidation and off-odor volatiles of irradiated pork homogenates and patties. Pork homogenates and patties treated with antioxidants (200 mM, final) were irradiated with an e-beam (0 or 4.5 kGy). Irradiation and antioxidants affected the TBARS values of pork homogenates during storage. Irradiated pork homogenates had higher TBARS than non-irradiated in all antioxidant treatments. The addition of an antioxidant (sesamol, gallate, trolox, or α -tocopherol) and their combinations decreased the release of off-odor volatiles and lipid oxidation of pork homogenates and patties by irradiation. Antioxidant combinations showed distinct beneficial reduction in lipid oxidation of aerobically packaged irradiated pork patties. Antioxidant combinations reduced the S-containing volatiles, which are the main off-odor compounds in irradiated, VP pork patties.

Jo and Ahn (2000) found that aerobic-packaged pork sausages irradiated (e-beam irradiation) at 4.5 kGy had higher TBARS than those irradiated at 0 or 2.5 kGy at 0 days of storage. TBARS of aerobic- or vacuum-packaged sausage prepared with lard were higher than those of sausage prepared with flaxseed oil or corn oil. The amount of *l*-heptene and *l*-nonene increased with increased irradiation doses. Aldehydes, ketones, and alcohols were not influenced by irradiation at 0 days of storage. However, irradiation accelerated lipid oxidation and increased the amount of aldehydes, ketones, and alcohols in aerobic-packaged sausage during storage. Furthermore, it was stated that the tocopherol content in the sausage affected the production of volatiles at different levels of unsaturated fatty acids.

Kang et al. (2007) separated cooked pork patties into three groups: uncoated control (C), coated with pectin-based materials (CP), and coated with pectin-based materials containing 0.5% green tea powder (CGP). The prepared patties were irradiated at 0 and 3 kGy using cobalt 60 γ -rays. Lipid oxidation, free radical scavenging effects, moisture content, total plate count, and sensory properties were evaluated during storage for 14 days at 10°C. Lipid oxidation decreased and radical scavenging increased in the pork patties in CGP or CP relative to those of the controls when VP. The numbers of total aerobic bacteria were significantly reduced by the coating treatments as well as by irradiation. There were no significant differences in sensory properties between the packaging methods, and none of the sensorial parameters were significantly affected by γ -irradiation. The only difference was in the odor of the VP sample, which was higher in CGP than in the control.

Ahn et al. (2004) investigated the irradiation effects on physicochemical characteristics of cooked pork sausage during storage at 4°C, packaged aerobically or under vacuum, γ -irradiated at 0, 5, 10, or 20 kGy. Redness in sausage was significantly reduced by irradiation at 5 kGy or higher during storage in both packagings. *N*-Nitrosodimethylamine contents in sausage with VP were decreased by irradiation at 10 and 20 kGy, whereas no difference was found in aerobic packaging at 0 week. Irradiation reduced *N*-nitrosopyrrolidine contents in sausage with aerobic packaging, and the *N*-nitrosopyrrolidine was not detected by irradiation at 5 kGy or higher.

After 4 weeks of storage, irradiation decreased *N*-nitrosopyrrolidine contents in sausage with vacuum packaging, whereas the packaging effect was not found during storage.

Zhu et al. (2004) studied the influence of temperature abuse on the quality of irradiated, pork loins vacuum packaged in low oxygen-permeable bags. Pork loins were randomly separated into three groups, sliced, and assigned to receive 0, 1.5, or 2.5 kGy e-beam irradiation. Mild temperature fluctuation had a minor effect on color, oxidation, and volatiles of irradiated pork loins. However, temperature fluctuation improved water-holding capacity of meat. Temperature abuse improved water-holding capacity of meat, which could be caused by the accelerated hydrolysis of muscle proteins at higher temperature. Irradiation also increased centrifugation loss that was partly reversed during refrigerated storage, which could be due to the hydrolysis of muscle proteins. Moreover, irradiation also increased water loss.

Houser et al. (2003) studied the affects of e-beam irradiation (4.5 kGy) on cured pork ham packaged under vacuum. Irradiation treatments included irradiation of raw uncured ham, raw cured ham, cured cooked ham, and a non-irradiated control. Irradiation processing increased lipid oxidation for all samples. The raw cured treatment resulted in significantly lower *L* values compared with the control, regardless of storage period. All treatments except for cured cooked ham had lower *b* values over the storage period. Irradiation treatment of cured cooked ham resulted in higher off-odor scores than all other treatments immediately following irradiation.

Table 6.3 summarizes the effect of irradiation in conjunction with hurdle technology on pork quality.

6.4 Additional Types of Meat

6.4.1 Effect of Irradiation on Quality

Lamb and buffalo meat was subjected to low-dose γ -irradiation (2.5 kGy) and stored at 0–3°C. Lipid peroxidation in terms of TBA number and carbonyl content was monitored during storage. Irradiated meat showed a slight increase in TBA number and carbonyl content on storage compared to non-irradiated meat. Free fatty acid content decreased markedly on irradiation. Irradiated meats were acceptable for up to 4 weeks in the nonfrozen state (0–3°C), whereas non-irradiated meat had a shelf life of less than 2 weeks (Kanatt et al., 1997).

Buffalo meat steaks were irradiated with γ -rays at doses of 5.5 and 11 kGy and stored at $2 \pm 1^\circ\text{C}$. The changes in lipids extracted from the steaks were investigated. Peroxides and carbonyl compounds accumulated during irradiation and subsequent storage of the irradiated meat. Oxidation products were higher if irradiation was carried out with 11 kGy than with 5.5 kGy. Soaking of the steaks in butylated hydroxytoluene (BHT) and sodium pyrophosphate before irradiation markedly reduced the amount of peroxides and carbonyl compounds formed during irradiation and storage (El-Zeany et al., 1980).

TABLE 6.3 Effect of Irradiation and Hurdle Technology on Pork

| Food Type | Irradiation Type/Dose | Other Technology | Temperature | Effect on Sensory Properties | Effect on Quality | Reference |
|------------|--|----------------------|-------------|--|--|------------------------------------|
| Pork loins | 3 kGy γ irradiation | Packaged aerobically | 4°C | — | The amounts of total volatiles and TBARS were higher than those of non irradiated samples. The amounts of volatiles in aerobically packaged irradiated samples decreased with storage, whereas those of non irradiated meats increased | Kim et al., 2002 |
| Pork | 1.5, 3, 4.5, 7.5, and 10.5 kGy E beam | Aerobically packaged | — | Irradiated pork became less red as a result of irradiation and display time. Visual evaluation of irradiated pork indicated an increase in brownness, whereas turkey increased in redness as dose increased. The surface color of irradiated pork became less uniform than that of non irradiated pork | — | Nanke et al., 1998 |

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|--|---|---|--|--|--|-------------------------|
| Chilled ($3 \pm 2^\circ\text{C}$) and frozen ($-17 \pm 3^\circ\text{C}$) boneless pork chops | 0, 1.5, or 2.5 kGy (chilled) or 0, 2.5, or 3.85 kGy (frozen) E beam or γ irradiation | Packaged in vacuum or air | 3 ± 2 and $17 \pm 3^\circ\text{C}$ | Irradiation source had varying but limited effects on color. Irradiation of vacuum packaged samples produced redder products. Less stable display color were noted for samples irradiated in aerobic packaging | More pronounced oxidative rancidity was noted for samples irradiated in aerobic packaging. Irradiation source had varying but limited effects on rancidity | Luchsinger et al., 1996 |
| Fresh pork chops | 1 kGy | 0.5% Sodium tripolyphosphate (STPP), 550 ppm sodium ascorbate (SA), or 0.1% potassium sorbate (PS) prior to irradiation | | Dipping with STPP decreased drip loss and improved color stability of irradiated chops and resulted in better tenderness and juiciness scores than nondipped, irradiated samples. Dipping with SA or PS had little effect compared with STPP but improved some sensory qualities | STPP treated samples had similar or better physicochemical properties than untreated (no irradiation, no dipping) samples | Zhao and Sebranek, 1996 |
| Raw pork muscle strips | 0, 5, or 10 kGy | Packaged aerobically or under vacuum | 4°C for 5 days | — | Irradiation had no effect on the production of volatiles related to lipid oxidation, but it produced a few sulfur containing compounds not found in non irradiated meat. Irradiated muscle strips produced more TBARS than non irradiated only in aerobic packaging during storage | Ahn et al., 2000b |

(Continued)

TABLE 6.3 Effect of Irradiation and Hurdle Technology on Pork—cont'd

| Food Type | Irradiation Type/Dose | Other Technology | Temperature | Effect on Sensory Properties | Effect on Quality | Reference |
|--|--|--|------------------------|--|--|--------------------------------------|
| Raw patties prepared from three pork muscles | 0 or 4.5 kGy E beam | Packaged either in oxygen permeable polyethylene bags or impermeable nylon/polyethylene bags | 4°C for 2 weeks | Oxygen availability during storage, however, was more important than irradiation on the color values of raw patties | Irradiated meat produced more volatiles than non irradiated patties, and the proportion of volatiles varied by the packaging irradiation conditions of patties. Irradiation produced many unidentified volatiles that could be responsible for the off odor in irradiated raw meat | Ahn et al., 1998 |
| Fresh pork loins | 6 kGy, at two different dose rates: 2 and 20 kGy/h | Air or vacuum packaging | 4 ± 1°C for 43 days | No marked difference in the intensity or red color or in the meat texture was found in samples during the first 20 days of storage. However, between 20 and 40 days of storage, the red color was more intense in samples packed under air. A more intense red color was observed in samples treated at 20 kGy/h compared to samples | No marked changes in emulsifying capacity and protein sulfhydryl content of proteins were noted throughout the storage period. The hydrophobicity was reduced by the faster dose rate of irradiation and by longer storage | Lacroix et al., 2000 |

| | | | | | | |
|------------------|---|-----------------------------|-------|---|--|--------------------------------------|
| | | | | treated at 2 kGy/h at the end of the experiment. A marked difference in the meat texture was also found between the air and vacuum packed pork throughout the storage | | |
| Fresh pork loin | 2.2 and 4.4 kGy E beam | Injected with a brine | 0 2°C | Color changes were observed with irradiation treatment, but injection did not appear to have an influence on irradiation induced color changes | Lipid oxidation, as measured by TBA values, increased with irradiation dosage, but the change in TBA value with irradiation did not seem to be affected by injection treatment | Davis et al., 2004 |
| Fresh pork loins | 2, 4, and 8 kGy γ irradiation | Packaged in plastic bags | 4°C | — | Results show a significant increase in deamidation with the irradiation dose. At a dose of 8 kGy, deamidation is almost complete, reaching a level of more than 98%. Moreover, γ irradiation had little effect on sulfhydryl groups | Dogbevi et al., 1999 |

(Continued)

TABLE 6.3 Effect of Irradiation and Hurdle Technology on Pork—cont'd

| Food Type | Irradiation Type/Dose | Other Technology | Temperature | Effect on Sensory Properties | Effect on Quality | Reference |
|-------------------|--|----------------------------|-------------|------------------------------|---|-------------------|
| Pork loin patties | Refrigerated patties were irradiated at 0, 1.5, 3, or 4.5 kGy absorbed dose and frozen ones were irradiated at 0, 2.5, 5, or 7.5 kGy, E beam | Vacuum or aerobic packaged | 4 or 40°C | — | Samples irradiated at 4.5 kGy and refrigerated for 1 week produced higher <i>n</i> hexanal than other irradiation doses with vacuum packaging, but the amount of <i>n</i> hexanal in patties non irradiated or irradiated at 1.5 kGy increased at 1 and 2 weeks of storage. Irradiation had no effect on the production of <i>n</i> hexanal in refrigerated, aerobic packaged pork patties. Storage in aerobic conditions, however, significantly increased the production of <i>n</i> hexanal in all irradiated pork patties | Ahn et al., 2000a |

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|--------------------------------------|------------------------------|--|---|---|--------------------|
| Pork homogenates and patties treated | 0 or 4.5 kGy E beam | Sesamol, gallate, trolox, or α tocopherol (200 mM, final) | Addition of an antioxidant and their combinations decreased, but carnosine did not affect, the production of off odor volatiles of pork homogenates and patties by irradiation. Antioxidant combinations reduced the S containing volatiles, which are the main off odor compounds in irradiated, VP pork patties | Irradiated pork homogenates had higher TBARS than non irradiated in all antioxidant treatments. Addition of an antioxidant and their combinations decreased, but carnosine did not affect, the production of lipid oxidation of pork homogenates and patties by irradiation | Nam and Ahn, 2003b |
| Pork sausage | 0, 2.5, or 4.5 kGy E beam | Aerobic or vacuum packaged | — | The amount of 1 heptene and 1 nonene increased with increased irradiation doses. Irradiation accelerated lipid oxidation and increased the amount of aldehydes, ketones, and alcohols in aerobic packaged sausage during storage | Jo and Ahn, 2000 |

(Continued)

TABLE 6.3 Effect of Irradiation and Hurdle Technology on Pork—cont'd

| Food Type | Irradiation Type/Dose | Other Technology | Temperature | Effect on Sensory Properties | Effect on Quality | Reference |
|---|--|--------------------------------------|-------------------|--|---|---------------------|
| Cooked pork sausage | 0, 5, 10, or 20 kGy γ Irradiated | Packaged aerobically or under vacuum | 4°C | Redness in sausage was reduced by irradiation at 5 kGy or above during storage in both packagings | <i>N</i> nitrosodimethylamine contents in sausage with VP were decreased by irradiation at 10 and 20 kGy, whereas no difference was found in aerobic packaging at 0 weeks. Irradiation reduced <i>N</i> nitrosopyrrolidine contents in sausage with aerobic packaging, and the <i>N</i> nitrosopyrrolidine was not detected by irradiation at 5 kGy or higher | Ahn et al., 2004 |
| Pork loins | 0, 1.5, or 2.5 kGy E beam | VP | Temperature abuse | Temperature abuse had a minor effect on the color of irradiated samples | Temperature abuse improved water holding capacity of meat. Irradiation increased centrifugation loss partly reversed during refrigerated storage. Temperature abuse had a minor effect on oxidation and volatiles of irradiated samples | Zhu et al., 2004 |
| Raw uncured, raw cured, and cured cooked pork ham | 4.5 kGy E beam | VP | 2 4°C for 90 days | Irradiation treatment of cured cooked ham resulted in higher off odor scores than all other treatments | Irradiation processing increased lipid oxidation for all samples | Houser et al., 2003 |

| | | | | | | | |
|--------------------------------|---|---|--------------------------------|---|--|---|--------------------|
| | | | | | | immediately following irradiation. The raw cured treatment resulted in significantly lower L^* values compared with the control, regardless of storage period. All treatments except for cured cooked ham had lower b^* values over the storage period | |
| Cooked pork chops and ham | 0.75 0.90 kGy | — | — | — | | Reduction of <i>L. monocytogenes</i> by more than 2 log | Fu et al., 1995 |
| Phosphate buffer (pH = 7.00) | 0 2 kGy γ irradiation | — | Irradiation at 0°C and at 40°C | — | | The survival curves irrespective of the suspending medium or irradiation temperature were observed to be exponential up to 1 kGy dose. However, additional irradiation resulted in tailing of the survivors. Whereas the tailing effect in meat was observed after 5 log cycle reduction, in buffer it was observed after 8 log cycle reduction. This phenomenon was not influenced by temperature of irradiation | Kamat et al., 1997 |
| 10% raw meat/salami homogenate | 0 2 kGy γ irradiation | — | Irradiation at 0°C and at 40°C | — | | | |
| Pork | 0, 0.5, 1, and 2 kGy γ irradiation | — | — | — | | The levels of putrescine, tyramine, spermine, and total amount of biogenic amines were significantly reduced | Min et al., 2007 |

The *m. Longissimus dorsi* from lamb was irradiated by γ -radiation up to a dose of 10 kGy. After irradiation, the lipids were extracted from the muscles to ascertain the effect of irradiation. Peroxide and iodine values along with malonaldehyde concentration were used to assess any damage made to the lipids and to note any significant differences in these compounds due to the type of muscle tissue. Peroxide and iodine values indicated that at low irradiation dose (<10 kGy) there was no significant change in any of the meat lipids (Hampson et al., 1996).

The suitability of potato peel extract (PPE) for controlling lipid oxidation of radiation processed lamb meat was investigated by Kanatt et al. (2005). When PPE (0.04%) was added to meat (packed in PE pouches) before radiation processing (2.5 and 5 kGy), it was found to delay lipid peroxidation of irradiated meat as measured by TBA number and carbonyl content. The antioxidant activity of PPE was shown to be comparable to that of BHT.

Kanatt et al. (2006) analyzed the lipids from control (non-irradiated) and irradiated lamb meat using thin-layer chromatography (TLC) to investigate if there was any change in the lipid profile due to γ -irradiation. No differences were observed in the lipid profile of the radiation processed and non-irradiated meat. TLC detected all five major classes of lipids in both irradiated and non-irradiated meat. However, there was a radiation dose-dependent decrease in phospholipid and cholesterol content, whereas an increase was observed in the free fatty acid content (oleic acid, palmitic acid, and stearic acid). There was a significant decrease in the ratio of PUFA/SFA of phospholipids on irradiation. There was a dose-dependent increase in TBA number on radiation processing (2.5 and 5 kGy) of lamb meat. Compared to the non-irradiated samples, irradiation at 2.5 and 5 kGy resulted in 34 and 89% increases in TBA values, respectively.

The effect of irradiation (2.5 kGy) on TBARS value of buffalo and lamb meat stored at 0–3°C is displayed in Figure 6.5.

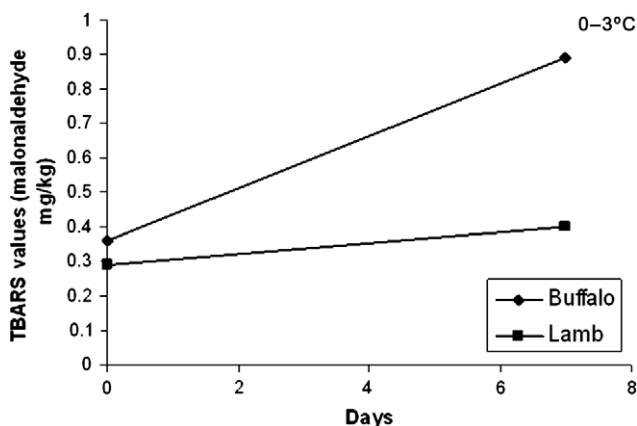


Figure 6.5: Effect of irradiation (2.5 kGy) on TBARS values of buffalo and lamb meat stored at 0–3°C (Kanatt et al., 1997, 2006).

Gomes et al. (2006) evaluated the effect of irradiation on Cornish game hen carcasses e-beam irradiated up to 7 kGy. Eighty frozen and vacuum-packaged Cornish game hens (*Gallus domesticus*) were irradiated and stored under vacuum in low-density polyethylene bags at $4 \pm 1^\circ\text{C}$ for 21 days; non-irradiated chickens served as controls. Fat oxidation (in terms of malonaldehyde content) increased with storage time and dose. Oxidation level in all samples exposed to 2 kGy reached a maximum on Day 14.

Table 6.4 provides an overview of the effect of irradiation on the quality of some additional types of meat (lamb, buffalo, raw game hen, and rabbit).

6.4.2 Effect of Irradiation on Microflora of Additional Types of Meat

According to Kanatt et al. (1997), the immediate effect of irradiation (2.5 kGy) was a decrease in the TPC by 3 log cycles in buffalo and 2 log cycles in lamb meat. Enterobacteriaceae and fecal coliforms were not detected in irradiated buffalo meat throughout the storage period; however, they were present in the control samples and their numbers increased on storage ($0\text{--}3^\circ\text{C}$). Initial count of *Staphylococcus* spp. in the non-irradiated control was 4.54 log CFU/g, which increased to 6.15 log CFU/g at the end of 2 weeks of storage. In the irradiated samples, *Staphylococcus* spp. were not detected up to 3 weeks, and during the fourth week the colonies (2.90 log CFU/g) recorded were not potentially pathogenic.

Vural et al. (2006) studied the effect of low-dose γ -irradiation application on microbiological quality of raw meat ball. The authors state that 1-, 2-, and 3-kGy irradiation doses decreased or eliminated the microorganism counts in raw meat ball, in parallel with the increased doses. Coliform bacteria counts were reduced under detectable value after application of 2-kGy irradiation doses; *Staphylococcus aureus*, sulfite-reducing *Clostridia*, yeast, and mould counts were reduced by the application of 3 kGy. They concluded that the low-dose γ -irradiation applications increased the hygienic quality of raw meat balls, and possible public health risks can be prevented.

Fresh salted and semidried natural pork and lamb casing was washed and irradiated at 0, 3, and 5 kGy by γ -ray and emulsion-type pork sausage was manufactured. The sausage was stored in a 4°C refrigerator. The numbers of total aerobic bacteria, Enterococcus, and coliform bacteria in the irradiated natural casing or sausage prepared from irradiated casing were significantly decreased or eliminated compared to those of the non-irradiated control. The D_{10} values of total aerobic bacteria of the pork and lamb casing were 0.87 and 0.92 kGy, respectively (Byun et al., 2001).

Irradiation significantly reduced the total viable microbial counts (TVCs) in the breast and thigh of Cornish game hen. Exposure to 3-kGy dose decreased the TVC by 0.3 log cycles on the surface of the skin. In less than 14 days, the non-irradiated hen carcasses had counts

TABLE 6.4 Effect of Irradiation on the Quality of Additional Types of Meat (Lamb, Buffalo, Raw Game Hen, and Rabbit)

| Food Type | Irradiation Type/Dose | Temperature | Shelf Life | Effect on Quality | Reference |
|--------------------------------|--|-------------|------------|---|-----------------------|
| Lamb and buffalo meat | | 0 3°C | 2 weeks | Irradiated meat showed slight increase in TBA number and carbonyl content on storage compared to non irradiated meat. Free fatty acid content decreased markedly on irradiation | Kanatt et al., 1997 |
| Lamb and buffalo meat | 2.5 kGy γ irradiation | 0 3°C | 4 weeks | | |
| Buffalo meat steaks | 5.5 and 11 kGy γ irradiation | 2 ± 1°C | — | Peroxides and carbonyl compounds accumulated during irradiation and subsequent storage of irradiated meat. Oxidation products were higher if irradiation was carried out with 11 kGy than with 5.5 kGy | El Zeany et al., 1980 |
| m. Longissimus dorsi from lamb | 0, 0.943, 2.83, 5.66, and 9.43 kGy γ irradiation | — | — | Peroxide and iodine values showed that at low irradiation dose (<10 kGy) there was no significant change in any of the meat lipids | Hampson et al., 1996 |
| Lamb meat | 2.5 and 5 kGy γ irradiation and potato peel extract (0.04%) was added | — | — | When PPE (0.04%) was added to meat before radiation processing, it delayed lipid peroxidation of irradiated meat as measured by TBA number and carbonyl content | Kanatt et al., 2005a |
| Lamb meat | 2.5 and 5 kGy γ irradiation | — | — | No differences were observed in the lipid profile of the radiation processed and non irradiated meat. There was a radiation dose dependent decrease in phospholipid and cholesterol content, whereas an increase was observed in the free fatty acid content. | Kanatt et al., 2006 |

| | | | | | |
|---------------------|---|---|---------|--|--------------------|
| | | | | There was a significant decrease in the ratio of PUFA/SFA of phospholipids on irradiation. There was a dose dependent increase in TBA number on radiation processing of lamb meat | |
| Raw game hen meat | 2, 3, and 7 kGy E beam | 4 ± 1°C for 21 days under vacuum in low density polyethylene bags | — | Fat oxidation (in terms of malonaldehyde content) increased with storage time and dose. Oxidation level in all samples exposed to 2 kGy reached a maximum on Day 14 | Gomes et al., 2006 |
| Rabbit meat samples | Packaged in polyethylene pouches | 4 ± 1°C | 6 days | Irradiated rabbit meat produced significantly higher TBARS than non irradiated samples, and the amounts of TBARS showed positive correlations with the applied dose and storage time. Irradiation of rabbit meat samples had no significant effects on their total volatile nitrogen content | Badr, 2004 |
| Rabbit meat samples | 1.5 kGy γ irradiation and packaged in polyethylene pouches | 4 ± 1°C | 12 days | | |
| Rabbit meat samples | 3 kGy γ irradiation and packaged in polyethylene pouches | 4 ± 1°C | 21 days | | |

greater than 6 log CFU/50 cm², whereas the 2- and 3-kGy irradiated samples reached these numbers only after 21 days of storage at 4 ± 1°C. The 7-kGy dose was the most effective treatment, with samples having no more than 2.5 log CFU/50 cm² throughout storage (Gomes et al., 2006).

The effect of irradiation on the microflora of some additional types of meat is summarized in Table 6.5.

6.4.3 Effect of Irradiation on Sensory Quality of Additional Types of Meat

Kanatt et al. (1997) reported that immediately after irradiation (2.5 kGy) there was no effect on the sensory attributes in lamb and buffalo meat. Within 2 weeks (0–3°C), when off-odor and signs of spoilage were evident, the mean sensory scores of non-irradiated samples were less than the acceptable score of 5. In contrast, irradiated meat had, even at the end of the storage period of 4 weeks, an overall acceptability score of above 5.

Millar et al. (2000a) studied the effect of irradiation (0 and 5 kGy) of goose and turkey breast and leg muscles and subsequent storage at 4°C in relation to color changes. L^* values of control and irradiated goose and turkey breast muscles changed little during storage post-irradiation. The a^* values for non-irradiated goose breast were significantly higher than those for irradiated goose breast but declined to values similar to those of irradiated goose breast after 7 days of storage. Millar et al. (2000b) investigated the effect of irradiation (0 and 5 kGy) of lamb portions in retail overwrap packs and subsequent storage at 4°C in relation to color changes. The color of both the exterior and a freshly cut surface of lamb, in similar retail overwrap packs, was measured at 2, 5, and 7 days post-irradiation, with different samples being used per day of measurement. For lamb, there was an increase in L^* and h_0 values and a decrease in a^* , b^* , and C^* values with storage. Sensory evaluation showed that e-beam irradiation (2, 3, and 7 kGy) caused significant textural toughening and increased the redness of raw hen meat packaged under vacuum in LDPE bags at 4 ± 1°C for 21 days. In terms of overall quality and aroma, lipid oxidation was not a major problem because it was not detected by panelists (Gomes et al., 2006).

Badr (2004) studied the use of irradiation to control foodborne pathogens and extend the refrigerated market life of rabbit meat aerobically packaged in PE pouches. Rabbit meat samples were γ -irradiated at doses of 0, 1.5, and 3 kGy. The samples were stored at 4 ± 1 kGy. Irradiation at 1.5 kGy significantly reduced the counts of *S. aureus*, *L. monocytogenes*, *E. faecalis*, and Enterobacteriaceae but was not enough for complete elimination of *Salmonella*. However, the 3-kGy dose reduced the counts of *S. aureus*, *L. monocytogenes*, *E. faecalis*, and Enterobacteriaceae by more than 3, 3, 1.4, and 4 log units, respectively, whereas *Salmonella* was not detected. On the other hand, irradiation at 1.5 and 3 kGy considerably reduced the counts of aerobic mesophilic bacteria, psychrophilic bacteria, and

TABLE 6.5 Effect of Irradiation on the Microflora of Additional Types of Meat

| Food Type | Irradiation Type/Dose | Temperature | Effect on Microflora | Reference |
|--------------------------------------|--|---|---|---------------------|
| Buffalo and lamb meat | 2.5 kGy γ irradiation | 0–3°C | Decrease in the total plate count by 3 log cycles in buffalo and 2 log cycles each in lamb meat. Initial count of <i>Staphylococcus</i> spp. in the non irradiated control was 4.54 log CFU/g, which increased to 6.15 log CFU/g at the end of 2 weeks of storage. In the irradiated samples up to 3 weeks, <i>Staphylococcus</i> spp. were not detected and in the fourth week the colonies (2.90 log CFU/g) observed were not potentially pathogenic | Kanatt et al., 1997 |
| Raw meat ball | 1, 2, and 3 kGy γ irradiation | — | Coliform bacteria counts were reduced under detectable value after application of 2 kGy irradiation doses; <i>Staphylococcus aureus</i> , sulfite reducing <i>Clostridia</i> , yeast, and mould by the application of 3 kGy | Vural et al., 2006 |
| Breast and thigh of Cornish game hen | 2, 3, and 7 kGy E beam | 4 ± 1°C for 21 days under vacuum in low density polyethylene bags | Exposure to 3 kGy dose decreased the TVC by 0.3 log cycles on the surface of the skin. In less than 14 days, the non irradiated hen carcasses had counts greater than 6 log CFU/50 cm ² , whereas the 2 and 3 kGy irradiated samples reached these numbers only after 21 days of storage. The 7 kGy dose was the most effective treatment, with samples having no more than 2.5 log CFU/50 cm ² throughout storage | Gomes et al., 2006 |
| Rabbit meat samples | No irradiation; packaged in polyethylene pouches 1.5 kGy γ irradiation and packaged in polyethylene pouches 3 kGy γ irradiation and packaged in polyethylene pouches | 4 ± 1 kGy | Irradiation at 1.5 kGy significantly reduced the counts of <i>S. aureus</i> , <i>L. monocytogenes</i> , <i>E. faecalis</i> , and Enterobacteriaceae but was not enough for complete elimination of <i>Salmonella</i> . However, the 3 kGy dose reduced the counts of <i>S. aureus</i> , <i>L. monocytogenes</i> , <i>E. faecalis</i> , and Enterobacteriaceae by more than 3, 3, 1.4, and 4 log units, respectively, whereas <i>Salmonella</i> was not detected | Badr, 2004 |

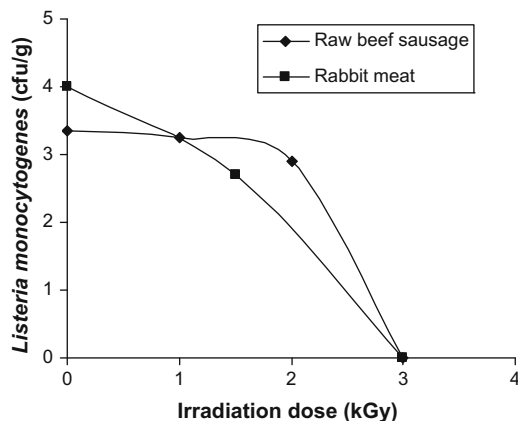


Figure 6.6: Effect of different doses of irradiation on *Listeria monocytogenes* population growth in raw beef sausage and rabbit meat aerobically packaged and stored at $4 \pm 1^\circ\text{C}$ (Day 3 of storage) (Badr, 2004, 2005).

molds and yeasts and prolonged the refrigerated shelf-life of samples to 12 and 21 days, respectively, compared to 6 days for non-irradiated controls. Irradiated rabbit meat produced significantly higher TBARS than non-irradiated samples, and the amounts of TBARS showed positive correlations with the applied dose and storage time. Irradiation of rabbit meat samples had no significant effects on their total volatile nitrogen content. On the other hand, refrigerated storage significantly increased their total volatile nitrogen content.

Figure 6.6 displays the impact of different doses of irradiation on *L. monocytogenes* population growth in raw beef sausage and rabbit meat aerobically packaged.

The effect of irradiation on the sensory quality of additional types of meat is shown in Table 6.6.

6.5 Effect of Irradiation on Sausages

In a study by Du and Ahn (2002), sausages were prepared from turkey thigh meat, NaCl (2.0%), phosphate (0.5%), water (10%), and one of five antioxidant treatments (none, vitamin E, sesamol, rosemary extract, or gallic acid at 0.02%). VP sausages were irradiated at 0, 1.5, or 3.0 kGy using an e-beam. Gallic acid was very effective in lowering the redness of irradiated and non-irradiated sausages. The redness (a^*) values of sausages with gallic acid irradiated at 0, 1.5, and 3.0 kGy were 1.49, 2.03, and 2.29, respectively, whereas those of control sausages under the same irradiation conditions were 2.58, 2.81, and 3.25, respectively. The reduction of redness in irradiated sausages by antioxidants was not related to CO because antioxidants had no effect on CO production by irradiation.

The effectiveness of low γ -irradiation doses in the destruction of *E. coli* O157:H7 and *L. monocytogenes* in raw beef sausages was investigated by Badr (2005). Raw samples of beef

TABLE 6.6 Effect of Irradiation on the Sensory Quality of Additional Types of Meat

| Food Type | Irradiation Type/Dose | Temperature | Sensory Quality | Reference |
|--|---|---|---|----------------------|
| Lamb and buffalo meat | 2.5 kGy γ irradiation | 0-3°C | Within 2 weeks, when off odor and signs of spoilage were evident, the mean sensory scores of non irradiated samples were less than the acceptable score of 5. In contrast, irradiated meat had, even at the end of the storage period of 4 weeks, an overall acceptability score of higher than 5 | Kanatt et al., 1997 |
| Fresh salted and semidried natural pork and lamb casing was washed and irradiated, and emulsion type pork sausage was manufactured | 0, 3, and 5 kGy γ irradiation | 4°C | Irradiation increased the tenderness of the sausage made with natural pork and lamb casing. Flavor, color, texture, and overall acceptance of the sausage prepared with irradiated natural casings evaluated by panels did not differ from those of non irradiated controls | Byun et al., 2001 |
| Goose and turkey breast and leg muscles | 0 and 5 kGy γ irradiation | 4°C | L^* values of control and irradiated, goose and turkey breast muscles changed little during storage post irradiation. The a^* values for non irradiated goose breast were significantly higher than those of irradiated goose breast but declined to values similar to those of irradiated goose breast after 7 days of storage | Millar et al., 2000a |
| Lamb portions | 0 and 5 kGy γ irradiation | 4°C for 7 days | For lamb there was a general increase in L^* and h_0 values and a decrease in a^* , b^* , and C^* values with storage | Millar et al., 2000b |
| Raw game hen meat | 2, 3, and 7 kGy E beam | 4 ± 1°C for 21 days under vacuum in low density polyethylene bags | Irradiation caused significant textural toughening and increased the redness. In terms of overall quality and aroma, lipid oxidation was not detected by panelists | Gomes et al., 2006 |

sausage were subjected to γ -irradiation at doses of 0, 1, 2, and 3 kGy. Samples were stored at $4 \pm 1^\circ\text{C}$. Samples of raw beef sausage inoculated with *E. coli* O157:H7 had an initial count of 2.11×10^4 CFU/g. Subjecting raw beef sausage, inoculated with *E. coli*, to γ -irradiation at doses of 1 and 2 kGy significantly reduced the initial count of this pathogen in the samples. However, refrigerated storage significantly increased the counts of *E. coli* O157:H7 that survived the 1-kGy dose as well as the counts in control non-irradiated samples. The initial count of *L. monocytogenes* naturally present in raw beef sausage was determined to be 1.78×10^3 CFU/g. Application of γ -irradiation at doses of 1 and 2 kGy induced significant reduction in the counts of *L. monocytogenes* in sausage. During storage at $4 \pm 1^\circ\text{C}$, further significant increases were observed in the counts of *L. monocytogenes* for both non-irradiated samples and those that received a 1-kGy irradiation dose.

Jo et al. (1999) investigated the effects of irradiation pork sausages with different fat content and packaging. Sausages (with 4.7, 10.5, and 15.8% fat content) were sliced and aerobically or vacuum packaged, e-beam irradiated (0 or 4.5 kGy), and stored at 4°C for 7 days. Irradiation increased the lipid oxidation of sausages with 10.5 and 15.8% fat content in both aerobic and vacuum packaging at Day 0. However, the irradiation effect on lipid oxidation disappeared during storage except for the sausages with 15.8% fat content in VP. The TBARS values of VP pork sausages were very similar throughout storage. Irradiation had no effect on Hunter L^* values of sausages both with aerobic and with vacuum packagings. In aerobic packaging, irradiation reduced Hunter a^* values of pork sausages at Day 0 but irradiation effect on the a^* value disappeared during storage. In vacuum packaging, however, irradiated samples had higher Hunter a^* values than non-irradiated samples.

Jo et al. (2002) prepared pork sausages with back fat or commercial soybean oil enriched with vitamin E to determine the effect of irradiation (0, 2.5, or 4.5 kGy) on lipid oxidation and volatile production during storage (4°C). The sausage prepared with soybean oil had a significantly higher amount of linoleic acid (C18:2) than that with back fat. Irradiation dose did not affect fatty acid composition of the products. The TBARS of aerobically packaged sausage prepared with back fat were increased by irradiation at 4.5 kGy. Storage for 7 days, exposed to air, increased the TBARS significantly. However, no irradiation effect in aerobically packaged sausages prepared with back fat was seen at 3 and 7 days of storage. The TBARS of sausages prepared with soybean oil also increased by irradiation at Day 0 and Day 3. TBARS of aerobically packaged sausages, prepared either with back fat or with soybean oil, increased during storage. However, the rate of TBARS increase during storage was higher in the sausages prepared with back fat than in those prepared with soybean oil. The TBARS value of VP sausages prepared with back fat or soybean oil was not changed by irradiation dose or storage. The pork sausage, prepared with soybean oil and irradiated at 4.5 kGy, initially had higher TBARS value than that at 0 or 2.5 kGy in VP products, but no difference was found after 3 and 7 days of storage. The TBARS values of the VP sausages prepared with back fat and soybean oil were not statistically different, although they had different fatty acid composition.

The production of volatiles with very short retention time (<1.80 min) was the most sensitive to irradiation. Hexanal production in the sausages was significantly suppressed by VP, and especially those prepared with soybean oil, because of the high vitamin E content in the sausages.

Jo et al. (2000) prepared pork sausages with lean pork meat, fat from different sources [back fat (BF), corn oil (CO), or flaxseed oil (FO); 10% of lean meat], NaCl (2%), and ice water (10%). Cooked sausages were sliced and vacuum or aerobic packaged individually. Sausages were e-beam irradiated at doses of 0, 2.5, or 4.5 kGy and stored in a 4°C refrigerator for 8 days. Aerobic-packaged, irradiated cooked sausages prepared with BF and FO showed higher Hunter L^* values than non-irradiated controls at Day 0, but the difference disappeared at Day 8. Irradiation increased the Hunter a^* value in VP cooked pork sausages regardless of the fat source used, and the increase in the Hunter a^* value was dose dependent. In contrast, the Hunter a^* value decreased by irradiation in aerobic-packaged cooked pork sausages prepared with BF or FO. The Hunter a^* value of cooked pork sausage with aerobic packaging was significantly reduced at Day 8. Hunter b^* values increased at Day 8 in irradiated cooked pork sausages except for the sausage prepared with CO at 2.5 kGy.

Jo et al. (2003) investigated the functional and sensory properties of raw and cooked pork patties with added irradiated freeze-dried green tea leaf extract powder. Components of green tea were extracted by 70% ethanol, and the extract was irradiated to obtain a bright color. The irradiated green tea extract was freeze-dried and the powdered sample (0.1%) was added to the pork patties. Pork patties without any ingredient and with non-irradiated, freeze-dried green tea extract powder were also prepared for comparison. Irradiated, freeze-dried green tea leaf extract powder did not have negative effects on physical and sensory properties. In contrast, the patties with added green tea leaf extract, both non-irradiated and irradiated, had beneficial biochemical properties.

Samelis et al. (2005) determined the survival of *Listeria* spp. (four-strain mixture of *L. innocua* plus a nonvirulent *L. monocytogenes* strain) and *E. coli* O157:H7 strain ATCC 43888 during fermentation and ripening of vacuum-packaged Greek dry sausages formulated from meat and pork fat trimmings previously inoculated with approximately 6 log CFU/g of the target bacteria and then irradiated in frozen (−25°C) blocks at doses of 0 (control), 2, or 4 kGy. Irradiation of the trimmings at 2 kGy reduced initial contamination of the sausage batter with *Listeria* and *E. coli* O157:H7 by 1.3 and 2.0 log CFU/g, respectively, whereas the corresponding reductions at 4 kGy were 2.4 and 5.5 log CFU/g, respectively. *Escherichia coli* O157:H7 was eliminated by 4 kGy at formulation (Day 0) compared to 7 and 21 days of ripening in samples treated at 2 and 0 kGy, respectively.

Byun et al. (2000) studied the effect of γ -irradiation (0, 1, 3, and 5 kGy) on Bologna sausage (made from beef). Aerobic and anaerobic bacteria growth was not observed with 3- or 5-kGy irradiated beef after cooking. Growth decrease was dependent on irradiation dose. Min et al.

TABLE 6.7 Effect of Irradiation on Quality and Microflora of Sausages

| Food Type | Irradiation Type/Dose | Temperature | Shelf Life | Effect on Quality | Effect on Microflora | Reference |
|--|---|-------------------------|---|--|---|-------------------|
| Raw beef sausages | 0, 1, 2, and 3 kGy γ irradiation | $4 \pm 1^\circ\text{C}$ | — | — | Doses of 1 and 2 kGy induced significant reduction in the counts of <i>L. monocytogenes</i> and <i>E. coli</i> O157:H7 in sausage | Bahr et al., 2005 |
| Pork sausages with lean pork meat, fat from different sources [back fat (BF), corn oil (CO), or flaxseed oil (FO); 10% of lean meat], NaCl (2%), and ice water (10%) | 0, 2.5, or 4.5 kGy E beam | Aerobic packaged | 4°C refrigerator for 8 days | Cooked sausages prepared with BF and FO showed higher Hunter L^* values than non irradiated controls at Day 0, but the difference disappeared at Day 8. Hunter a^* value decreased by irradiation in aerobic packaged cooked pork sausages prepared with BF or FO | — | Jo et al., 2000 |
| Pork sausages (with 10.5, and 15% fat content at Day 0) | 0 or 4.5 kGy E beam | Aerobically packaged | 4°C for 7 days | Irradiation had no effect on Hunter L^* values of sausages. Irradiation reduced Hunter a^* values of pork sausages at 0 days but irradiation effect on a^* value disappeared during storage. Irradiation increased the lipid oxidation of sausages with 10.5 and 15.8% fat content at Day 0. | — | Jo et al., 1999 |
| | | VP | | Irradiation had no effect on Hunter L^* values of sausages. Irradiated samples had higher Hunter a^* values than non irradiated samples. Irradiation increased the lipid oxidation of sausages with 10.5 and 15.8% fat content at Day 0 | — | |

| | | | | | | |
|--------------------|--|-----|--|---|---|----------------------|
| Greek dry sausages | 0, 2, and 4 kGy γ irradiation | VP | — | — | Initial contamination of the sausage batter with <i>Listeria</i> and <i>E. coli</i> O157:H7 was reduced by 1.3 and 2.0 log CFU/g, respectively, while the corresponding reductions at 4 kGy were 2.4 and 5.5 log CFU/g, respectively. <i>E. coli</i> O157:H7 was eliminated by 4 kGy at formulation | Samelis et al., 2005 |
| Bologna sausage | 0, 1, 3, and 5 kGy γ irradiation | 4°C | Started to lose value after 30 days of storage | — | Growth decrease was dose dependent. Aerobic and anaerobic bacteria growth was not observed with 3 or 5 kGy irradiated beef after cooking. | Byun et al., 2000 |

(Continued)

TABLE 6.7 Effect of Irradiation on Quality and Microflora of Sausages—cont'd

| Food Type | Irradiation Type/Dose | Temperature | Shelf Life | Effect on Quality | Effect on Microflora | Reference |
|---|---------------------------|----------------------|----------------|--|----------------------|-----------------|
| Pork sausages with back fat | 0, 2.5, or 4.5 kGy E beam | Aerobically packaged | 4°C for 7 days | The TBARS of aerobically packaged sausage prepared with back fat were increased by irradiation at 4.5 kGy. Storage for 7 days, exposed to air, increased the TBARS significantly. However, no irradiation effect in aerobically packaged sausages prepared with back fat was seen at 3 and 7 days of storage | — | Jo et al., 2002 |
| Pork sausages with commercial soybean oil enriched with vitamin E | 0, 2.5, or 4.5 kGy E beam | Aerobically packaged | 4°C for 7 days | The TBARS of sausages prepared with soybean oil also increased by irradiation at Day 0 and Day 3 | — | |
| | | VP | 4°C for 7 days | The TBARS value of vacuum packaged sausages prepared with back fat or soybean oil was not changed by irradiation dose or storage | — | |
| | | VP | 4°C for 7 days | The TBARS values of the vacuum packaged sausages prepared with back fat and soybean oil were not statistically different | — | |

Fresh salted and semidried natural pork and lamb casing was washed and irradiated, and emulsion type pork sausage was manufactured

0, 3, and 5 kGy γ irradiation 4°C

— —

The numbers of total aerobic bacteria, Enterococcus, and coliform bacteria in the irradiated natural casing or sausage prepared from irradiated casing were significantly decreased or eliminated compared to those of the non irradiated control

Byun et al., 2001

(2007) investigated the effect of irradiation (0, 0.5, 1, and 2 kGy). The levels of putrescine, tyramine, spermine, and the total amount of biogenic amines were significantly reduced by irradiation of ground beef inoculated with the different microorganisms tested (*B. cereus*, *Enterobacter cloacae*, and *A. faecalis*). Irradiation was effective in reducing the inoculated bacteria and achieved approximately three decimal reductions by 2 kGy.

In a study by Byun et al. (2001), fresh salted and semidried natural pork and lamb casing was washed and γ -irradiated (0, 3, and 5 kGy) in order to make emulsion-type pork sausage. The sausage prepared was stored at 4°C. The sausages prepared with both irradiated natural pork and lamb casing showed lower total working force for shear than that of controls. The results indicate that irradiation increased the tenderness of the sausage made with natural pork and lamb casing, improving sensory properties. Flavor, color, texture, and overall acceptance of the sausage prepared with irradiated natural casings evaluated by panels did not differ from non-irradiated controls.

The effect of irradiation on quality and microflora of sausages is summarized in Table 6.7.

6.6 Conclusions

Meat was one of the first foods, after spices, to be widely irradiated in the United States. In fact, the irradiation dose varies depending on the size and dimensions of the piece of meat. Most studies clearly proved that irradiated meat did not show any worse organoleptic properties than non-irradiated meat. On the contrary, on several occasions, panelists claimed that irradiation had a beneficial effect on organoleptic properties. Furthermore, irradiation of meat, pork, and processed meat and game, either on its own or in combination with other techniques (additives, essential oils, spices, and packaging under vacuum or modified atmosphere packaging within the frame of hurdle technology), proved to be very effective in decreasing the microflora and, in particular, the pathogenic microorganisms. This result, in conjunction with no alteration of most physical properties of meat (following its irradiation), has encouraged the further usage of irradiation.

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Irradiation of Poultry and Eggs

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7.1 Introduction

7.1.1 Poultry

Food irradiation has been shown to eliminate pathogenic and spoilage microorganisms, providing a safer, longer lasting food supply for human consumption (Bruhn, 1995; Monk, et al., 1995; Murano, 1995). It is one of the best emerging technologies to ensure the microbiological safety of meat (Kanatt et al., 2006). A number of investigators have shown that irradiation is effective in eliminating foodborne pathogens associated with poultry, such as *Salmonella typhimurium*, *Campylobacter jejuni*, and *Listeria monocytogenes* (Yoon, 2003). There is also abundant literature on the effects of ionizing radiation on the sensory characteristics of poultry meat (Gomes et al., 2003).

7.1.2 Eggs

Eggs are one of the most complete nutritional protein foods. Based on the amino acid profile, egg products are an excellent source of essential amino acids, including sulfur amino acids (Schmidt et al., 2007). Therefore, it is necessary to develop and implement methodologies that can guarantee a safe product with preservation of the main properties. Microbial contamination of eggs is a well-established phenomenon and has important economic implications to the poultry industry (Bruce and Drysdal, 1994; Wong and Kitts, 2003). The number of food poisoning outbreaks in which different *Salmonella* serovars have been involved has increased in industrialized countries (Tood, 1996). Eggs and egg products have been the foods most frequently involved (Anonymous, 2002). Eggs are responsible for 230,000 cases of foodborne illnesses annually (Bufano, 2000). The most common procedure for inactivation of microorganisms is thermal destruction, although other energy transfers such as ionizing radiation is an attractive alternative to heat pasteurization for egg products (Pinto et al., 2004). The egg industry's primary intervention to improve the microbiological safety of liquid eggs is thermal treatment. Liquid whole egg (LWE) heat

pasteurization treatments must provide a 5- to 12-log reduction in the populations of the most frequently isolated *Salmonella* serovars, such as *S. Enteritidis* and *S. Typhimurium*, but would attain less than a 4-log reduction in the population of heat-resistant *Salmonella* strains such as *S. senftenberg* 775W (Manas et al., 2003). Ionizing radiation is a safe and effective technology that can be used to inactivate foodborne pathogens such as *Salmonella* and lower the incidence of foodborne illness in at-risk populations without increasing the temperature of the irradiated medium (Radomyski et al., 1994). Furthermore, a few studies have examined the combination of irradiation with other methods such as heat following irradiation treatments (Alvarez et al., 2006) and γ -radiation combined with cold storage (Badr, 2006).

This chapter provides a detailed review of the available data regarding the irradiation effects on poultry, eggs, and egg products.

7.2 Turkey Meat

7.2.1 Effect of Irradiation on Quality, Sensory Characteristics, and Microflora of Turkey Meat

Mayer-Miebach et al. (2005) applied an irradiation dose of 1 kGy [electron (e-) beam] to the nonpathogenic strain of *Escherichia coli*, DSM 498, grown and irradiated in nutrient broth. They showed that reductions of three or four decimal units were achieved ($D_{10} = 0.27$ kGy). If grown on minced turkey meat, however, reduction rates were lower ($D_{10} = 0.47$ kGy). Even lower reduction rates were obtained during irradiation of frozen meat ($D_{10} = 0.72$ kGy) compared to treatments at cooling temperatures ($D_{10} = 0.48$ kGy). These results emphasize the necessity to determine inactivation kinetics in food matrices of target extrinsic factors (e.g., temperature).

Nanke et al. (1998) found that irradiated (1.5, 3.0, 4.5, 7.5, and 10.5 kGy, e-beam irradiation) turkey packaged in a 2S polyfoam tray overwrapped with fresh meat film and stored at $0 \pm 2^{\circ}\text{C}$ became redder due to irradiation. The extent of color change was irradiation dose dependent and was not related to myoglobin concentration.

Zhu et al. (2004) prepared turkey breast rolls with six antimicrobial additive treatments: no preservatives (control); 0.1% potassium benzoate (PB); 2% sodium lactate (SL); 0.1% potassium benzoate plus 2% sodium lactate (PB + SL); 2% sodium lactate plus 0.1% sodium diacetate (SL + SDA); and 0.1% potassium benzoate, 2% sodium lactate, and 0.1% sodium diacetate (PB + SL + SDA). The samples were irradiated at 0, 1.0, or 2.0 kGy. Adding 2% SL increased the hardness, springiness, cohesiveness, chewiness, and resilience of breast rolls. The addition of PB or SDA and irradiation had no significant effect on texture. Adding 2% SL affected color values. The color a^* and b^* values of turkey rolls with 2% SL added were significantly lower than those of the control, and this difference

was maintained after irradiation and during storage. No difference in color and texture was observed between turkey rolls with SL added and those with SL + PB + SDA added.

Zhu et al. (2005) combined antimicrobial ingredients (2% SL, 0.1% SDA, and 0.1% PB) and low-dose irradiation and studied the effects on the growth of *L. monocytogenes* and turkey ham. The log₁₀ reductions of *L. monocytogenes* in hams following exposure to 1.0–2.5 kGy of irradiation ranged from 2.0 to 5.0. The *D*₁₀ values were 0.52 kGy for control ham or ham with PB, SL, or PB + SL; 0.49 kGy for ham with SL+SDA; and 0.48 kGy for ham with PB + SL + SDA (PSS). Addition of SL + SDA or PB + SL in combination with 1.0 kGy of irradiation was effective in suppressing the growth of *L. monocytogenes* for approximately 6 weeks when stored at 4°C, whereas 2.0 kGy of irradiation was listeristatic. Ham irradiated with 1 kGy in combination with PSS was listeristatic throughout storage. SL increased firmness of turkey hams, and sensory panelists noted that the saltiness was slightly higher in products containing SL, but its overall impact on quality was minimal. Amounts of benzene were detected in irradiated hams with PB, showing that PB was not fit as an antimicrobial ingredient for irradiated foods.

In a study by Fan et al. (1996), turkey bologna was prepared from ground turkey emulsions with or without rosemary extraction at a final concentration of 0.075%. After cooking, bologna was sliced, sealed in gas-impermeable bags, exposed to 0, 1.5, and 3.0 kGy γ -rays, and then stored at 5°C for up to 8 weeks. In a second experiment, the authors reported that slices of turkey bologna were dipped in water or 0.75% of rosemary extract for 2 min followed by irradiation at 3.0 kGy. Results showed that rosemary extract applied in formulation inhibited lipid oxidation in both irradiated and non-irradiated samples. Irradiation increased redness and lightness and reduced yellowness of samples. Rosemary extract inhibited the irradiation-induced color changes. Irradiation induced production of volatile sulfur compounds, such as methanethiol and dimethyl disulfide. Rosemary extract applied either in formulation or as a dip, however, did not significantly reduce the formation of the volatile sulfur compounds (Fan et al., 2006).

Nam and Ahn (2002a) studied turkey breast muscles aerobically or VP and irradiated at 0, 2.5, or 5.0 kGy using a linear accelerator (e-beam) and stored at 4°C. Irradiation increased the *a* value of both aerobically and VP turkey breast, but VP meat had stronger intensity than the aerobically packaged meat. The increased redness in VP meat was stable during the 2 weeks of storage. The production of CO in meat, which can bind to myoglobin as a sixth ligand, was proportional to irradiation dose. The oxidation–reduction potential was decreased by irradiation but was increased during storage. Lipid oxidation values were lower in VP than those in aerobically packaged turkey breast.

The effect of irradiation and packaging conditions on the content of cholesterol oxidation products (COPs) and lipid oxidation in cooked turkey was studied by Ahn et al. (2001). Ground turkey leg was cooked, packaged either in oxygen-permeable or in oxygen-impermeable bags, and

irradiated at 0 or 4.5 kGy. Lipid oxidation and COPs were determined after 0 and 7 days of storage at 4°C. Packaging of cooked meat was more important than irradiation in developing COPs and lipid oxidation in cooked meats during storage. Irradiation had no significant effect on the amounts of any of the COPs found in cooked turkey, but it increased the amounts of α - plus 7 β -hydroxycholesterol, β -epoxide, 7-ketocholesterol, and total COPs in aerobically packaged cooked pork.

Lee and Ahn (2005) studied the effects of adding 1, 2, and 3% plum extract on VP, irradiated turkey breast rolls. Turkey breast rolls were sliced, packaged, and irradiated at 0 or 3 kGy using a linear accelerator and stored at 4°C. Addition of plum extract had no detectable effect on the proximate analysis of turkey breast rolls. Plum extract increased a^* and b^* values and decreased the L^* value of turkey breast rolls due to the original color of plum extract. Addition of more than 2% plum extract to turkey breast rolls was effective in controlling lipid oxidation of irradiated meat and the production of aldehydes (hexanal, heptanal, octanal, and nonanal) in non-irradiated meat at day 0. The texture of turkey breast rolls was not influenced, whereas juiciness increased by plum extract.

Fresh skinless turkey breasts packaged in air or nitrogen gas were either irradiated (2.4–2.9 kGy) or not and stored at 2°C. Samples of raw and cooked turkey were evaluated by a descriptive panel at 2, 5, 8, 19, and 22 days of storage. Half of each cooked sample was sealed in a polyethylene bag, stored for an additional 3 days, and then evaluated. Irradiation affected color, odor, and flavor. Irradiated samples had more intense pink color and acid/irradiation odor. Irradiated cooked turkey had less turkey flavor, but higher metallic flavor, than non-irradiated turkey. After the additional 3 days of storage at 2°C, cooked samples originally packaged in air had a stale flavor of low intensity that was absent in originally nitrogen-packaged samples (Bagorogoza et al., 2001).

Sammel and Claus (2006) determined the impact of citric acid (0.15, 0.3%) and sodium citrate (0.5, 1.0%) on pink color development in ground turkey following irradiation (0, 2.5, and 5.0 kGy). Citric acid and sodium citrate had little effect on pink color when samples were irradiated prior to cooking. On the other hand, when samples were cooked prior to irradiation, citric acid (0.3%) and sodium citrate (1.0%) reduced redness as indicated by eliminating a reflectance minimum at approximately 571 nm, lessening greater reflectance in the red wavelength region, and preventing greater reducing conditions caused by irradiation. Citric acid significantly reduced pH and yields, whereas sodium citrate reduced pH and yields to a lesser extent.

Nam and Ahn (2003) studied the effects of the combination of aerobic and anaerobic packaging on irradiated raw turkey meat. Irradiating (3 kGy) and storing turkey breast meat for 1–3 days under aerobic conditions and then storing under vacuum conditions (A1/V9 or A3/V7 double packaging) could minimize irradiation off-odor by volatilizing S-volatile compounds. Vacuum packaging was required to minimize lipid oxidation during the

remaining storage period. The authors stated that this double packaging can be an efficient way to minimize the quality changes in poultry breast meat caused by irradiation without adding any additives. Moreover, the effects of double packaging (combinational use of vacuum and aerobic packaging conditions) and acid (citric or ascorbic acid) combinations on color, lipid oxidation, and volatiles of irradiated (0–1.5 kGy) raw turkey breast at 4°C for 10 days were also determined by [Nam and Ahn \(2002b\)](#). Acid did not affect the *a* values but increased the *L* values of meat after irradiation. Citric acid promoted lipid oxidation of irradiated turkey meat, whereas ascorbic acid had an antioxidant effect. The amounts of total volatile and dimethyl sulfide in doubly packaged turkey meat were 35–56% and 58–73% lower than those of the irradiated vacuum-packaged control, respectively, and dimethyl disulfide and dimethyl trisulfide were not found in double-packaged meat.

The effect of irradiation on thiobarbituric acid reactive substances (TBARS) of turkey breast rolls and raw turkey patties at different packages is shown in [Figure 7.1](#).

The effect of e-beam irradiation on the quality of ready-to-eat (RTE) turkey ham was studied by [Zhu et al. \(2003\)](#). Turkey hams were sliced into 0.5-cm-thick pieces and VP. The ham samples were randomly separated into three groups and irradiated at 0, 1, or 2 kGy, and they were stored at 4°C for up to 14 days. Volatiles, color, TBARS values, and sensory characteristics were determined to compare the effect of irradiation and storage on the quality of RTE turkey ham. Irradiation had little effect on color and TBARS values of RTE turkey hams. According to the sensory panel, odor or flavor associated with irradiation off-odor/flavor were metal-like, oxidized, sulfur, and sweet. The sensory attribute most strongly correlated with irradiation was sulfur odor/flavor, and when ham was irradiated at 2 kGy this was more intense than in non-irradiated control, but it was not different than that irradiated at 1 kGy. However, the overall quality changes in RTE turkey hams by

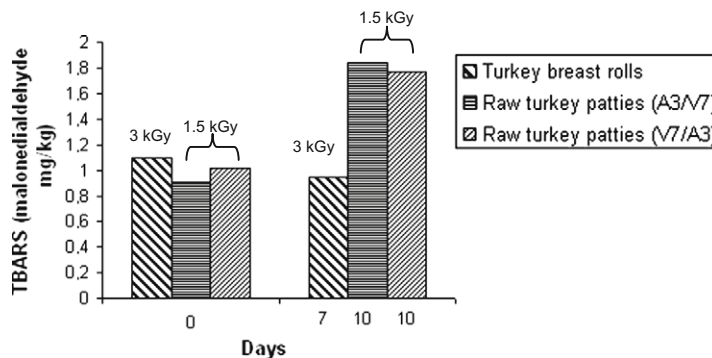


Figure 7.1: Effect of irradiation on TBARS of turkey breast rolls ([Lee and Ahn, 2005](#)) and raw turkey patties ([Nam and Ahn, 2002](#)). A3/V7, aerobically packaged for 3 days and then VP for 7 days; V7/A3, VP for 7 days and then aerobically packaged for 3 days.

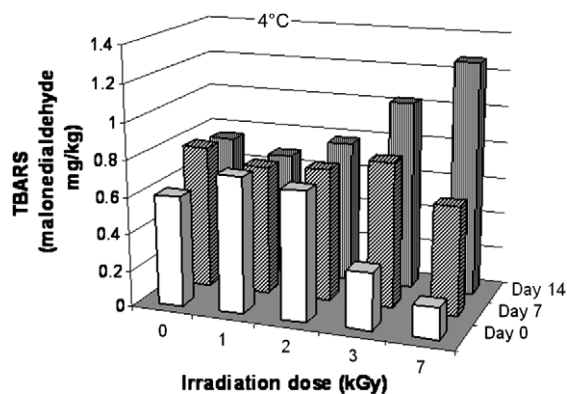


Figure 7.2: Effect of irradiation on TBARS of Cornish game hen and turkey ham. Irradiation with 0 kGy, turkey ham (Zhu et al., 2003); irradiation with 1 kGy, turkey ham (Zhu et al., 2003); irradiation with 2 kGy, turkey ham (Zhu et al., 2003); irradiation with 3 kGy, Cornish game hen (Gomes et al., 2006); and irradiation with 7 kGy, Cornish game hen (Gomes et al., 2006).

irradiation up to 2 kGy were minor. Figure 7.2 displays the impact of irradiation on TBARS of Cornish game hen and turkey ham.

The effect of irradiation (0 and 5 kGy) of turkey breast and leg muscles and subsequent storage at 4°C was studied in relation to color changes by Millar et al. (2000). L^* values of control and irradiated turkey breast muscles changed little during storage post-irradiation. The b^* values for irradiated turkey breast were significantly higher than those for non-irradiated turkey breast at all times post-irradiation treatment. The a^* values of leg of turkey at 7-day post-irradiation were significantly higher in the irradiated treatment than in the controls. The results for the turkey leg indicate that this effect may be mainly due to higher a^* values of the freshly cut surface.

The effect of irradiation on quality, sensory characteristics, and microflora of turkey meat is summarized in Table 7.1.

7.3 Chicken Meat

7.3.1 Effect of Irradiation on the Quality and Microflora of Chicken Meat

Hanis et al. (1989) studied chilled (10°C) and frozen (−15°C) broiler carcasses initially artificially contaminated with *Pseudomonas aeruginosa*, *Salmonella typhimurium*, or *Serratia marcescens* [10^6 colony forming units (CFU)/g] and then irradiated (^{60}Co) with doses of 0.5, 1.0, 2.5, 5.0, and 10.0 kGy. *Ps. aeruginosa* was eliminated by doses of 1–2.5 kGy, *Serratia marcescens* by doses of 2.5–5.0 kGy, and *S. typhimurium* by a dose of 10 kGy. Furthermore, irradiation resulted in increases in acid and peroxide values and

TABLE 7.1 Effect of Irradiation on Quality, Sensory Characteristics, and Microflora of Turkey Meat

| Food Type | Irradiation Type/Dose | Other Technology | Temperature | Effect on Sensory Quality | Effect on Quality | Reference |
|---------------------|-----------------------|--|-------------|---------------------------|---|------------------|
| Turkey breast rolls | 0, 1, or 2 kGy e beam | Sodium lactate (SL) | — | — | Addition of 2% SL increased the hardness, springiness, cohesiveness, chewiness, and resilience. | Zhu et al., 2004 |
| Turkey breast rolls | 0, 1, or 2 kGy e beam | Potassium benzoate plus sodium lactate (PB + SL) | — | — | Addition of PB or SDA and irradiation had no significant effect on texture | |
| Turkey breast rolls | 0, 1, or 2 kGy e beam | Sodium lactate plus sodium diacetate (SL + SDA) | — | — | The color a^* and b^* values of turkey rolls with 2% SL added were significantly lower than those of the control, and this difference was maintained after irradiation and during storage | |
| Turkey breast rolls | 0, 1, or 2 kGy e beam | Potassium benzoate, sodium lactate, and sodium diacetate (PB + SL + SDA) | — | — | No difference in color and texture between turkey rolls added with SL and those added with SL + PB + SDA | |

(Continued)

TABLE 7.1 Effect of Irradiation on Quality, Sensory Characteristics, and Microflora of Turkey Meat—cont'd

| Food Type | Irradiation Type/Dose | Other Technology | Temperature | Effect on Sensory Quality | Effect on Quality | Reference |
|--------------------------|--------------------------|--|-----------------------|---|---|------------------|
| Turkey ham | 1 2.5 kGy | — | 4°C | | The log ₁₀ reductions of <i>L. monocytogenes</i> in hams following exposure to 1.0 2.5 kGy of irradiation ranged from 2.0 to 5.0 | Zhu et al., 2005 |
| Turkey ham | 1 kGy | 2% SL and 0.1% SDA and 0.1% PB | 4°C | SL increased firmness of turkey hams, and sensory panelists noted that the saltiness was slightly higher in products containing SL, but its overall impact on quality was minimal. Amounts of benzene were detected in irradiated hams with PB, showing that PB was not fit as an antimicrobial ingredient for irradiated foods | Listeristatic effect | |
| Turkey ham | 1 kGy | 2% SL and 0.1% SDA | 4°C | | Suppressing the growth of <i>L. monocytogenes</i> for approximately 6 weeks. | |
| Turkey ham | 1 kGy | 2% SL and 0.1% PB | 4°C | | Suppressing the growth of <i>L. monocytogenes</i> for approximately 6 weeks | |
| Slices of turkey bologna | 3.0 kGy γ irradiation | Dipping in water or 0.75% of rosemary extract for 2 min and sealed in gas impermeable bags | 5°C for up to 8 weeks | Irradiation increased redness and lightness and reduced yellowness of samples. Rosemary extract inhibited the irradiation induced color changes | Rosemary extract did not significantly reduce the formation of the volatile sulfur compounds produced by irradiation | Fan et al., 2006 |

| | | | | | | |
|-------------------------|--|---|-----|---|---|-------------------------|
| Turkey breast muscles | 0, 2.5, or 5.0 kGy using a linear accelerator (e beam) | Aerobically or VP | 4°C | Irradiation increased the <i>a</i> value of both aerobically and VP turkey breast, but vacuum packaged meat had stronger intensity than the aerobically packaged meat | The oxidation reduction potential was decreased by irradiation but was increased during storage. Lipid oxidation values were lower in VP than those in aerobically packaged turkey breast | Nam and Ahn, 2002a |
| Skinless turkey breasts | 2.4 2.9 kGy e beam irradiation | Packaged in air or nitrogen | 2°C | Irradiation affected color, odor, and flavor. Irradiated samples had a more intense pink color and acid/irradiation odor. Irradiated cooked turkey had less turkey flavor, but higher metallic flavor, than non irradiated turkey | — | Bagorogoza et al., 2001 |
| Ground turkey | 0, 2.5, 5.0 kGy e beam irradiation | Citric acid (0.15, 0.3%) and sodium citrate (0.5, 1.0%) | — | Little effect on pink color when samples were irradiated prior to cooking. | — | Sammel and Claus, 2006 |
| Ground turkey | 0, 2.5, 5.0 kGy e beam irradiation | Citric acid (0.15, 0.3%) and sodium citrate (0.5, 1.0%) | — | When samples were cooked prior to irradiation, citric acid (0.3%) and sodium citrate (1.0%) reduced redness | — | |

(Continued)

TABLE 7.1 Effect of Irradiation on Quality, Sensory Characteristics, and Microflora of Turkey Meat—cont'd

| Food Type | Irradiation Type/Dose | Other Technology | Temperature | Effect on Sensory Quality | Effect on Quality | Reference |
|-------------------------|---|---|-----------------------|--|---|--------------------|
| Raw turkey meat | 3 kGy using a linear accelerator | Combination of aerobic and anaerobic packaging | — | Minimize irradiation off odor by volatilizing 5 volatile compounds | VP minimized lipid oxidation during the remaining storage period | Nam and Ahn, 2003 |
| Ready to eat turkey ham | 0, 1, or 2 kGy e beam irradiation | VP | 4°C for up to 14 days | Irradiation had little effect on color. The sensory attribute most strongly correlated with irradiation was sulfur odor/flavor, and when ham was irradiated at 2 kGy it was more intense than non irradiated control but not different from that irradiated at 1 kGy | Irradiation had little effect on TBARS values. The amount of dimethyl disulfide was significantly higher in irradiated ham than in non irradiation samples; furthermore, dimethyl disulfide was also greater for 2 kGy than for 1 kGy | Zhu et al., 2003 |
| Turkey | 1.5, 3.0, 4.5, 7.5, and 10.5 kGy e beam irradiation | Packaged in a 2S polyfoam tray overwrapped with fresh meat film | 0 ± 2°C | Irradiated turkey became redder due to irradiation. The extent of color change was irradiation dose dependent and was not related to myoglobin concentration | — | Nanke et al., 1998 |

| | | | | | | |
|-------------------------------|----------------------------------|---|-----|---|---|----------------------------|
| Nutrient broth | 1 kGy e beam | — | — | — | <i>E. coli</i> , DSM 498, reductions of three or four decimal units were achieved ($D_{10} = 0.27$ kGy). | Mayer Miebach et al., 2005 |
| Minced turkey meat | 1 kGy e beam | — | — | — | Reduction rates were lower than <i>E. coli</i> , DSM 498, grown and irradiated in nutrient broth ($D_{10} = 0.47$ kGy) | |
| Turkey breast and leg muscles | 0 and 5 kGy γ irradiation | — | 4°C | — | L^* values of control and irradiated turkey breast muscles changed little during storage post irradiation. The b^* values for irradiated turkey breast were significantly higher than those for non irradiated turkey breast at all times post irradiation treatment. The a^* values of leg of turkey at 7 days post irradiation were significantly higher in the irradiated treatment than in the controls | Millar et al., 2000 |

destruction of thiamine (up to 57%/10 kGy) and riboflavin (up to 27%/10 kGy); a lower increase in fat indices and lower destruction of vitamins were observed at lower irradiation temperature. Content of amino acids was not affected by the treatment.

Gursel and Gurakan (1997) determined γ -irradiation sensitivity of a strain of *L. monocytogenes* in trypticase soy broth supplemented with yeast extract (TSB-YE) and in a slurry of chicken breast meat. D_{10} values in these different media were 0.364 and 0.599 kGy, respectively. This organism appeared most sensitive in TSB-YE and more resistant in minced fresh chicken breast meat. It was found that irradiation at 2.5 kGy prior to refrigeration is an efficient way to preserve meat products contaminated at 10^3 to 10^4 per gram initial load of *L. monocytogenes* for approximately 7 days.

Patterson (1995) tested the sensitivity of *C. jejuni* (three strains), *C. coli* (three strains), *C. fetus* (one strain), and *C. lari* (one strain) to irradiation in poultry meat. There was no significant difference in the counts obtained on blood or Skirrow agar. Preston agar gave a significantly lower recovery of the pathogens after irradiation, so these results were not included in calculations of D_{10} values. The D_{10} values ranged from 0.12 to 0.25 kGy, and there was a significant difference in the radiation sensitivity between different *Campylobacter* spp. and within strains of the same species. These values indicate that *Campylobacter* spp. are more radiation sensitive than *Salmonella* and *L. monocytogenes* irradiated under similar conditions. Therefore, irradiation treatments suggested that to eliminate the latter from poultry carcasses would also be sufficient to remove *Campylobacter*.

Franqueira De Toledo et al. (2005) compared the sensory aspects of non-irradiated chicken (control) and chicken irradiated with ^{60}Co at 2, 4, 6, and 8 kGy doses, both fresh and frozen at 18°C for 90 days. Eight trained panelists provided descriptive analysis of eight attributes of appearance (color, brightness, humidity, shredded, appetizing, fresh, dark spots, and characteristic), four attributes of aroma (characteristic, strange, intensity, and oily), seven attributes of flavor (typical, bitter, salty, metallic, intensity, smoked, and strange), and six attributes of texture (tenderness, fibrosity, uniformity, elasticity, juiciness, and humidity). The fresh meat presented differences regarding appearance, flavor, and texture, and the frozen-stored one presented differences regarding appearance, aroma, and flavor. One can conclude that the irradiation treatment promoted alterations in the sensory quality of the chicken breast with the doses used in this study, with the 8-kGy dose differentiated the most from the control. The alterations were positive in some cases, especially when after-frozen meat was considered.

Gomes et al. (2003) experimented with samples of mechanically deboned chicken meat (MDCM) that were irradiated in the frozen form with doses of 0, 3, and 4 kGy and stored at $2 \pm 1^\circ\text{C}$ for up to 12 days. Results obtained for psychrotrophic bacterial counts showed higher counts for non-irradiated MDCM throughout refrigeration than for irradiated (3 and

4 kGy) samples. Samples irradiated with doses of 0, 3, and 4 kGy were acceptable under refrigerated storage for 4, 10, and 6 days, respectively.

A comparison of the effect of irradiation with X-rays and e-beams on the microbiological quality of minced chicken breast meat was evaluated by Van Calenberg et al. (1999). An analysis of variance showed that there was a significant dose effect but not of dose rate. Fecal coliforms were less resistant to irradiation than other coliform species. There was a significant effect of radiation dose on all tested microorganisms. All bacteria (fecal coliforms, *Staphylococcus* spp., and *Pseudomonas* spp.) except for total coliforms were reduced to levels below the detection limit of the methods after irradiation with a dose of 1.5 kGy. Significant differences between the two irradiation techniques were not observed.

Yoon (2003) reported that irradiated (minimum and maximum doses observed were 2.2 and 2.9 kGy, respectively) chicken breasts had more cooking loss than non-irradiated samples throughout a 14-day storage period (4°C); statistically significant differences between non-irradiated and irradiated chicken breasts were only observed in the sample tested at day 12. Shear force values of irradiated chicken breasts were significantly higher than those of control, resulting in firmer texture throughout the post-irradiation storage period of 14 days. Mean value of shear force of irradiated chicken breasts during 14 days of refrigerated storage was significantly higher than those of the non-irradiated samples.

Irradiation (1, 2, or 3 kGy) significantly improved the microbiological quality of the chicken chilly by reducing the total bacterial count (TBC). Moreover, the decrease in TBC was dose dependent. The numbers increased with storage time (at 0–3°C), and there was a significant difference between the irradiation doses. In less than 14 days, non-irradiated chicken chilly had counts greater than 6 log CFU/g, whereas in irradiated chicken (3 kGy) this number was not reached even after 28 days. In chicken chilly, non-irradiated control samples had initial *Staphylococcus* spp. counts of 2.32 log CFU/g, which increased to 5.12 log CFU/g by 21 days. In all irradiated chicken chilly samples, *Staphylococcus* spp. were not detected throughout the storage period. Fecal coliforms were detected in only one batch of non-irradiated control chicken chilly samples. In all the irradiated samples, fecal coliforms were not detected (Kanatt et al., 2005).

Figure 7.3 displays the effect of irradiation (3 kGy) on TBARS values on turkey ham and chicken chilly. The impact of irradiation on the quality and microflora of chicken meat is summarized in Table 7.2.

7.3.2 Effect of Irradiation on the Sensory Quality of Chicken Meat

Lewis et al. (2002) studied e-beam irradiated (1.0 and 1.8 kGy) boneless, skinless chicken breasts. Consumer taste panels (product stored for 0, 14, and 28 days at 0°C) indicated that at day 0, there were no differences among controls and treatment groups for any of the

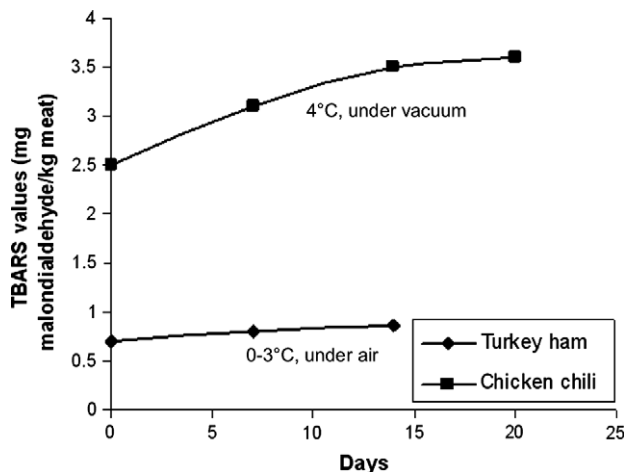


Figure 7.3: Effect of irradiation (3 kGy) on TBARS values on turkey ham (Zhu et al., 2003) and chicken chili (Kanatt et al., 2005) during storage.

quality attributes tested. At day 14, texture and flavor attributes were lower for the irradiated groups. At day 28, samples irradiated with 1.0 and 1.8 kGy were less desirable, with decreased texture, flavor, and overall acceptability. Irradiated samples also had higher a^* values, indicating that they were pinker in color.

Heath et al. (1990) determined the effect of e-beam irradiation on chicken tissues. Broiler breasts and whole thighs were irradiated with an e-beam accelerator at levels to produce adsorbed doses of 1, 2, and 3 kGy on the surface of the sample. For cooked breast tissue, the shear values and moisture content were not affected by the absorbed radiation. Cooking losses of aged breast tissue were not affected by irradiation, but cooking losses were reduced in breast tissue that had not been aged. Irradiating uncooked thigh and uncooked breast samples produced a characteristic odor that remained after the thighs were cooked but was not detectable after the breast samples were cooked.

Liu et al. (2003) studied the color characteristics of chicken breasts as a function of irradiation dose (0.2, 0.5, 1, 2, 3, 4, and 5 kGy) and subsequent storage process at $4 \pm 2^\circ\text{C}$. Ratios of $R_1 = A_{485 \text{ nm}}/A_{560 \text{ nm}}$ and $R_2 = A_{635 \text{ nm}}/A_{560 \text{ nm}}$, which are related to absorbances of the visible bands at 485 nm (metmyoglobin), 560 nm (oxymyoglobin), and 635 nm (sulfmyoglobin), suggested that a relative amount of oxymyoglobin either increases as a result of irradiation or decreases with the storage process. The plot of R_1 and R_2 versus storage time showed that the increments of both R_1 and R_2 are dose dependent and that the relative amount of oxymyoglobin species in irradiated meats begins to decompose 7–12 days later than in raw meats. Moreover, they found that R_1 and R_2 values were correlated with color index E^* of chicken breasts.

TABLE 7.2 Effect of Irradiation on the Quality and Microflora of Chicken Meat

| Food Type | Irradiation Type/Dose | Temperature | Shelf Life | Effect on Quality | Effect on Microflora | Reference |
|------------------------------------|---|---------------------------|------------|---|--|--------------------|
| Broiler chicken | 0.5, 1.0, 2.5, 5.0, and 10.0 kGy γ irradiation | — | — | Irradiation resulted in a increase in acid and peroxide values and destruction of | <i>Ps. aeruginosa</i> was reduced by doses of 1 kGy | Hanis et al., 1989 |
| | 0.5, 1.0, 2.5, 5.0, and 10.0 kGy γ irradiation | — | — | thiamine (up to 57%/10 kGy) and riboflavin (up to 27%/10 kGy). A lower increase of fat indexes and lower destruction of vitamins were observed at lower irradiation temperature. Content of amino acids was not affected by the treatment | <i>S. typhimurium</i> was reduced by a dose of 10 kGy | |
| | 0.5, 1.0, 2.5, 5.0, and 10.0 kGy γ irradiation | — | — | | <i>S. marcescens</i> was reduced by doses of 2.5–5.0 kGy | |
| Boneless, skinless chicken breasts | 1.0 and 1.8 kGy e beam irradiated | — | — | The degree of lipid oxidation increased as storage time and level of irradiation increased | Populations of coliforms, generic <i>E. coli</i> , and psychrotrophs were not detected after the samples were irradiated with 1.0 or 1.8 kGy. Irradiation also rendered the fillets free of <i>Salmonella</i> and <i>Campylobacter</i> | Lewis et al., 2002 |
| Mechanically deboned chicken meat | 0 kGy | 2 ± 1°C for up to 12 days | 4 days | — | Psychrotrophic bacterial counts were higher for non irradiated samples throughout refrigeration than for irradiated samples | Gomes et al., 2003 |
| | 3 kGy | 2 ± 1°C for up to 12 days | 6 days | — | | |
| | 4 kGy γ irradiation | 2 ± 1°C for up to 12 days | 10 days | — | | |

(Continued)

TABLE 7.2 Effect of Irradiation on the Quality and Microflora of Chicken Meat—cont'd

| Food Type | Irradiation Type/Dose | Temperature | Shelf Life | Effect on Quality | Effect on Microflora | Reference |
|----------------------------|--|--------------------------------|------------|--|---|----------------------------|
| Minced chicken breast meat | 0 1.5 kGy X rays and e beams | 18°C until the day of analysis | — | — | Fecal coliforms were less resistant to irradiation than other coliform species. There was a significant effect of radiation dose on all tested microorganisms. All bacteria (fecal coliforms, <i>Staph. spp.</i> , and <i>Pseudomonas spp.</i>) except total coliforms were reduced to levels below the detection limit after irradiation with a dose of 1.5 kGy. Significant differences between the two irradiation techniques were not observed | Van Calenberg et al., 1999 |
| Chicken breasts | Minimum and maximum doses observed were 2.2 and 2.9 kGy γ irradiation | 4°C for 14 days | — | Shear force values of irradiated chicken breasts were significantly higher than control, resulting in firmer texture throughout the post irradiation storage period of 14 days. Mean value of shear force of irradiated chicken breasts during 14 days of refrigerated storage was significantly higher than those of the non irradiated samples | — | Yoon, 2003 |

Chicken chilly 1, 2, or 3 kGy 0 3°C — —

In chicken chilly, non irradiated control samples had initial *Staphylococcus* spp. counts of 2.32 log CFU/g, which increased to 5.12 log CFU/g by 21 days. In all irradiated chicken chilly samples. *Staphylococcus* spp. were not detected throughout the storage period. Fecal coliforms were detected in only one batch of non irradiated control chicken chilly samples. In all the irradiated samples, fecal coliforms were not detected. Reduction of TBC was in a dose dependent manner

Kanatt et al.,
2005

The results for MDCM showed that volatile compounds associated with irradiation odor were dissipated from irradiated MDCM samples during refrigerated storage. Irradiated samples with 3 and 4 kGy had more pronounced oxidation odor than non-irradiated samples and the oxidation odor values were in agreement with the TBARS values. Irradiated MDCM showed higher values for a^* (redness) than the non-irradiated samples beginning on the 4th day under refrigeration. In addition, the MDCM samples irradiated with doses of 0, 3, and 4 kGy were acceptable under refrigerated storage for 4, 10, and 6 days, respectively (Gomes et al., 2003).

The effect of irradiation on the sensory parameters of chicken is summarized in [Table 7.3](#).

7.3.3 Effect of Irradiation and Hurdle Technology on Chicken

[Rababah et al. \(2005\)](#) irradiated (3.0 kGy) fresh boneless and skinless chicken breast meat infused with plant extracts—green tea (GT) and commercial grape seed (GS) extracts alone or in combination—to evaluate their effectiveness on sensory properties of non-irradiated and irradiated chicken meats. The results showed that irradiation did not affect the sensory flavor attributes except that of brothy flavor, and irradiation increased texture attributes of hardness, cohesiveness, and hardness and cohesiveness of mass. Consumer results showed that GT and water control gave the best color, followed by the combination of GS and GT extracts and GS extract, and the panel indicated that irradiation decreased the tenderness of the samples. Instrumental measurements showed that irradiation increased maximum shear force, shear work, hardness, and chewiness of cooked meats, and addition of GT extract improved the color compared with the GS extract and the combination of raw and cooked meats. Extracts infused into chicken breasts increased lightness and decreased redness and hardness of the meat texture.

In a study by [Du et al. \(2001\)](#), chicken breast fillets were divided into three groups. One group was VP, cooked in a water bath (cooked-in-bag) at 82°C for 25 min, and then irradiated at 0 or 3 kGy with a linear accelerator (V-C-I). The other two groups were irradiated at 0 or 3 kGy in vacuum packaging (V-I-C) or aerobic packaging (A-I-C). After 3 days of storage at 4°C, the irradiated meats were cooked in a water bath (cooked-in-bag) at 82°C for 25 min. Meats were then repackaged under vacuum and stored at 4°C. Irradiation accelerated lipid oxidation of breast fillets. Three days of storage of raw meat in aerobic conditions after irradiation had only minor influences on lipid oxidation after cooking. However, irradiation had a significant effect on the volatile production in meat. Dimethyl disulfide, related to irradiation odor, was significantly higher in irradiated fillets than in non-irradiated fillets for V-C-I and V-I-C, whereas it was only slightly higher for A-I-C. These results showed that irradiating cooked meat induced slightly more changes in volatiles than irradiating raw meat and then cooking. The amount of dimethyl disulfide between irradiated and non-irradiated samples for A-I-C was not different because the dimethyl disulfide produced by irradiation disappeared during the 3 days in aerobic storage before cooking. The color a^* value of irradiated fillets was higher than that of non-irradiated fillets. Irradiation also

TABLE 7.3 Effect of Irradiation on the Sensory Quality of Chicken

| Food Type | Irradiation Type/Dose | Temperature | Shelf Life | Effect on Sensory Quality | Reference |
|------------------------------------|---|----------------------------|------------|---|-----------------------------------|
| Boneless, skinless chicken breasts | 1.0 and 1.8 kGy e beam irradiated | 0°C for 0, 14, and 28 days | — | At day 0, no differences among controls and treatment groups for any of the quality attributes tested. At day 14, texture and flavor attributes were lower for the irradiated groups. At day 28, samples irradiated with 1.0 and 1.8 kGy were less desirable, with decreased texture, flavor, and overall acceptability. Irradiated samples also had higher a^* values, indicating they were more pink in color | Lewis et al., 2002 |
| Chicken tissues | 1, 2, and 3 kGy e beam | | — | For cooked breast tissue, the shear values were not affected by the absorbed radiation. Irradiating uncooked thigh and uncooked breast samples produced a characteristic odor that remained after the thighs were cooked but was not detectable after the breast samples were cooked | Heath et al., 1990 |
| Chicken | 2, 4, 6, and 8 kGy γ irradiation | 18°C for 90 days | — | Irradiation treatment promoted alterations in the sensory quality of the chicken breast with the doses used in this study; the 8 kGy dose differed the most from the control. The alterations were positive in some cases, especially after frozen meat was considered | Franqueira De Toledo et al., 2005 |
| Chicken breasts | 0.2, 0.5, 1, 2, 3, 4, and 5 kGy | 4 ± 2°C | — | Ratios of $R_1 = A_{485 \text{ nm}}/A_{560 \text{ nm}}$ and $R_2 = A_{635 \text{ nm}}/A_{560 \text{ nm}}$, which are related to absorbances of the visible bands at 485 nm (metmyoglobin), 560 nm (oxymyoglobin), and 635 nm (sulfmyoglobin), suggested that the relative amount of oxymyoglobin either increases as a result of irradiation or decreases with the storage process. R_1 and R_2 values were correlated with color index E^* of chicken breasts | Liu et al., 2003 |
| Mechanically deboned chicken meat | 0 kGy | 2 ± 1°C for up to 12 days | 4 days | Irradiated samples with 3 and 4 kGy had more pronounced oxidation odor than non irradiated samples and were in agreement with the TBARS values. Irradiated MDCM showed higher values for a^* than the non irradiated samples from the fourth day under refrigeration | Gomes et al., 2003 |
| Mechanically deboned chicken meat | 3 kGy | 2 ± 1°C for up to 12 days | 6 days | | |
| Mechanically deboned chicken meat | 4 kGy γ irradiation | 2 ± 1°C for up to 12 days | 10 days | | |

induced color L^* and b^* value changes. After 3 days of aerobic storage after irradiation of raw meat, the influence of irradiation on color after cooking was reduced.

Thayer and Boyd (1991a) examined the response to γ -radiation (0–3.60 kGy) of *S. typhimurium* in sterile MDCM in the absence of competing microflora. Response was determined at temperatures of -20 to $+20^\circ\text{C}$ and when the MDCM was packaged in vacuum or in the presence of air. Predictive equations were developed from the analyses of variances of the resulting data. The accuracy of each predictive equation was tested by further studies of the effects of γ -radiation on *S. typhimurium* in the presence or absence of air at -20 , 0 , and $+20^\circ\text{C}$. All data were then analyzed to further refine the predictive equations. Both the original and the refined equations adequately predicted the response of *S. typhimurium* in MDCM to γ -radiation doses up to 3.60 kGy in the presence of air or *in vacuo*. Gamma irradiation was significantly more lethal for *S. typhimurium* in the presence of air and at higher temperatures. The final equations predict a reduction in the number of surviving *Salmonella* in MDCM irradiated to 1.50 kGy at -20°C of 2.53 log in air or 2.12 log if irradiated in vacuum. If the contaminated MDCM were to receive a dose of 3.0 kGy at -20°C in air, the number of *Salmonella* would decrease by 4.78 log, and if irradiated in vacuum the number would decrease by 4.29 log.

Thayer and Boyd (1991b) used response surface methodology to develop predictive equations for the response of *S. typhimurium* ATCC 14028 on the surface of chicken legs or within MDCM to the effects of γ -radiation doses of 0–3.6 kGy at temperatures of -20 to $+20^\circ\text{C}$ in air or vacuum. The response of *S. typhimurium* to γ -radiation was similar on both chicken legs and MDCM. The radiation was significantly more lethal to the bacterial cells at temperatures above freezing. The response surface equations developed from the studies predict that the number of viable cells per gram of MDCM or per square centimeter of the surface of chicken legs would be reduced approximately 2.8–5.1 log units at 0°C by radiation doses within the range of 1.5–3.0 kGy. The results of this study are similar to those obtained previously with sterile MDCM.

Rababah et al. (2006) studied the effect of irradiation on TBARS and volatile compounds in raw and cooked non-irradiated and irradiated chicken breast meat infused with green tea and grape seed. Chicken breast meat was vacuum infused with green tea extract (3000 ppm), grape seed extract (3000 ppm), or a combination (total of 6000 ppm), irradiated with an e-beam, and stored at 5°C for 12 days. The targeted irradiation dosage was 3.0 kGy, and the average absorbed dosage was 3.12 kGy. TBARS values ranged from 15.5 to 71.4 mg of malondialdehyde/kg for non-irradiated raw chicken and from 17.3 to 80.1 mg of malondialdehyde/kg for irradiated raw chicken. Values for cooked chicken ranged from 31.4 to 386.2 and 38.4 to 504.1 mg of malondialdehyde/kg for non-irradiated and irradiated chicken, respectively. Irradiation increased TBARS and hexanal values of controls and meat infused with plant extracts. Hexanal had the highest intensity of volatiles, followed by pentanal and other volatiles. Although irradiation increases lipid oxidation, infusion of chicken meat with plant extracts could reduce lipid oxidation caused by irradiation.

Sarjeant et al. (2005) studied the effect of energy e-beam irradiation on the survival of *Salmonella enterica* serovar Typhimurium and psychrotrophic bacteria on commercial chicken breast meat. Fresh chicken breast meat was inoculated with $8 \log_{10}$ CFU/ml *Salmonella*, packaged in Styrofoam trays and overwrapped with a polyvinyl chloride film, and subjected to 0, 1, 2, or 3 kGy of irradiation. The packaged samples were stored at 4°C and analyzed for *S. Typhimurium* and psychrotrophic organisms at 0, 2, 4, 6, 8, 10, 12, and 14 days of storage. The direct plating method revealed a 4-log reduction in *Salmonella* for chicken breasts inoculated and treated with 1, 2, or 3 kGy of irradiation. Psychrotrophic counts were conducted at 7°C for 10 days and 25°C for 5 days to determine the effect of incubation methods on the recovery of psychrotrophic organisms. The enrichment method resulted in the repair of injured *Salmonella* cells and an elevated *S. Typhimurium* count for all irradiation dosages compared with data reported for the direct plating method. In general, psychrotrophic counts increased as storage time increased. However, psychrotrophic counts decreased as the irradiation dosage increased.

Crawford et al. (1996) studied the combination of high pressure and irradiation in reducing microbial contaminants in chicken breasts. Irradiation at a medium dose (3.0 kGy) before and after pressurization at 6800 atm and 80°C for 1, 10, and 20 min revealed no significant differences in spore counts between samples that were pressurized and then irradiated or vice versa. Furthermore, the effect of high pressure in lowering the irradiation dose necessary to eliminate all spores was examined. The irradiation *D* value of *Clostridium sporogenes* spores was calculated to be 4.1 kGy. Samples were then irradiated at various doses followed by pressurization at 6800 atm at 80°C for 20 min. The irradiation *D* value was lowered to approximately 2 kGy, indicating that a combination of high hydrostatic pressure and irradiation can be used to produce chicken with an extended shelf life without the use of high irradiation doses.

Javanmard et al. (2006) investigated the effects of γ -irradiation and frozen storage as a combination process for the improvement of chicken meat shelf life. Broiler chickens were treated with 0, 0.75, 3, and 5 kGy γ -irradiation and held frozen for 9 months. The control and irradiated samples were stored at -18°C. The number of aerobic plate counts decreased with increasing irradiation dose and during storage. Mean bacterial loads and coliform counts were $5.0 \times 10^7 \pm 2.7 \times 10^7$ and $1.0 \times 10^7 \pm 7.8 \times 10^6$ CFU/g at 0 kGy irradiation dose (control), respectively. The combination of irradiation and frozen storage was more effective than either treatment alone at decreasing total and coliform counts. Irradiation reduced the bacterial population in a dose-dependent manner. Gamma irradiation of chicken meat at the doses previously mentioned had no significant effects on the initial sensory attributes of the raw meat samples. Panelists gave similar preference scores for both irradiated and non-irradiated samples, which indicated that all were highly acceptable as judged by appearance and odor.

The effect of different irradiation types and doses on the population of coliforms in chicken breast meat and chicken meat is shown in [Figure 7.4](#).

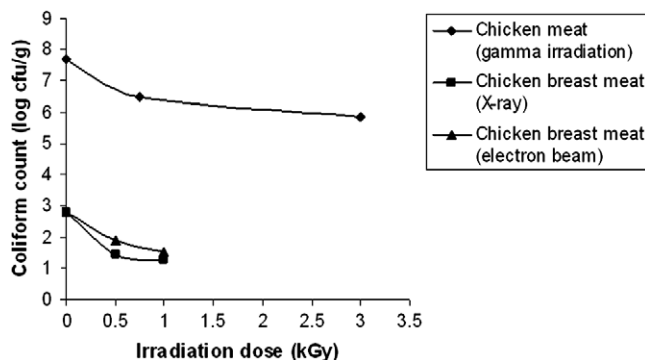


Figure 7.4: Effect of different irradiation types and doses on the population of coliforms in chicken breast meat (X-ray and electron beam) (Van Calenberg et al., 1999) and chicken meat (γ -irradiation) (Javanmard et al., 2006).

In a study by Du et al. (2002), raw breast fillets were divided into two groups and either vacuum or aerobically packaged. The fillets in each group were subdivided equally into two groups and then irradiated at 0 or 3 kGy using a linear accelerator. After 0, 3, and 7 days of storage at 4°C, fillets were cooked in an 85°C water bath (cook-in-bag) to an internal temperature of 74°C. Oxidation–reduction potential (ORP) of raw fillets was measured before cooking, and color and sensory characteristics were analyzed after cooking. Irradiation decreased the ORP of meat, but the potential in aerobically packaged fillets increased during storage. After cooking, color a^* value of irradiated fillets was higher than that of the non-irradiated. Irradiation of raw meat also changed color L^* and b^* values after cooking. Aerobic storage reduced the redness of cooked meat induced by irradiation. Irradiated raw broiler fillets stored for 0 and 3 days under aerobic conditions before cooking produced an oxidized chicken-like odor. However, the odor disappeared after 7 days of storage under aerobic conditions before cooking. For raw broiler samples stored under vacuum conditions, significant differences in color and odor between irradiated and non-irradiated fillets remained throughout the 7-day storage period after cooking. Finally, irradiation had only a minor influence on lipid oxidation of raw breast fillets, as indicated by low TBARS values.

Table 7.4 presents the effect of irradiation and hurdle technology on chicken quality parameters (physical and sensory).

7.4 Eggs

7.4.1 Effect of Irradiation on the Quality of Eggs

Meszaros et al. (2006) irradiated shell eggs with increasing radiation doses in the 0.5- to 3.0-kGy dose range. The flow behavior of irradiated fresh eggs differed from that of the

TABLE 7.4 Effect of Irradiation and Hurdle Technology on Chicken Quality Parameters (Physical and Sensory)

| Food Type | Irradiation Type/Dose | Other Technology | Temperature | Effect on Sensory Quality | Effect on Quality | Reference |
|---------------------|--|---|-----------------|---------------------------|--|-----------------------|
| Chicken breast meat | Targeted irradiation dosage was 3.0 kGy and the average absorbed dosage was 3.12 kGy, e beam irradiation | Vacuum infused with green tea extract (3000 ppm), grape seed extract (3000 ppm), or their combination (total of 6000 ppm) | 5°C for 12 days | — | Irradiation increased TBARS and hexanal values of controls and meat infused with plant extracts. Hexanal had the highest intensity of volatiles, followed by pentanal and other volatiles. Although irradiation increases lipid oxidation, infusion of chicken meat with plant extracts could reduce lipid oxidation caused by irradiation | Rababah et al., 2006 |
| Chicken breast meat | 0, 1, 2, or 3 kGy | Packaged in Styrofoam trays and overwrapped with a PVC film | 4°C | — | 4 log reduction (8 log initial population) in <i>Salmonella typhimurium</i> for chicken breasts inoculated and treated with 1, 2, or 3 kGy of irradiation | Sarjeant et al., 2005 |
| Chicken breasts | 3.0 kGy | Pressurization at 6800 atm and 80°C for 1, 10, and 20 min | — | — | No significant differences in spore counts between samples that were pressurized and then irradiated or vice versa. | Crawford et al., 1996 |
| | 4.1 kGy | Pressurization at 6800 atm and 80°C for 20 min | — | — | The irradiation <i>D</i> value of <i>C. sporogenes</i> spores was 4.1 kGy. Samples were then irradiated at various doses followed by pressurization. The irradiation <i>D</i> value was lowered to approximately 2 kGy | |

(Continued)

TABLE 7.4 Effect of Irradiation and Hurdle Technology on Chicken Quality Parameters (Physical and Sensory)—cont'd

| Food Type | Irradiation Type/Dose | Other Technology | Temperature | Effect on Sensory Quality | Effect on Quality | Reference |
|--------------------|---|---|-------------|--|--|------------------------|
| Broiler chicken | 0, 0.75, 3, and 5 kGy of γ irradiation | 18°C for 9 months | — | Panelists gave similar preference scores for both irradiated and non irradiated samples, which indicated that all were highly acceptable as judged by appearance and odor | The number of APC decreased with increase of irradiation dose and during storage time. Mean bacterial loads and coliform counts were $5.0 \times 10^7 \pm 2.7 \times 10^7$ and $1.0 \times 10^7 \pm 7.8 \times 10^6$ CFU/g at 0 kGy irradiation dose (control), respectively | Javanmard et al., 2006 |
| Raw breast fillets | 0 or 3 kGy γ beam | Packaged under vacuum or under air and then cooked in an 85°C water bath (cook in bag) (cooked after irradiation) | 4°C | After cooking, color a^* value of irradiated fillets was higher than that of the non irradiated. Irradiation of raw meat also changed color L^* and b^* values after cooking | Irradiation decreased the oxidation reduction potential of meat, but the potential in aerobically packaged fillets increased during storage. Irradiation had only a minor influence on lipid oxidation of raw breast fillets, as indicated by low TBARS values | Du et al., 2002 |

| | | | | |
|--|------------------------------|--|---|--|
| Boneless and skinless chicken breast meats | 3.0 kGy γ irradiation | — | — | <p>Irradiation did not affect the sensory flavor attributes except that of brothy flavor, and irradiation increased texture attributes of hardness, cohesiveness, and hardness and cohesiveness of mass.</p> <p>Extracts infused into chicken breasts increased lightness and decreased redness and hardness of the meat texture. Consumer search showed that GT and water control gave the best color, followed by the combination of GS and GT extracts and GS extract, and the panel indicated that irradiation decreased the tenderness of the samples</p> |
| | | Infused with green tea (GT), commercial grape seed (GS) extracts alone or in combination | — | |

Rababah et al., 2005

untreated ones after the 0.5-kGy dose. The egg white became progressively more runny and the thick part of the egg white became much thinner, similar to the effect of aging of eggs. The irradiated yolk ruptured more easily during the breaking procedure as the irradiation weakened the yolk membrane (0.5–3.0 kGy).

Katugin-Raiem et al. (1992) examined radiation-induced oxidative chemical changes in whole egg and egg yolk powder after irradiation as a function of dose, dose rate, and storage atmosphere. In evacuated samples of whole egg powder, the decay of lipid hydroperoxides (LOOH) was pseudo-first order ($k = 0.088/\text{day}$), whereas carotenoids did not decay at all. In the presence of air, both lipid hydroperoxides and carotenoids decayed during post-irradiation storage. The decay of LOOH could be treated by dispersive kinetics with the measure of dispersion, $a = 0.51 \pm 0.05$, independent of dose and the effective lifetime τ inversely related to dose. The decay of carotenoids could also be treated by dispersive kinetics, with the values of a decreasing with increasing dose. The effective lifetimes of carotenoids did not depend on dose in samples irradiated in vacuum.

According to Bakalivanov et al. (2008), during a 4-year period of storage at room temperature of the freeze-dried (control group) and the freeze-dried and γ -irradiated (2.0 and 3.5 kGy) whole hen's egg melange, no significant changes in the sensory and functional properties of the γ -treated samples (up to 3.5 kGy) were found in comparison with the control group until the 28th month. The protein spectra in all three groups consisted of 15 fractions, the most important of which were ovalbumin + β -livetin, conalbumin + α -livetin, and ovomucin and ovoglobulin. A slight reduction of their amounts occurred at the end of the storage, and in group 3, irradiated with 3.5 kGy it was clearly expressed—from 1.56 to 6.47%.

Narvaiz and co-workers (1992) examined the physicochemical characteristics of egg powder extracts irradiated with 0, 2, 5, and 10 kGy of γ -radiation for peroxide number, spectrophotometric measurements in the visible and ultraviolet regions, functional properties on sponge cakes made with egg powder (height and compression–relaxation cycle parameters), foam stability, and viscosity. It was found that γ -radiation at the dose of 2 kGy did not cause significant changes in these parameters. Higher radiation doses (5 and 10 kGy) did increase rancidity, pigment loss, and protein chain scission. The results of sensory evaluation performed on egg powder, and on cakes manufactured with it, were in agreement with the physicochemical results. After 110 storage days, 2 kGy was the most suitable of the tested doses.

A comparative study was undertaken by Wong et al. (1996) to determine the effect of irradiation and thermal pasteurization on the functional and physical properties of liquid egg white. The liquid egg white was irradiated or thermally pasteurized and then stored at 4°C for 3 months. Irradiated samples had 47% lower foam drainage and more stable viscosity than samples that were thermally pasteurized. Moreover, the color did not differ between treatments.

In a study by [Huang et al. \(1997\)](#), raw yolk of eggs (1 day old) was either subjected to linear e-beam irradiation at 2.5 kGy dosage or not processed. Both irradiated and non-irradiated egg yolk samples were stored at 15°C. Development of storage modulus (G') was delayed in irradiated samples after 7 days, which suggests that less structure was developed in irradiated egg yolk than in non-irradiated egg yolk during storage. Irradiated samples retained more soluble protein within the first 7 days and showed slightly improved emulsion capacity over that of non-irradiated samples. However, irradiated egg yolk was less bright than non-irradiated samples. Results indicated that e-beam irradiation did not cause significant physical, chemical, or functional changes of egg yolk or cleavage of egg yolk protein.

Frozen egg white and egg yolk were subjected to γ -irradiation at pasteurization dosages of 1–4 kGy. The apparent viscosity of frozen egg yolk significantly decreased by radiation treatment. Polyacrylamide gel electrophoretic patterns and differential scanning calorimetric profiles of the egg white proteins were not affected by irradiation. The functional properties (foaming, emulsifying, and gelling) of the egg products were generally not significantly affected by irradiation, or they were slightly decreased ([Ma et al., 1993](#)).

In a study by [Min et al. \(2005\)](#), shell eggs were irradiated and the physicochemical and functional properties of egg yolk and white were determined. The color of egg yolk was not affected, but the viscosity of egg white was dramatically lowered and became watery by irradiation. The foam capacity and foam stability of egg white were significantly decreased due to protein oxidation by irradiation. However, the texture characteristics of egg white were not changed by irradiation, indicating that irradiation may not alter the thermal characteristics of egg white proteins. Sulfur volatiles were generated by irradiation but disappeared during storage under aerobic conditions.

[Pinto et al. \(2004\)](#) studied the effect of irradiation (0.5 up to 5 kGy at a dose rate of 1.0 kGy/h) on some functional and nutritional egg properties. Analysis of asymptotic viscosimetry data suggests that irradiation of shell egg induced a slight increase in the viscosity of the yolks and a marked decrease in the viscosity of the whites. Irradiated white egg products also show a decrease in viscosity with increasing doses of irradiation. The results obtained from chromatography analysis demonstrate no differences in the phospholipids of pasteurized, irradiated, and non-irradiated yolk egg products, which suggests that phospholipids are not affected by irradiation. Irradiation of shell eggs seems to have no effect on the protein pattern of yolks, independent of the irradiation dose. With regard to the whites, there seems to be a slight degradation of the higher molecular-weight proteins with an irradiation dose of 5 kGy. However, no degradation of the major egg white protein (albumin), was reported.

[Badr \(2006\)](#) found that γ -irradiation at a dose of 3 kGy caused no significant changes in the levels of amino acids either for liquid egg white or for liquid egg yolk. Furthermore, irradiation of liquid egg yolk samples at 3 kGy showed no significant effects on the

fatty acid profiles of their lipids except for one of the unknown compounds, which significantly decreased.

According to Wong and Kitts (2003), e-beam irradiation (2, 3, and 4kGy) of shell eggs led to a loss of quality of egg albumen due to possible changes to the native structure of the protein, which in turn resulted in a reduced capacity to foam and gel. Yolk quality was minimally affected by irradiation, except for the loss of color and weakening of the vitelline membrane. Emulsifying capacity and gelling ability of irradiated egg yolk were also not affected, even though the emulsion stability was reduced with the use of irradiated egg yolk.

Dvorak et al. (2005) irradiated eggs using γ -rays at doses of 1, 2.5, and 5 kGy. The increase in the acidity number is statistically significant at doses of 2.5 and 5 kGy. The increased acidity number of the yolk may lead to a significant reduction of shelf life.

Al-Bachir and Zeinou (2006) investigated the impact of γ -irradiation on some characteristics of eggs. They found that there were no significant differences in saturated fatty acids (C14:0, C16:0, and C18:0) or in TBA values between the yolk lipid extracted from irradiated eggs and that of non-irradiated ones. Furthermore, all doses used (0.5, 1.0, 1.5, and 2 kGy) significantly reduced the viscosity of white eggs compared with the control.

7.4.2 Effect of Irradiation on the Sensory Properties of Eggs

Meszaros et al. (2006) irradiated shell eggs with doses between 0.5 and 3.0 kGy. Statistically significant differences (off-odor) of raw albumen were noted by a sensory panel at 1-kGy or higher doses. Results showed that the visual clarity of the egg white was decreased by irradiation even at the 0.5-kGy dose level, because the yolk membrane ruptured more frequently at breaking of the egg, and a part of yolk material diffused into the egg white in irradiated samples. Moreover, no significant differences in yolk odor were noted in the whole dose range; however, the rank scores showed an increasing tendency as the radiation dose increased. At 1-kGy or higher doses, the bright yolk color tended to be slightly faded, but the average ranks became statistically significantly higher than that of the control only at 3 kGy.

In a study by Pinto et al. (2004), a visual evaluation of yolks and whites of shell eggs and egg products showed that irradiation (0.5 kGy up to 5 kGy at a dose rate of 1.0 kGy/h) induced color changes: The yolk color die (pale yellow) and the white egg were modified to a turbid yellow. These alterations were dependent on the irradiation dose and were more significant for irradiation doses higher than 2 kGy.

Badr (2006) showed that irradiation treatments (0, 1, 2, 3, and 4 kGy) had no significant effects on the acceptability of appearance and color for liquid egg white and yolk as recorded by the panelists. Moreover, a slight loss in the visual yellowness was noticed upon irradiation with the highest dose, but the visual yellow color of the egg yolk was still highly acceptable by the panelists.

Tellez et al. (1995) irradiated inoculated fresh shell eggs (108 CFU of *S. enteritidis*) and found that irradiation at 1, 2, or 3 kGy resulted in a significant decrease (approximately 50%) in Haugh units. Furthermore, irradiation of intact shell eggs at 2 or 3 kGy significantly reduced yolk color regardless of the level of irradiation exposure implemented. The impact of irradiation on egg quality (shelf life and sensory properties) is given in Table 7.5.

7.4.3 Effect of Irradiation on the Microflora of Eggs

Alvarez et al. (2006) studied the effect of γ -radiation in combination with thermal treatment on the survival of *Salmonella* serovars. The radiation resistance (D_γ values) of the six investigated *Salmonella* serovars was determined. D_γ values of 0.60 ± 0.07 , 0.63 ± 0.12 , 0.49 ± 0.01 , 0.67 ± 0.08 , 0.65 ± 0.06 , and 0.44 ± 0.04 kGy were obtained for *Salmonella* Anatum, *Salmonella* Dublin, *Salmonella* Enteritidis, *Salmonella* Newport, *Salmonella* Senftenberg, and *Salmonella* Typhimurium, respectively. Most of the serovars investigated had similar radiation resistance. Significant differences were observed between D_γ values of *S. Enteritidis* and *S. Typhimurium* and the other *Salmonella* serovars tested. Irradiation followed by thermal treatment at 55 or 57°C improved the pasteurization process. Radiation doses as low as 0.1 kGy prior to thermal treatments synergistically reduced the $D_{55^\circ\text{C}}$ and $D_{57^\circ\text{C}}$ of *S. Senftenberg* 3.6- and 2.5-fold, respectively. The $D_{55^\circ\text{C}}$ and $D_{57^\circ\text{C}}$ of *S. Typhimurium* were reduced 2- and 1.4-fold, and those of *S. Enteritidis* were reduced 2- and 1.6-fold, respectively.

The effect of combining irradiation followed by heat (IR-H) on *S. Enteritidis* and *S. Senftenberg* inoculated into liquid whole egg with added nisin, EDTA, sorbic acid, carvacrol, or combinations of these generally recognized as safe (GRAS) additives was investigated by Alvarez et al. (2007a). Synergistic reductions of *Salmonella* populations were observed when liquid whole egg samples containing GRAS additives were treated by γ -radiation (0.3 and 1.0 kGy), heat (57 and 60°C), or IR-H. For both *Salmonella* serovars, the presence of additives reduced the initial radiation D_γ values (radiation doses required to eliminate 90% of the viable cells) by 1.2- to 1.5-fold, respectively; the thermal decimal reduction times (D_t values) by up to 3.5- and 1.8-fold at 57 and 60°C, respectively; and the thermal D_t values after irradiation treatments by up to 3.4- and 1.5-fold at 57 and 60°C, respectively.

Irradiation sensitivity of five *Salmonella enteritidis* isolates inoculated either on the surface or inside of whole shell eggs were determined by Serrano et al. (1997). The shell eggs were irradiated at doses of 0, 0.5, 1.0, and 1.5 kGy. A minimal dose of 0.5 kGy was sufficient to eliminate all the isolates from the surface of whole eggs; however, the same isolates were more resistant to irradiation when present inside the eggs. The ATCC 13076 isolate was significantly more sensitive to irradiation (D value of 0.32 kGy) than the other four isolates from animal origin. Irradiation D values of the latter ranged from 0.39 to 0.41 kGy. Furthermore, the results showed that the thermal characteristics of the whole or liquid eggs were unaffected by a 1.5-kGy dose of irradiation.

TABLE 7.5 Irradiation Effect on Egg Quality

| Product | Irradiation Dose/ Irradiation Type | Other Technology | Storage Period | Effect on Quality | Effect on Sensory Properties | Reference |
|--|--|------------------------------|---------------------------------------|---|--|--|
| Egg powder extracts | 0, 2, 5, and 10 kGy γ radiation | — | — | 2 kGy did not cause significant changes in peroxide number, spectrophotometric measurements in the visible and ultraviolet regions, functional properties on sponge cakes made with egg powder (height, compression relaxation cycle parameters), foam stability, and viscosity. Higher radiation doses increased rancidity, pigment loss, and protein chain scission | Sensory evaluation performed on egg powder, and on cakes manufactured with it, agreed with the physicochemical results | Narvaiz et al., 1992 |
| Whole hen's egg melange Whole hen's egg melange | — 2.0 and 3.5 kGy γ irradiation | Freeze dried Freeze dried | At room temperature for 4 years | No significant changes in the sensory and functional properties of the γ treated samples (up to 3.5 kGy) in comparison with the control group until the 28th month. The protein spectra in all three groups consisted of 15 fractions, the most considerable of which were ovalbumin + β livetin, conalbumin + α livetin, ovomucin, and ovoglobulin. Slight reduction in their amount occurred at the end of the storage 3 (irradiated with 3.5 kGy) it was better expressed and was from 1.56 to 6.47% | — | Bakalivanov et al., 2008 |
| Raw yolk Raw yolk | — 2.5 kGy e beam irradiation | — — | 15°C | Irradiated samples retained more soluble protein within the first 7 days and showed slightly improved emulsion capacity over that from non irradiated samples. Development of storage modulus (G') was delayed in irradiated samples after 7 days | Irradiated egg yolk was less bright than non irradiated samples | Huang et al., 1997 |

| | | | | | | |
|--------------------------------------|--|---|---|---|---|--------------------|
| Frozen egg white and egg yolk | 1-4 kGy γ irradiation | — | — | The apparent viscosity of frozen egg yolk was significantly decreased by radiation treatment. Foaming, emulsifying, and gelling of the egg products were generally not significantly affected by irradiation, or they were slightly decreased | — | Ma et al., 1993 |
| Shell egg, yolks, and whites | 0.5 kGy up to 5 kGy γ irradiation | — | — | Irradiation of shell egg induces a slight increase in the viscosity of the yolks and a marked decrease in the viscosity of the whites. Irradiation of shell eggs does not have an effect on the protein pattern of yolks, independent of the irradiation dose. Regarding the whites, there seems to be a slight degradation of the higher molecular weight proteins with an irradiation dose of 5 kGy | Irradiation induced color changes the yolk color (pale yellow) and the white egg was altered to a turbid yellow. The alterations were dose dependent and were more significant for an irradiation dose above 2 kGy | Pinto et al., 2007 |
| Liquid egg white and liquid egg yolk | 0, 1, 2, 3, and 4 kGy γ irradiation | — | — | 3 kGy dose caused no significant changes in the levels of amino acids neither for liquid egg white nor liquid egg yolk. Irradiation of liquid egg yolk samples at 3 kGy showed no significant effects on the fatty acid profiles of their lipids, except for one of the unknown compounds, which significantly decreased | Irradiation had no significant effects on the acceptability of appearance as recorded by the panelists. Moreover, a slight loss in the visual yellowness was noticed upon irradiation with the highest dose; the visual yellow color of the egg yolk was still highly acceptable by the panelists | Badr, 2006 |

(Continued)

TABLE 7.5 Irradiation Effect on Egg Quality—cont'd

| Product | Irradiation Dose/ Irradiation Type | Other Technology | Storage Period | Effect on Quality | Effect on Sensory Properties | Reference |
|---------------------|--|---------------------|----------------|---|--|----------------------------|
| Fresh shell eggs | 1, 2, or 3 kGy γ irradiation | — | — | An approximately 50% reduction in Haugh units | Irradiation of intact shell eggs at 2 or 3 kGy significantly reduced yolk color | Tellez et al., 1995 |
| Shell eggs | 2, 3, and 4 kGy e beam irradiation | — | — | Yolk quality was minimally affected by irradiation, except for the loss of color and weakening of the vitelline membrane. Emulsifying capacity and gelling ability of irradiated egg yolk were also not affected | — | Wong and Kitts, 2003 |
| Eggs | 1, 2.5, and 5 kGy γ irradiation | — | — | Increase in the acidity number at doses of 2.5 and 5 kGy | Parameters describing the color of egg yolk, such as L^* , a^* , and b^* , dropped upon ionizing radiation | Dvorak et al., 2005 |
| Eggs | 0.5, 1.0, 1.5, and 2 kGy γ irradiation | — | — | No significant differences in saturated fatty acids and thiobarbituric acid values between the yolk lipid extracted from irradiated eggs and that of non irradiated ones. Furthermore, all doses used reduced the viscosity of white eggs | — | Al Bachir and Zeinou, 2006 |

Kohler et al. (1989) investigated the effect of ^{60}Co γ -irradiation on the number of *S. tennessee* and *S. agona* in artificial contaminated spray-dried whole egg powder and liquid whole egg. Irradiation of liquid whole egg was carried out at deep frozen conditions. The irradiation doses used were between 0.05 and 8.0 kGy. Whole egg powder tolerates a maximal irradiation dose of 2.0 kGy without deterioration of sensorial food quality. Irradiation dose of 1.0 kGy eliminates approximately 100–1000 *Salmonella* bacteria per kilogram whole egg powder, if the egg powder is stored 3–5 weeks after irradiation.

Narvaiz et al. (1992) treated egg powder with 0, 2, 5, and 10 kGy of γ -radiation at 20°C to inactivate *Salmonella* and to stabilize its microbial load. Microbial analysis was performed during 4 months of storage to select the optimal radiation dose to attain the objective without significantly reducing egg quality. Microbial results showed that 2.0 kGy inactivated *Salmonella* and reduced microbial load to levels below those stipulated by the Argentine regulations.

Bakalivanov et al. (2008) studied freeze-dried (control group) and the freeze-dried and γ -irradiated (2.0 and 3.5 kGy) whole hen's egg melange during a 4-year period of storage at room temperature. In the three investigated groups, during the entire period of storage no pathogenic microorganisms were isolated, including *Salmonella* bacteria. The total count of aerobic and facultative anaerobic mesophilic and psychrotrophic bacteria in all three groups decreases during storage, and this tendency was more clearly expressed in the γ -treated samples.

Alvarez et al. (2007b) developed mathematical models that describe the inactivation of *S. Enteritidis*, *S. Typhimurium*, and *S. Senftenberg* suspended in LWE by irradiation followed by heat treatments (IR-H treatments). *Salmonella* viability decreased exponentially (primary model) with heat treating time for all the radiation doses (0, 0.1, 0.3, 0.5, 1.0, and 1.5 kGy) and temperatures investigated (55, 57, and 60°C). Two secondary models that related the D_T values (time required to eliminate 90% of viable cells at a given temperature) with irradiation dose, heating temperature, and recovery medium after treatments were also developed. Process criteria to obtain the established performance criteria, a 5- \log_{10} reduction, on the investigated *Salmonella* serovars were determined to be 57.7°C/3.5 min following 1.5 kGy when treated cells were recovered in tryptic soy agar and 59.3°C/3.5 min following 0.5 kGy when cells were recovered in tryptic soy agar amended with 3% NaCl.

In a study by Badr (2006), samples of liquid egg white and liquid egg yolk were subjected to γ -irradiation doses of 0, 1, 2, 3, and 4 kGy at room temperature followed by storage at $4 \pm 1^\circ\text{C}$. A dose of 3 kGy appeared to be an optimum irradiation dose for improving the microbial safety of liquid egg white and yolk. This dose was effective in the destruction of *Salmonella*, *S. aureus*, and Enterobacteriaceae, which were not detected in samples that received this dose during storage at $4 \pm 1^\circ\text{C}$, in addition to the observed significant reduction in the total plate count.

Fresh shell eggs were inoculated with 10^8 CFU of *S. enteritidis*; the purpose of the experiment was to study the effect of three doses (1, 2, and 3 kGy) of γ -irradiation on the bacteriologic population of eggs. After irradiation, eggs were maintained at 4°C for 42 h prior to culture. Irradiation with 1 kGy resulted in a significant, 3.9-log reduction in detectable *S. enteritidis* in the shell and a highly significant 95% reduction in detectable *S. enteritidis* in the internal shell membranes. Irradiation of eggs with either 2 or 3 kGy reduced bacterial contamination to nondetectable levels in both the shell and the internal membranes (Tellez et al., 1995).

The effects of ultra-high hydrostatic pressure (UHP) treatment and γ -irradiation levels on fresh liquid egg whites were investigated by Seregely et al. (2006). Samples were subjected to UHP of 400 MPa for 15 min at 4°C and γ -irradiation of 3-kGy doses. Based on the results, it can be concluded that the irradiation causes more drastic changes in the volatile compounds and in the NIR properties than the UHP treatment (Seregely et al., 2006).

Low dosages of e-beam irradiation (2, 3, and 4 kGy) were applied to shell eggs to examine potential antimicrobial effects on shell eggs. Dosages of e-beam irradiation at 3 and 4 kGy were shown to be effective at reducing *L. monocytogenes*, *E. coli*, and *S. typhimurium* counts in shell eggs to an undetectable level. *S. typhimurium* was found to be relatively more resistant to irradiation, followed by *L. monocytogenes* and *E. coli* (Wong and Kitts, 2003).

In a study by Cabo Verde et al. (2004), whole eggs were artificially contaminated with strains of *S. typhimurium*, *S. enteritidis*, *C. coli*, and *C. jejuni* and γ -irradiated with doses in the range of 0.5–5 kGy. *D* value varied between 0.31–0.26 and 0.20–0.19 kGy in *S. typhimurium* and *S. enteritidis*, respectively, and between 0.21–0.18 kGy and 0.07–0.09 in *C. coli* and *C. jejuni*, respectively, for shell and yolk + white.

Shell eggs were irradiated at doses of 0, 0.5, 1.0, and 1.5 kGy of γ -irradiation. The total counts of mesophilic aerobic bacteria and coliform found in shell eggs on Day 0 were 212 CFU and 50 coliform MPN/g egg, respectively. Shell eggs treated with γ -irradiation had significantly lower total mesophilic aerobic bacteria and coliform counts compared with the control samples. On Day 0, 1 kGy of γ -irradiation caused a reduction of approximately 2 and 1 \log_{10} cycles in mesophilic aerobic bacteria and coliform counts, respectively. However, a dose of 1.5 kGy reduced the total microorganisms and coliforms load up to less than 10 microbes/g (Al-Bachir and Zeinou, 2006).

Fengmei et al. (2000) studied the effects of γ -irradiation (0, 0.3, 0.6, 0.9, 1.2, 1.5, 2.0, and 2.5 kGy absorbed dose) on frozen egg liquid and showed that the survival of the bacteria coli number was dose dependent.

The effect of irradiation on egg microflora is summarized in Table 7.6.

TABLE 7.6 Irradiation Effect on Egg Microflora

| Product | Irradiation Dose/ Irradiation Type | Other Technology | Storage Temperature | Effect on Microflora | Reference |
|---|--|------------------|---------------------------------|--|-----------------------------|
| Whole hen's egg melange | — | Freeze dried | Room temperature for 4 years | No pathogenic microorganisms were isolated, including <i>Salmonella</i> bacteria. The total count of aerobic and facultative anaerobic mesophilic and psychrotrophic bacteria decreased during the storage, and this tendency was more clear in irradiated | Bakalivanov et al., 2008 |
| | 2.0 and 3.5 kGy γ irradiation | Freeze dried | | | |
| Egg powder | 0, 2, 5, and 10 kGy γ radiation | — | — | Microbial results show that 2.0 kGy inactivated <i>Salmonella</i> | Narvaiz et al., 1992 |
| Spray dried whole egg powder and liquid whole egg | 0.05 and 8.0 kGy γ irradiation | — | — | Irradiation dose of 1.0 kGy eliminates 100 1000 <i>Salmonella</i> bacteria per kilogram of whole egg powder | Kohler et al., 1989 |
| Eggs | 0, 0.5, 1.0, and 1.5 kGy γ irradiation | — | — | A minimal dose of 0.5 kGy was sufficient to eliminate all five <i>Salmonella enteritidis</i> isolates from the surface of whole eggs; however, the same isolates were more resistant to irradiation when present inside the eggs. The ATCC 13076 isolate was significantly more sensitive to irradiation (<i>D</i> value of 0.32 kGy) than the other four isolates from animal origin. Irradiation <i>D</i> values of the latter ranged from 0.39 to 0.41 kGy | Serrano et al., 1997 |
| Liquid egg white and yolk | 0, 1, 2, 3, and 4 kGy γ irradiation | — | 4 ± 1°C | 3 kGy appeared to be an optimum irradiation dose for improving the microbial safety of liquid egg white and yolk. This dose was effective in the destruction of <i>Salmonella</i> , <i>S. aureus</i> , and Enterobacteriaceae, which were not detected in samples that received this dose during storage. In addition, there was a significant reduction in the total plate count | Badr, 2006 |

(Continued)

TABLE 7.6 Irradiation Effect on Egg Microflora—cont'd

| Product | Irradiation Dose/ Irradiation Type | Other Technology | Storage Temperature | Effect on Microflora | Reference |
|-------------------|---|------------------|------------------------|---|----------------------------|
| Shell eggs | 1 kGy γ irradiation | — | — | 3.9 log reduction in detectable <i>S. enteritidis</i> in the shell and a highly significant 95% reduction in detectable <i>S. enteritidis</i> in the internal shell membranes. | Tellez et al., 1995 |
| | 2 and 3 kGy γ irradiation | — | — | Reduction bacterial contamination to nondetectable levels in both the shell and the internal membranes | |
| Shell eggs | 2, 3, and 4 kGy e beam irradiation | — | — | Irradiation at 3 and 4 kGy was effective at reducing <i>L. monocytogenes</i> , <i>E. coli</i> , and <i>S. typhimurium</i> counts in shell eggs to an undetectable level. <i>S. typhimurium</i> was found to be relatively more resistant to irradiation, followed by <i>L. monocytogenes</i> and <i>E. coli</i> | Wong and Kitts, 2003 |
| Whole eggs | 0.5–5 kGy γ irradiation | — | — | <i>D</i> value varied between 0.31–0.26 and 0.20–0.19 kGy in <i>S. typhimurium</i> and <i>S. enteritidis</i> , and between 0.21–0.18 and 0.07–0.09 kGy in <i>C. coli</i> and <i>C. jejuni</i> , for shell and yolk + white | Cabo Verde et al., 2004 |
| Eggs | 0, 0.5, 1.0, and 1.5 kGy γ irradiation | — | — | 1 kGy of γ irradiation caused a reduction of approximately 2 and 1 log ₁₀ cycles in mesophilic aerobic bacteria and coliform counts, respectively. 1.5 kGy reduced the total microorganisms and coliforms load up to less than 10 microbes/g | Al Bachir and Zeinou, 2006 |
| Frozen egg liquid | 0, 0.3, 0.6, 0.9, 1.2, 1.5, 2.0, and 2.5 kGy γ irradiation | — | — | The survival of bacteria coli number was dose dependent | Fengmei et al., 2000 |

7.5 Conclusions

Ionizing radiation is a safe and effective technology that can be used to inactivate foodborne pathogens associated with poultry such as *S. typhimurium*, *C. jejuni*, and *L. monocytogenes* and minimize the occurrence of foodborne illness in at-risk populations without increasing the temperature of the irradiated medium. The effect of hurdle technology (ionizing radiation with plant/fruit extracts) on poultry and eggs has been repeatedly studied with promising results. Although irradiation increased lipid oxidation, infusion of chicken meat with plant extracts could substantially reduce the lipid oxidation caused by irradiation. Addition of more than 2% plum extract to turkey breast rolls was effective in controlling lipid oxidation of irradiated meat and the production of aldehydes (hexanal, heptanal, octanal, and nonanal).

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Application of Irradiation on Milk and Dairy Products

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8.1 Introduction

Application of ionizing radiation treatment of foods on an industrial scale started in the early 1980s after the joint Food and Agriculture Organization/International Atomic Energy Agency (IAEA)/World Health Organization (WHO) expert committee accepted the application of a 10-kGy overall average dose for foods (WHO, 1981). Vast knowledge has now accumulated on the chemical and biological effects of ionizing irradiation, which has contributed to the promotion of its utilization (Diehl and Josephson, 1994; Olsen, 1998; Radomyski et al., 1994).

Irradiation is used as a food preservation method to destroy microorganisms and increase shelf life. The radiation dose unit, previously referred to as the rad, is currently known as the Gray (Gy). The Gy is the absorption of 1 J of energy per kilogram irradiated material and is equivalent to 100 rads (Diehl, 1990; Ingram and Farkas, 1998). Irradiation doses usually range from 10 Gy to 1 kGy for sprouting inhibition of potatoes, onions, garlic, etc.; 1 to 10 kGy for fresh meat and seafood as well as vegetables and fruits; and 10 to 100 kGy mainly for food sterilization (IAEA, 2002). The recommended dose levels are as follows: low level at 1 kGy to inhibit insect infestation and delay ripening; medium level at 1–10 kGy to reduce bacterial load (particularly of pathogens); and high level at 10–50 kGy for commercial sterilization and elimination of viruses (WHO, 1981, 1999). Irradiation of foodstuffs has an additional advantage: it can be used in prepackaged foodstuffs to avoid microbial recontamination, in addition to allowing the use of different packaging materials [Agencia Nacional de Vigilancia Sanitaria, 2001; EC, 1999; U.S. Food and Drug Administration (FDA), 2005].

According to the *Codex General Standard for Irradiated Foods* (Codex Alimentarius Commission, 2003), ionizing radiations for food processing are limited to high-energy photons (γ -rays of radionuclides ^{60}Co and, to a much smaller extent, ^{137}Cs , or X-rays from machine sources with energies up to 5 MeV or accelerated electrons with energies up to 10 MeV). In the United States, the FDA amended the food additive regulations by establishing a new maximum

permitted energy level of X-rays for treating food of 7.5 MeV provided that the X-rays are generated from machine sources that use tantalum or gold as the target material (U.S. FDA, 2004).

High-energy electron beams are produced by electron accelerating machines. X-Ray production starts with high-energy electrons: X-ray machines convert electron energy to electromagnetic X-rays called Bremsstrahlung. These types of radiation are chosen for the following reasons:

1. They produce the desired food preservative effects.
2. They do not induce radioactivity in foods or packaging materials.
3. They are available in quantities and at costs that allow commercial use of the irradiation process (Farkas, 2004).

The chemical changes resulting from the irradiation of proteins food have been the subject of many studies (Delincée, 1983; Elias and Cohen, 1997; WHO, 1999). These studies indicate that in addition to protein structure, the state of protein—whether it is native or denatured, dry or wet, liquid or frozen, or present with other substances—affects the radiolytic products formed. Irradiation condition (e.g., absorbed dose, dose rate, and the presence or absence of oxygen) also plays an important role (Molins, 2001). When proteins were treated with ionizing energy, large protein molecules were cleaved into smaller ones that upon digestion yielded the same amino acids as the original proteins. Some of these studies demonstrated the occurrence of both fragmentation and aggregation. Moreover, minimal changes were reported in total amino acid profile as a result of treatment with irradiation; consequently, no effects of major nutritional significance were found (Murano, 1995; WHO, 1994). The effects of irradiation on dairy products are given in Table 8.1.

8.2 Irradiation of Dairy

8.2.1 Irradiation of Milk

Milk β -lactoglobulin was used as a model food allergen for experiments on allergenic and molecular properties by γ -irradiation. The amount of intact allergens in an irradiated solution was reduced by γ -irradiation depending on the dose. These results showed that epitopes on the allergens were structurally altered by radiation treatment and that the irradiation technology can be applied to reduce allergenicity of allergic foods. Binding abilities (allergenities) of most irradiated proteins were changed with different slopes of the inhibition curves in competitive indirect enzyme-linked immunosorbent assay formatted with patients' IgE. The patients' IgE did not readily recognize the irradiated allergens, depending on the dose. When quantifying allergens in irradiated solutions, the amount of intact allergens in an irradiated solution was reduced by γ -irradiation, depending on the dose (Buyn et al., 2002).

TABLE 8.1 Irradiated Dairy Products, Type and Dose of Irradiation, and Results

| Dairy Product | Irradiation Type | Irradiation Dose | Results | Reference |
|-----------------------------------|-------------------------------------|---|--|--------------------------|
| Milk | γ irradiation | 0, 3, 5 and 10 kGy | Reduction of β lactoglobulin | Buyn et al., 2002 |
| Milk protein | Ionization irradiation | 4 kGy Temperature: 8 and 16°C | Affect the bacterial groups but not the psychrotrophs | Seisa et al., 2004 |
| Milk protein | γ irradiation | — | Reduction of water vapor permeability Increase of the resistance to microbial and enzymatic biodegradation | Quattara et al., 2002 |
| Milk protein | γ irradiation | 0, 5, 15, and 25 kGy | Thermal treatment with γ irradiation increased the viscosity of proteins. Thermal and irradiation treatments under inert atmosphere resulted in improvement in whey solutions containing plasticizer | Camillo and Sabato, 2004 |
| Baby food (with skim milk powder) | γ Cells (^{60}Co) | 0, 0.5, 1.5, 6, 10, 15, 30, and 50 kGy Room temperature in the presence of air | Increase of leucine, alanine, and glutamine acid Decrease of histidine and methionine | Matloubi et al., 2004 |
| Milk whey protein | Microwave irradiation | 2450 MHz Temperature: 40–50°C during 5 min of treatment | Irradiation increased the degree of hydrolysis by all enzymes | Izquierdo et al., 2008 |
| Infant milk | γ irradiation | ≤ 5 kGy | Increase of storage length Increase in the resistance of <i>Enterobacter sakazakii</i> strains | Osaili et al., 2008 |
| Milk protein | γ Rays (^{60}Co) | 0 and 32 kGy | Increase in viscosity of irradiated proteins solutions | Ciesla et al., 2004 |
| Cow's milk | γ irradiation | 3, 5, and 10 kGy Room temperature in the presence of air | 10 kGy dose increased the milk identification | Kaddouri et al., 2008 |

(Continued)

TABLE 8.1 Irradiated Dairy Products, Type and Dose of Irradiation, and Results—cont'd

| Dairy Product | Irradiation Type | Irradiation Dose | Results | Reference |
|--|---|---|---|-------------------------------|
| UHT milk | UV irradiation | 7000 lux light for 2.5 h | Decrease of AR concentration | Trang et al., 2008 |
| Milk protein | γ irradiation | 0, 5, 15, and 25 kGy | The apparent viscosity for dispersions containing either sodium caseinate with glycerol or whey with glycerol | Sabato and Lacroix, 2002 |
| Dry casein and milk powder | γ irradiation | 5 kGy | Reduction of microflora | Zegota and Malolepszy, 2008 |
| Film for cheese | γ irradiation (^{60}Co) | 3, 7 and 12 kGy | Increase of caprolactam levels with the increase of irradiation dose | Araujo et al., 2008 |
| Film for cheese | γ irradiation (^{60}Co) | 12 kGy | Migration of compound from multilayer PA 6 film | Felix et al., 2008 |
| Soft whey cheese Anthotyros | γ irradiation | 0.5, 2, and 4 kGy | Irradiation increased the yeast population | Tsiotsias et al., 2002 |
| Cheddar and mozzarella cheeses | Irradiation (^{60}Co) | 40 kGy | Little change in product color or texture | Hashisaka et al., 1990 |
| Palmita type white cheese | γ irradiation (^{60}Co) | 1, 2, and 5 kGy Room temperature | Shelf life extension Control of foodborne diseases | Lalaguna, 2003 |
| Vanilla, chocolate, and strawberry ice cream | γ irradiation | 3 kGy for vanilla ice cream 5 kGy for chocolate and strawberry ice cream | Low dose irradiation improves the microbial quality Risk was reduced by the foodborne pathogens | Jo et al., 2007 |
| Vanilla, raspberry, peach, and milk jam ice creams | γ irradiation | 3, 6, and 9 kGy | Microbial decontamination | Adeil Pietranera et al., 2003 |
| Vanilla, strawberry, and chocolate ice cream | γ irradiation | 1, 2, 5, 10, and 30 kGy | Doses higher than 2 kGy irradiation induced off odor and aftertaste in vanilla ice cream | Kamat et al., 2000 |

Kaddouri et al. (2008) evaluated the effects of γ -radiation on the antigenic properties of β -lactoglobulin in cow's milk. Liquid and lyophilized samples of cow's milk and whey were irradiated with γ -cells (^{60}Co) at dose levels of 3, 5, and 10 kGy at room temperature in the presence of air. Effects of treatment on proteins were monitored with Lowry's method, sodium dodecyl sulfate–polyacrylamide gel electrophoresis, and enzyme-linked immunosorbent assay. Radiation did not affect the molecular-weight distributions of proteins, but it did reduce their solubility. Furthermore, results showed that irradiation at 10 kGy increased the recognition of milk and whey powders by anti- β -lactoglobulin (β -Lg) rabbit immunoglobulin G, with the other samples remaining antigenically stable. These results indicate that γ -rays do not reduce cow's milk β -Lg antigenicity.

The structural properties of whey concentrate milk protein can be improved when some treatments are applied, such as thermal and γ -irradiation, or when some compounds are added (Sabato et al., 2001). Whey proteins, enriched protein fractions from milk, are of great interest as ingredients due to the nutritional value associated with their functional properties. The structural properties of these proteins can be improved when some treatments are applied, such as thermal and γ -irradiation, or when some compounds are added. The viscometer behavior of whey dispersions submitted to the following two different combined treatments was studied: (i) thermal plus irradiation; and (ii) thermal plus vacuum and N_2 plus irradiation. Dispersions of whey protein in water [5 and 8% protein (w/v) base] and containing proteins and glycerol at ratios of 1:1 and 2:1 (protein:glycerol) were submitted to both combined treatments. The irradiation doses were 0, 5, 15, and 25 kGy. The thermal treatment combined with γ -irradiation contributed to the increase of the viscosity as irradiation doses increased for both (5 and 8%) concentrations of proteins ($p \leq 0.05$). For protein and glycerol solutions, the irradiation dose seemed to result in slight increases. The vacuum applied before the irradiation had a small contribution (Camillo and Sabato, 2004). The diagram for this study is given in Figure 8.1.

The efficacy of γ -radiation decontamination of industrial casein, a milk protein used as a component of many food and nonfood products, has been studied. Low-fat milk powder was also included, with the purpose of studying the microflora survival in protein-rich materials. Microbial analysis of the samples prior to irradiation showed that the initial total viable count was higher than 6.0 log colony-forming units (CFU)/g in both casein and milk powders. The contamination of casein with moulds and yeasts was found to be equal to 3.56 log CFU/g. The coliforms counts have not exceeded the value of 2.48 log CFU/g. Radiation processing of casein and milk powder has substantially reduced the microbial population of all samples. The dose of 5 kGy was sufficient to decrease the total microflora and coliforms counts to the level permissible for food products. Storage for 1 month did not influence the number of surviving micro-organisms in irradiated casein and milk powders. Fitting the experimental results of micro-organism's survival according to the generalized exponential equation led to the concave survival curve (Zegota and Malolepszy, 2008).

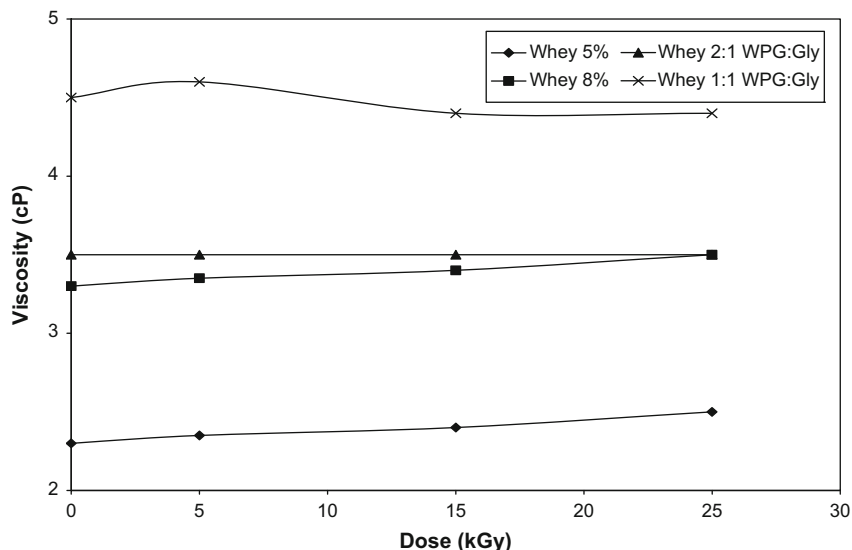


Figure 8.1: Viscosity versus irradiation dose for whey dispersions (5 and 8%) and whey protein concentrate and glycerol solution (2:1 and 1:1) [adapted from [Sabato and Lacroix \(2002\)](#) and [Camillo and Sabato \(2004\)](#)].

Due to their good functional properties allied to their excellent nutritional value, milk protein isolates and soy protein concentrates have gained a crescent interest ([Sabato and Lacroix, 2002](#)). Protein solutions mixed with glycerol have been studied related to their moist and plasticizer functions ([Stuchell and Krochta, 1994](#)). Plasticizer added in protein-based solutions and combined with the γ -irradiation process showed a better cohesion force ([Brault et al., 1997](#)). The structural properties of these proteins can be improved when some treatments are applied, such as γ -irradiation, alone or in the presence of other compounds, such as a plasticizer. In a study by [Sabato and Lacroix \(2002\)](#), solutions of these proteins were mixed with a generally recognized as safe (GRAS) plasticizer, glycerol. These mixtures [8% protein (w/v) base] at two ratios, 1:1 and 2:1 (protein:glycerol), were submitted to a γ -irradiation treatment (^{60}Co) at doses of 0, 5, 15, and 25 kGy, and their rheological performance studied. As irradiation dose was increased, viscosity measurements decayed significantly ($p < 0.05$) for a mixture of soy/glycerol and calcium caseinate/glycerol. The mixture of sodium caseinate/glycerol showed a trend to form aggregation of macromolecules with a dose of 5 kGy, whereas the apparent viscosity for dispersions containing whey/glycerol remained almost constant as the irradiation dose increased.

Gamma irradiation was used to produce free-standing cross-linked milk proteins. Film-forming solutions were prepared according to a method previously developed in our laboratory using calcium caseinate (CAS) with various proportions of whey protein isolate (WPI) or whey protein concentrate (WPC). The following caseinate–whey protein (CAS:WP) ratios were

prepared: 100:0, 75:25, 50:50, 25:75, and 0:100. The water vapor permeability (WVP) of the films was determined gravimetrically at 23°C using a modified ASTM procedure. Molecular properties characterization was performed by size exclusion chromatography (SEC). Ouattara et al. (2002) used γ -irradiation cross-linking to improve the water vapor permeability and the chemical stability of milk protein films. The results showed that γ -irradiation significantly ($p \leq 0.05$) reduced the WVP and increased the resistance to microbial and enzymatic biodegradation. An increase in the concentration of high-molecular-weight proteins in the film-forming solution was also observed. Two hypotheses may explain the effect on γ -irradiation: (i) participation of more molecular residues in intermolecular interactions of protein that have different physicochemical properties; and (ii) the formation of inter- and/or intramolecular covalent cross-links in the film-forming solutions (Quattara et al., 2002).

Matloubi et al.'s (2004) work is mainly concerned with the effect of γ -irradiation on amino acids content of a manufactured baby food that was irradiated with a γ -cell (^{60}Co) at dose levels of 0, 0.5, 1.5, 6, 10, 15, 30, and 50 kGy at room temperature and in the presence of air. The samples were analyzed immediately after irradiation. The destruction pattern of amino acids in this formulated food (whose ingredients were wheat starch, skim milk powder, sugar, vegetable oils, vitamins, minerals, and essences) was not very different from that of whole foods.

Generally, amino acids of baby food proteins increased or decreased with increasing irradiation dose, with no clear trend of the change. For this sample, leucine, alanine, and glutamic acid showed an increase as the irradiation dose increased. On the contrary, histidine and methionine decreased in the samples as the dose irradiation increased. These results could be related to the structure of amino acids. Simple amino acids due to irradiation undergo reductive deamination and decarboxylation (Matloubi et al., 2004).

Comparing amino acid changes due to irradiation of this formulated food with whole foods, such as wheat (Srinivas et al., 1972), red gram (Nene and Sreenivasan, 1975), fish (Al-Kahtani et al., 1998; Kardashev et al., 1970; Underal et al., 1973), and poultry meat (Josephson et al., 1978; Thayer, 1990), showed no significant differences between the results. The amino acid changes of a multicomponent food that is formulated with several ingredients were similar to those of whole irradiated foods. It has been observed that there is a mutual protection exerted when different substances are irradiated together (Diehl, 1995).

Microwave irradiation (MWI) during enzymatic hydrolysis could be an alternative to conventional heating (CH) to reduce the antigenicity of milk proteins; several studies on enhanced enzymatic proteolysis both in solution (Izquierdo et al., 2005; Pramanik et al., 2002) and in gel (Juan et al., 2005) under MWI have been reported. The peptide fragmentation in solution of several biologically active proteins, including cytochrome *c*, ubiquitin, lysozyme, myoglobin, and interferon α -2b, by endoproteases, trypsin, or lysine C was achieved in minutes using MWI, in contrast to the hours required when CH was used (Pramanik et al., 2002).

The effects of MWI treatment on the hydrolysis of a commercial bovine whey protein concentrate by Pronase, chymotrypsin, and five food-grade enzymes (papain, Corolases 7089 and PN-L 100, Alcalase, and Neutrase) were analyzed. Digestions were conducted for 5 min at 40 or 50°C depending on the enzyme. Proteolysis was measured with *o*-phthaldialdehyde, reverse-phase high-performance liquid chromatography (RP-HPLC), and sodium dodecyl sulfate–polyacrylamide gel electrophoresis. The residual immunochemical reactivity was assessed by an enzyme-linked immunosorbent assay using two pools of seven sera from children allergic to bovine milk. The MWI increased the degree of hydrolysis by all enzymes. Pronase showed the highest proteolysis under MWI, followed by papain and Alcalase, and very low immunoreactivity was detected by using either pool of sera in the respective hydrolysates. Proteolysis of dairy whey proteins by either of these enzymes in combination with MWI treatment has the potential to more efficiently produce hypoallergenic dairy hydrolysates (Izquierdo et al., 2008).

Infant milk formula has been identified as a potential source of *Enterobacter sakazakii*, which has been implicated in neonatal meningitis and necrotizing enterocolitis. The study by Osaili et al. (2008) was undertaken to determine whether the length of *E. sakazakii* storage in powdered infant milk formula (PIMF) affected the ability of the pathogen to survive subsequent reconstitution of the powder with hot water or treatment with γ -radiation. Five *E. sakazakii* strains were mixed individually with PIMF and stored for up to 12 months at 25°C. After storage, PIMF was reconstituted with water at 60–100°C or was exposed to ≤ 5 kGy of γ -radiation. Without any treatment secondary to drying, *E. sakazakii* counts decreased < 1 log/g after 1 month but decreased approximately 4 log/g during storage for 8–12 months. Dry storage decreased thermal resistance but increased resistance of *E. sakazakii* to ionizing radiation in PIMF. Reconstitution of contaminated powder with water at 70°C after 1 month of dry storage reduced *E. sakazakii* viability slightly (> 2 log/g), and after powder was stored for 12 months all *E. sakazakii* strains were eliminated. In contrast, desiccation substantially increased the resistance of *E. sakazakii* strains to ionizing radiation. Although the *D* value for *E. sakazakii* IMF1 following overnight storage in PIMF was 0.98 kGy, > 4 kGy was required to kill 1.5 log/g of the same strain that had survived 12 months in dry PIMF. Results suggested that low-dose milk will more effectively eliminate *E. sakazakii* from PIMF if the treatment is applied soon after PIMF manufacture.

Although proteins are known to have good film-forming capabilities, protein films have rather moderate barrier properties. Thus, there is a strong need to identify new compositions and processes permitting better products to be obtained. Cross-linking induced by using γ -irradiation was found to be an effective method for the improvement of both barrier and mechanical properties of the edible films and coatings based on calcium and sodium caseinates alone or combined with some globular proteins (Brault et al., 1997; Lacroix et al., 2002; Le Tien et al., 2000; Sabato et al., 2001). Irradiation of solutions was carried out with ^{60}Co γ -rays applying doses of 0 and 32 kGy. An increase in viscosity of the irradiated protein solutions

compared to the controls was found due to radiation-induced cross-linking. On the basis of the lower values of viscosity found after heating for the irradiated solutions compared to the controls, it can be concluded that gels obtained from the irradiated solutions reveal better developed “fine-stranded” structure than gels prepared from the control solutions. Creation of the better ordered gels after irradiation corresponds well to rearrangement of the cross-linked β -phase (accompanied by reorganization of a periodic phase) found by Fourier transform infrared spectroscopy. In particular, higher content of the strongly bonded β -strands was detected in the irradiated and heated samples compared to those that were only heated. The use of γ -irradiation therefore causes a better improvement in well-organized β -conformation than thermal treatment alone. The presence of the better ordered protein conformations in gels obtained from irradiated solutions leads to production of the more “crystalline” films. These films are characterized by improved barrier properties and mechanical resistance and higher rigidity than those prepared from the non-irradiated solutions (Ciesla et al., 2004).

Milk and dairy products are important sources of riboflavin in the diet (Cardoso et al., 2005). Riboflavin is stable to heat and oxidation, but it is rapidly photodegraded (Woodcock et al., 1982). This strong photosensitizer is able to absorb visible and UV light and transfers this energy into highly reactive forms of oxygen, such as superoxide anion and singlet oxygen (Min and Boff, 2002). The effects of aminoreductone (AR) on photodegradation of riboflavin were studied for a riboflavin solution (1.5 mg/l) and ultra-high-temperature (UHT)-treated milk during exposure to irradiation at 7000 lux light intensity for 2.5 h. In riboflavin solution, AR protected riboflavin against degradation under exposure to light, and this ability depended on the concentration of AR. In addition, the protective ability of AR was higher than that of ascorbic acid, which has the ability to reduce photodegradation of riboflavin. The study in milk clarified that heat treatment of milk enhanced the protective ability against photodegradation of riboflavin because of the generation of AR during the Maillard reaction. In parallel with the decrease in AR concentration in UHT-treated milk by the addition of Cu^{2+} , the protective ability correspondingly decreased. Thus, it may be concluded that AR was a principal compound responsible for the photostability of riboflavin in UHT-treated milk (Trang et al., 2008).

8.2.2 Irradiation of Cheese

Extending the shelf life and/or sterilization of dairy products for immunocompromised patients using radiation treatment is not a widely accepted practice. The main reason for its limited use is that ionizing energy, through the formation of radiolytic products especially in high lipid-based foods, generates unacceptable off-odors and flavors via oxidation, polymerization, decarboxylation, and dehydration reactions even at low doses (Giroux and Lacroix, 1998; Urbain, 1986). In particular, polyunsaturated fatty acids are prone to oxidation by free radicals produced during treatment. Moreover, oxidation of casein and the production of methyl radicals have been shown to result in the generation of “wet dog” off-flavors (Hsu et al., 1972). These chemical reactions, to some extent, can be reduced if the products are initially frozen and/or

treated in an environment with limited water, light, and oxygen. However, despite these shortcomings, low-dose radiation for the specific purpose of extending dairy product shelf life does hold promise. In such applications, the treatment should be considered as supplemental or complementary with the use of other preservation techniques including refrigeration and/or preservatives such as sorbic acid (Blank and Cumming, 2000).

The use of irradiation to aid in lipolysis, proteolysis, and glycolysis during the ripening of cheddar cheese was investigated. Irradiation of food is normally only applied to control microorganisms (Diehl, 1990; WHO, 1997). The effect of 4-kGy ionization irradiation, combined with ripening temperatures at 8 and 16°C on the ripening of cheddar cheese, was investigated. Changes in cheeses were monitored by sensory, microbiological, and chemical analyses. Sensorically, no one cheese was preferred over the other. At 16°C ripening, irradiation affected the bacterial groups but not the psychrotrophs. The free fatty acid content of the cheeses was not affected by irradiation, but higher thiobarbituric acid (TBA) values were observed after ripening at 16°C, as well as higher water-soluble nitrogen/total nitrogen. Differences in proteolysis products were detected by urea polyacrylamide gel electrophoresis and RP-HPLC (Seisa et al., 2004). The counts in the non-irradiated cheese at 8 and 16°C remained fairly constant until 6 weeks of ripening, after which they decreased by approximately 1 log CFU/g up to 12 weeks of ripening. This is probably an indication of the reduction in the amount of viable starter culture cells during ripening, and is in accordance with the results of Folkertsma et al. (1996).

Araujo and co-workers (2008) attempted to determine the amount of caprolactam in multilayer polyamide 6 (PA-6) films used for cheese and meat foodstuffs and to develop an analytical high-resolution gas chromatography method to determine the amount of caprolactam in these films. Multilayer PA-6 films were irradiated in the Radiation Technology Center of the Nuclear and Energetic Research Institute, SP, Brazil, using a Gamacell ⁶⁰Co irradiator of 12 KCi. Multilayer PA-6 films (10 × 10 cm²) were disposed in hermetically closed glass vials (50 ml) and submitted to 3, 7, and 12 kGy (IAEA, 2002). The results revealed that the effect of irradiation in the multilayer PA-6 films might promote increase, reduction, or no modification of the residual level of caprolactam compared to non-irradiated multilayer PA-6 films used for meat foodstuffs and cheese. The increase of caprolactam level could be explained by degradation of polymer, whereas reduction could be due to the cross-linking of residual caprolactam with other compounds. The different behavior of multilayer PA-6 films may occur due to the different constitutions of the packaging and, especially, due to the doses and dose rates (Araujo et al., 2008).

Bongirwar and Kumta (1967) reported that cheddar cheese developed off-odors when irradiated at 0.5 kGy; however, none was detected when the dose was reduced to 0.2 kGy. A dose greater than 1.5 kGy, when applied to Turkish Kashar cheese, not only resulted in off-flavor development but also contributed to color deterioration (Yuceer and Gunduz, 1980).

By decreasing the dose to 1.2 kGy, the sensory problems were eliminated and the mold-free shelf life was extended 12–15 days when stored at room temperature. In contrast, non-irradiated cheese became moldy within 3–5 days. When combined with refrigeration storage, radiation increased the shelf-life period of the cheese fivefold. With Gouda cheese, however, no taste difference was reported between irradiated (3.3 kGy) and non-irradiated samples (Rosenthal et al., 1983).

The goal of the work of Felix et al. (2008) was to attempt to identify the degradation compounds produced during irradiation of multilayer PA-6 films and to study their migration into water and 95% ethanol food simulant. After irradiation of multilayer PA-6 films at 3, 7 (meat foodstuff), and 12 kGy (cheese), degradation compounds were extracted using solid-phase microextraction, for which the time and temperature of extraction and stirring were optimized, and identified by gas chromatography–mass spectrometry (GC-MS). ϵ -Caprolactam, 2-cyclopentylcyclopentanone, and aldehydes, among other compounds, were identified in the headspace of the films. Polydimethylsiloxane was considered the best fiber for extraction. The optimum conditions of time, temperature, and stirring to extract the compounds were 20 min, 80°C, and 225 rpm, respectively. For validation purposes, the compounds were quantified in water and 95% ethanol, and the results showed high sensitivity and good precision and accuracy. Migration of compounds from irradiated and non-irradiated multilayer PA-6 films into water and 95% ethanol food simulants was carried out at 40°C for 10 days. The method was efficient for the quantification of decaldehyde, 2-cyclopentylcyclopentanone, and caprolactam that migrated from multilayer PA-6 films into food simulants.

Soft whey cheese Anthotyros has the following characteristics: moisture content, 65%; protein content, 9.6%; fat content, 16.6%; salt concentration in the aqueous phase, less than 1%; and pH 6.4. The average counts of the product were 4.54, 3.80, and 1.2 log CFU/g for aerobic mesophilic bacteria, yeasts, and Enterobacteriaceae, respectively (Tsotsias et al., 2002). *Listeria monocytogenes* has been shown to be capable of growing readily in milk (Rosenow and Marth, 1987). The feasibility of γ -radiation for eliminating *L. monocytogenes* Scott A inoculated into the freshly produced product, and following its counts during refrigerated storage at 4 and 10°C under vacuum packaging, was investigated. Cheese samples were exposed to doses of 0.5, 2, and 4 kGy of γ -irradiation at 4°C. Irradiation at 0.5 kGy slightly reduced the aerobic mesophilic bacteria counts, whereas irradiation doses of 2 and 4 kGy reduced the microbial load by approximately 1 or 2 log cycles (Tsotsias et al., 2002). The diagram for this study is shown in Figure 8.2.

A Gouda-based process cheese was initially frozen to -78°C and then γ -irradiated at 40 kGy (Hashisaka et al., 1990). Although mozzarella cheese was similarly treated, the result of sensory evaluation was far less favorable. Interestingly, both cheeses maintained their characteristic mouth-feel properties despite being frozen. In addition, the relatively high treatment dose

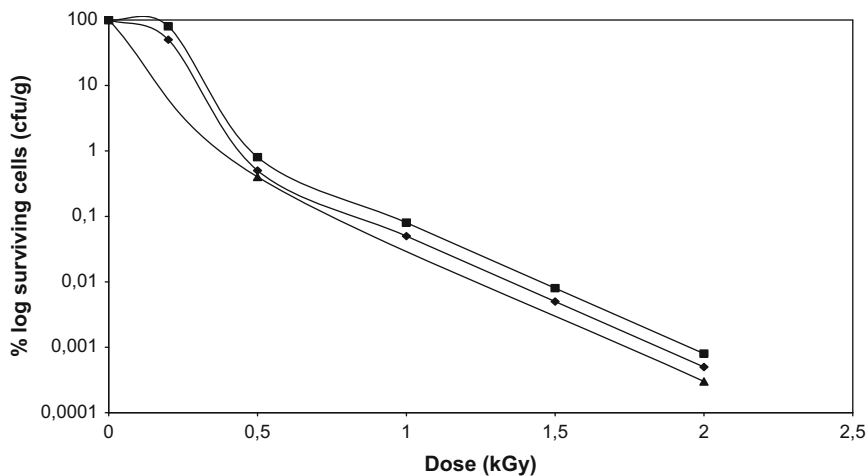


Figure 8.2: Radiation sensitivity of *Listeria monocytogenes* in ice cream and in soft whey cheese Anthotyros. Cells in ice cream were irradiated at 72°C (■) and 0°C (◆) and in soft whey cheese Anthotyros at 4°C (▲) [adapted from Kamat et al. (2000) and Tsiotsias et al. (2002)].

resulted in only slight color changes. It should be noted that although higher doses are required for sterilization purposes, the product once treated has an indefinite shelf life from a microbiological standpoint, provided of course that sterility is maintained. For Camembert cheese, flavor changes described as burnt or musty first became noticeable when the cheese was treated with 0.3 kGy (Jones and Jelen, 1988).

Observing the microflora of the irradiated samples, it can be concluded that low-dose irradiation, like any other nonsterilizing treatment, has a selective effect on the natural microflora of the soft whey cheese Anthotyros. The problems of the surviving microflora vary according to the nature of the food and its associated microorganisms (Farkas, 1989). Enterobacteriaceae could not be detected in irradiated samples. Irradiation decreased the yeast population that was detected during later stages of storage. Molds were not detected in any of the samples. The calculated D_{10} value for *L. monocytogenes* was 1.38 kGy. Surviving microbial cells could be detected throughout the entire 42 days of storage. Sensory scores indicated that irradiation doses up to 4 kGy do not adversely affect Anthotyros sensory properties (Tsiotsias et al., 2002). On the other hand, the D_{10} value of 1.38 kGy is in good agreement with a D_{10} value of 1.4 kGy for *L. monocytogenes* Scott A in mozzarella cheese at 78°C reported by Hashisaka et al. (1990), even though in the frozen state, D_{10} values are expected to be significantly higher than those at refrigeration temperatures.

In order to stabilize the cheese by preventing additional growth of *Penicillium roqueforti*, a minimal dose of 2 kGy was recommended. Results from a subsequent study, however, indicated that full-fat Camembert cheese underwent no off-flavor development up to a dose

of 3 kGy (Langley, 1988) and that treatment at 2.5 kGy was sufficient to eliminate initial populations of 10^3 to 10^4 CFU/g of the pathogen *L. monocytogenes* (Bougle and Stahl, 1994). Sensory evaluations by healthy individuals were conducted on ^{60}Co irradiated retail dairy products that were to be incorporated into the low microbial diets of immunosuppressed patients. Irradiation (40 kGy at 78°C) caused little change in product color or texture, but generally there was a decrease in overall acceptability and an increase in off-flavor and aftertaste. Modified atmosphere packaging (nitrogen, helium, or air) or antioxidant addition (ascorbyl palmitate or a combination of butylated hydroxyanisole and butylated hydroxytoluene) prior to irradiation were effective in preserving specific sensory attributes, which in some cases resulted in improved overall acceptability (helium-packed peppermint ice cream and ascorbyl palmitate-treated strawberry yogurt bars) compared to untreated irradiated products (Hashisaka et al., 1990).

Flavor changes were quite noticeable when radiation treatment was applied to cottage cheese, with the minimal threshold dose being 0.75 kGy. At this dosage, the cheese was described as having a slight bitter, cooked, or foreign taste. However, to reduce spoilage by psychrotrophic bacteria by at least 3 log, the applied dose would have to be nearly doubled (Jones and Jelen, 1988). This resulted in cheese with a definite burnt off-flavor. Using e-beam irradiation and doses of 0.21 and 0.522 kGy, the shelf life of vacuum-packaged cheddar cheese at 10°C containing $10\text{ CFU}/\text{cm}^2$ *Aspergillus ochraceus* spores was extended by approximately 42 and 52 days, respectively (Blank et al., 1992).

The physicochemical tolerance of Palmita-type white cheese to low-dose irradiation, as applicable to enhance shelf life and—it is hoped—food safety, was studied. The response of cheese to doses between 1 and 5 kGy was followed both by chemical analysis of substances important as indicators of quality and radiation effect and by sensory detection of modification. The experiment was replicated twice, and samples were analyzed immediately after irradiation and after 21 days of storage at $11.9 \pm 0.4^\circ\text{C}$. Dose effects, although statistically significant for some substances, were small. Consequently, no objectionable sensory characteristics were detected. Palmita-type cheese tolerated low radiation doses applicable for sanitizing food, which suggests the potential use of irradiation to control Palmita cheese foodborne diseases (Lalaguna, 2003).

8.2.3 Irradiation of Ice Cream

Gamma radiation applied at substerilizing doses represents a promising potential for applying “clean” diets (Josephson, 1983; Pryke, 1994; Pryke and Taylor, 1995). At the same time, it can widen the variety of available meals for these patients, allowing the inclusion of some products normally considered as “high risk” due to their microbial load but that can be nutritionally or psychologically adequate. One of these products is ice cream, a minimally processed type of meal that does not suffer enough microbial inactivation during its processing. Particularly, ice

cream of natural origin can carry undesirable contamination, sometimes causing disease to the consumer.

Vanilla, raspberry, peach, and milk jam ice creams were γ -irradiated with doses of 3, 6, and 9 kGy in order to achieve microbial decontamination (Adeil Pietranera et al., 2003). Results revealed that the 3-kGy dose was enough to achieve a three-magnitude order reduction in total bacterial counts, a two-magnitude order reduction in moulds and yeasts, and inactivate total coliforms and *Staphylococcus* spp., attaining an acceptable microbiological condition according to “clean” diets for immunosuppressed patients. “Clean” or “low-microbe” diets have been defined as containing <500 *Bacillus* CFU/g of food, or <1000 CFU/g of coagulase-negative *Staphylococci* or *Streptococcus viridans* and <10,000 CFU/ml *Bacillus* species, diptheroids, or *Micrococcus* (Pryke and Taylor, 1995). No microbiological determinations were performed after extended storage time for raspberry and peach ice creams because it was considered unnecessary, taking into account vanilla ice cream stability observed after 2 months of storage (Adeil Pietranera et al., 2003).

Kamat et al. (2000) investigated the efficacy of low-dose irradiation to improve the microbial safety of ice cream. Initially, three flavors of ice cream (vanilla, strawberry, and chocolate) were exposed, at 72°C, to doses of 1, 2, 5, 10, and 30 kGy γ -radiation. Irradiation at 1 kGy resulted in the reduction of microbial populations by 1 log cycle, thus meeting the requirement limits prescribed by the Bureau of Indian Standards. The pathogens *L. monocytogenes* 036, *Yersinia enterocolitica* 5692, and *Escherichia coli* O157:H19, respectively, showed *D* values of 0.38, 0.15, and 0.2 kGy in ice cream at 72°C, suggesting the efficacy of low doses (1 kGy) in eliminating them. Sensory evaluation studies of ice cream irradiated at 1, 2, 3, and 5 kGy by a 15-member panel demonstrated that doses higher than 2 kGy irradiation induced off-odor and an aftertaste was evident in vanilla ice cream. A radiation dose of 1 kGy was sufficient to eliminate the natural number of pathogens present in the ice cream. No statistically significant differences were observed in the sensory attributes of all three flavors of ice cream either non-irradiated or exposed to 1 kGy ($p < 0.05$).

Microbial contamination was investigated in ice creams with a vanilla, chocolate, and strawberry flavor commercially available in Korea (Jo et al., 2007). Ice cream is a good medium for microbial growth due to its nutrient content, almost neutral pH (pH 6–7), and long storage duration (Kanbakna et al., 2004). A relatively low storage temperature and pasteurization steps during its processing are considered to eliminate most of the hazard microorganisms. However, there remains concern regarding the microbial safety of ice creams. During the processing after a pasteurization step, there is a potential hazard by addition of contaminated ingredients or improper handling of the final products, including an abuse of the storage temperature. This is especially important in the preparation of soft ice cream because its final stage of production is carried out at the sales point (M-E-Elahi et al., 2002). Radiation sensitivity of the foodborne pathogens was also determined by an inoculation test. Foodborne pathogens used were *Listeria*

ivanovii, *E. coli*, and *Salmonella typhimurium* (Farber and Peterkin, 1991; Walker et al., 1990). Total aerobic bacteria (TAB), moulds and yeasts, and coliforms in the ice creams ranged from 2 to 3 log CFU/g. Irradiation of 3 kGy was enough to inactivate the total aerobic bacteria for the vanilla ice cream, but that of 5 kGy was needed for the chocolate and strawberry ice creams at a frozen condition (-20°C). To inactivate ($>\log 6.5$) the inoculated *L. ivanovii*, *E. coli*, and *S. typhimurium* into ice cream, irradiation of 3, 1, and 0.1 kGy was needed, respectively. The D_{10} value of *L. ivanovii* and *E. coli* was calculated as 0.71–0.77 and 0.28–0.38 kGy for the ice cream with different flavors at -72°C , respectively. The D_{10} value of *S. typhimurium* could not be calculated in this study because even 0.1 kGy of irradiation reduced the number of *S. typhimurium* to undetected level. Results suggest that a low-dose irradiation can improve the microbial quality and reduce the risk by the foodborne pathogens of ice cream, which has limited alternative sterilization methods due to the temperature characteristics of the products (Jo et al., 2007).

8.3 Conclusions

Irradiation processing has been extensively analyzed and is currently used for many food commodities. It has been successfully used to reduce pathogenic bacteria, eliminate parasites, and extend the shelf life of fresh food. Acceptance of the idea of irradiated food products in the United States has been slower than in other countries. The main problems for industry are that there is no clear definition of the need for irradiation, the large capital investment required, transportation logistics, and consumer concerns. Contrary to consumer misinformation, all irradiated food studied to date have found that irradiated food is safe for human consumption and suffers no reduction in nutritional quality for doses less than 2 kGy (Morris, 1997).

The main advantages of irradiation are as follows (Fellows, 2000):

1. There is little or no heating of the food and therefore negligible change to sensory characteristics.
2. Packaged and frozen foods may be treated.
3. Fresh foods may be preserved in a single operation and without the use of chemical preservatives.
4. Energy requirements are very low.
5. Changes in nutritional value of foods are comparable with those of other methods of food preservation.
6. Processing is automatically controlled and has low operating costs.

The following are the main disadvantages of irradiated food (Webb and Henderson, 1986; Webb and Lang, 1990; Welt, 1985):

1. The process could be used to eliminate high bacterial loads to make otherwise unacceptable foods sellable.
2. If spoilage microorganisms are destroyed but pathogenic bacteria are not, consumers will have no indication of the unwholesomeness of a food.
3. There will be a health hazard if toxin-producing bacteria are not destroyed after they have contaminated the food with toxins.
4. It is possible for resistance to radiation to develop in microorganisms.
5. There may be a loss of nutritional value.
6. Until the late twentieth century, there were inadequate analytical procedures for detecting whether foods had been irradiated.
7. There is public resistance due to fears of induced radioactivity or other reasons associated with concerns regarding the nuclear industry.

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Effect of Irradiation on Fish and Seafood

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9.1 Introduction

The consumption of diets rich in fish by various populations and by groups participating in clinical trials has been associated with a wide range of positive health effects (Kromhout et al., 1985; Yamori et al., 1985). However, the major problem with respect to distribution of seafood or fishery products is their susceptibility to spoilage, mainly due to the contamination of spoilage and pathogenic microorganisms (Colby et al., 1993). Bacterial spoilage of saltwater fish is caused by nonfermenting gram-negative bacteria such as *Pseudomonas*, *Achromobacter*, *Acinetobacter*, *Flavobacterium*, *Alteromonas*, and *Shewanella* spp. (Hubbs, 1991; Liston, 1992). Irradiation produces some chemical changes, which, although lethal to foodborne bacteria (Alur et al., 1994), do not affect the nutritional quality of the food (Doyle, 1999) but lead to the production of small amounts of radiolytic products (Merritt, 1988). Gamma irradiation has been considered as an interesting method of preservation to extend the shelf life of fish and also to reduce qualitatively and quantitatively the microbial population in fish and fish products (Abu-Tarboush et al., 1996; Laycock and Regier, 1970). Irradiation doses of 2–7 kGy can reduce important food pathogens such as *Salmonella*, *Listeria*, and *Vibrio* spp., as well as many fish-specific spoilers such as Pseudomonaceae and Enterobacteriaceae that can be significantly decreased in number (Murano, 1995; Rodriguez et al., 1993). This chapter presents a comprehensive review of fish and fishery products irradiation research and irradiation combined with other preservation technologies. The data include results on freshwater and marine fish, shellfish, crustaceans, and mollusks.

9.2 Quality of Irradiated Fishery Products and Shelf Life Extension

9.2.1 Fish

Emerson et al. (1964, 1965) found that the optimum irradiation dose for channel catfish (*Ictalurus punctatus*) was 1–2 kGy, which results in a shelf life of approximately 20 days at 0°C (from 4 days). The maximum irradiation dose was found to be 5 kGy.

The optimum dose for irradiating fillets of ocean perch (*Sebastes alutus*) is 1–2 kGy, which yields a shelf life of 25–28 days at 0.6°C. It should be noted that higher quality fish respond much better to irradiation than do poorer quality fish (Miyachi et al., 1967; Teeny and Miyachi, 1970). For air-packed fillets of pollock (*Pollachius virens*), the optimum dose is 1.5 kGy with an adjoining darkening of the flesh. At this dose, the shelf life is 28–30 days at 0.6°C and less than 20 days at 7.8°C. The maximum acceptable dose has not been clearly established, but reports place it at 2.3–2.5 or 5–8 kGy if blanched prior to irradiation (Ampola et al., 1969; Slavin and Ronsivalli, 1964).

Lemon sole (*Microstomus kitt*), if packed under nitrogen, has an optimum dose of 2.5 kGy, but if frozen the optimum dose is 5 kGy. The maximum dose was reported to be 5–10 kGy (Coleby and Shewan, 1965). The optimum irradiation dose for mackerel (*Scomber scombrus*) was found to be 2.5 kGy, which yields a shelf life of 30–35 days at 0.6°C (Slavin et al. 1966).

Ostovar et al. (1967) found that non-irradiated whitefish (*Coregonus clupeaformis*) has a shelf life of 12–15 days. On the other hand, irradiated whitefish with an optimum dose of 1.5–3 kGy had a shelf life of 15–29 days under refrigeration. According to Graikowski et al. (1968), the optimum irradiation dose for lake trout (*Salvelinus namaycush*) was 3 kGy, which yielded a shelf life of 26 days at 0.6°C. The normal shelf life is 8 days. The pigment in irradiated samples does not disappear until doses of 7 kGy are employed. Fillets of sole (*Parophrys vetulus*) were reported to have an optimum irradiation dose of 2–3 kGy, yielding a 4- or 5-week shelf life (Teeny and Miyachi, 1970). On the other hand, fillets of gray sole (*Glyptocephalus cynoglossus*) had an optimum dose of 1–2 kGy, which results in a shelf life of 29 days at 0.6°C or 10 or 11 days at 5.6°C (Miyachi et al., 1968).

European hake (*Merluccius merluccius*) can be irradiated optimally at 1–1.5 kGy, which yields a shelf life of 24–28 days at 0.5°C (De la Sierra Serrano, 1970). The maximum acceptable dose for this fish is 2 kGy. Argentine whiting (*Merluccius hubsi*) has an optimum irradiation dose of 5 kGy, with a shelf life reaching 48 days at 4°C (Ritacco, 1976). For haddock fillets (*Melanogrammus aeglefinus*), the optimum irradiation dose is 1.5–2.5 kGy, yielding a shelf life of 22–25 days at 5.6°C and greater than 30–35 days at 0.6°C. A maximum acceptable dose was found to be 6–7 kGy (Rosnivalli et al., 1968, 1970).

The shelf life of refrigerated Bombay duck (*Harpodon nehereus*) was found to be approximately 5–7 days. Radiation doses of 1.0–2.5 kGy extended the shelf life to approximately 18–20 days. It was determined that 5 kGy is the maximum acceptable dose for this fish because an off-flavor develops at this dose but will subside after 4 days (Gore and Kumta, 1970; Kumta et al., 1973). The optimum dose for white pomfret (*Stomateus cinereus*) and black pomfret (*Parastomatus niger*) is 1 kGy, with a shelf life of 4 weeks and 10–16 days, respectively, when stored at 0–2°C. The maximum acceptable dose for both species is 3 kGy (Aiyar, 1976; Kumta and Sreenivasin, 1970). Aiyar (1976) found that the optimum irradiation dose for threadfin

(*Eleutheronema tetradactylum*) was approximately 1–2.5 kGy, with a three- to fourfold increase in shelf life.

According to Carver et al. (1969), herring smelt (*Argentina silus*) has an optimum dose between 0.5 and 1 kGy, which resulted in an increase in shelf life by 6 days at 0.6°C. Moreover, herring (*Clupea herring*), an extremely fatty fish, was found to have an optimum irradiation dose of 1–2 kGy, which yields a shelf life of 10–14 days at 2°C. The maximum acceptable dose was found to be less than 5 kGy due to loss of color and natural flavor at 3 kGy and higher (Snauwert et al., 1977).

The optimum dose for ocean perch (*Sebastes marinus*) has been determined to be 1.5–2.5 kGy, which yields a shelf life of 30 days at 0.6°C and 15 days at 7.8°C. However, due to the higher fat content and the associated specific fine flavor, doses higher than 1 kGy are not recommended because of sensory changes (Reinacher and Ehlermann, 1978; Ronsivalli and Slavin, 1965). According to Sofyan (1978), Kembung fish (*Rastrelliger neglectus*) that is stored at 2–5°C for 12 days has a significant increase in total volatile base nitrogen (TVB-N) and hypoxanthine, with a decrease in the specific activity of SH-protease and acid phosphatase. Gamma irradiation at doses of 1–2 kGy had no significant affect on the activity of SH-protease or acid phosphatase. However, there were significantly lower TVB-N values and hypoxanthine concentrations in samples irradiated at 2 kGy compared to samples irradiated at 2 kGy after 7 days of storage.

Hussain (1980) and Ghadi et al. (1978) determined that for mackerel (*Rastrellinger kanagurta*), the optimum dose was 1.5 kGy, which results in a shelf life of 21–24 days at 0°C, 13–15 days at 5°C, and 7–11 days at 7.8°C. Skinned cod fillets were minced and hydrocolloids were added and they were frozen in 1-kg portions and irradiated at 3 kGy and subsequently stored at 18°C. Chemical and physical indices showed no significant differences between irradiated and non-irradiated samples during a 3-month storage period (De Ponte et al., 1986). Chuaqui-Offermanns et al. (1988) determined the degree of radiation-induced lipid oxidation in whitefish (*Coregonus clupeaformis*) stored at 3°C. The thiobarbituric acid (TBA) values for non-irradiated samples remained low and almost unchanged throughout the study. In fish irradiated at 0.82 and 1.22 kGy, TBA values increased with the time of storage. However, on Day 28, TBA still remained in the acceptable range, less than 20 g/kg. The average shelf life of samples based on chemical, sensory, and microbiological analyses irradiated at 0.0, 0.82, and 1.22 kGy was 7.8 ± 1 , 16.4 ± 3.6 , and 20.9 ± 3.9 days, respectively.

Liu et al. (1991) irradiated fillets of tilapia (*Oreochromis mosambicus*) and silver carp (*Hypophthalmichthys molitrix*) with 1 kGy at 2.4°C. It was found that there was a significant reduction of thiamine content in silver carp. Furthermore, the nucleotide catabolite concentrations in the irradiated fish were not changed after irradiation. The bacterial levels were maintained for 5 days after irradiation at 1°C.

A low dose of γ -irradiation was employed to treat Indian mackerel (*Rastrellinger kanagartha*), white pomfret (*Scomberomorus guttatus*), and seer (*Stromateus cinerius*), which were then stored on ice for 3 or 4 weeks. TBA values increased in both irradiated and non-irradiated samples, particularly in the mackerel and the seer. However, it was observed that the TBA values in mackerel did decrease during storage. Only the pomfret skin exhibited skin oxidation after treatment, and this value continued to rise throughout storage (Doke et al., 1992).

Poole et al. (1994) irradiated sweetlip (*Lethrinus miniatus*), red emperor (*Lutjanus sebae*), mackerel (*Scomberomorus commerson*), whiting (*Sillago ciliate*), mullet (*Mugil cephalus*), barramundi (*Lates calcalifer*), sand crab (*Portunus pelagicus*), Moreton Bay prawns (*Metapenaeus* spp.), and king prawns (*Penaeus plubujus*) with 0, 1, 3, and 5 kGy. All samples were stored in crushed ice. It was observed that a 1-kGy dose resulted in a 1.5- to 4-log reduction in bacteria compared to a 3.7- to 5.7-log reduction at 5 kGy. All species studied, except the Moreton Bay prawns and cooked king prawns, had acceptable flavor, texture, and odor after irradiation of 5 kGy.

Cho et al. (1992) irradiated dried fish powders with 5–10 kGy, which did not change the amino acid levels, TBA value, trimethylamine (TMA) nitrogen, and the color of the samples. The sensory quality had greater acceptability than the controls for 3 months post-irradiation. Armstrong et al. (1994) used γ -irradiation (1, 2, and 6 kGy) for preservation of two species of Australian marine fish, black bream (*Acanthopagrus australis*) and redfish (*Centroberyx affinis*). This resulted in no significant changes in their fatty acid compositions, even when performed at up to three times the commonly recommended maximum dose for fish. Vitamin E loss was evident in some fillets but could not be correlated with the treatment dosage. All irradiated fillets were found to have vitamin E muscle contents above the levels believed to be desirable for human consumption (0.936, 0.512, and 0.510 mg/100 g for redfish and 0.246, 0.274, and 0.253 mg/100 g for black bream irradiated with 1, 2, and 6 kGy, respectively), relative to the amounts of accompanying polyunsaturated fatty acids.

Al-Kahtani et al. (1996) determined the influence of different doses of γ -irradiation (1.5–10 kGy) and post-irradiation storage up to 20 days at $2 \pm 2^\circ\text{C}$ on some chemical criteria of tilapia and Spanish mackerel. TVB-N formation was lower in irradiated fish than in the non-irradiated fish. Irradiation also caused a larger increase in TBA values, which continued gradually during storage. Some fatty acids decreased by irradiation treatments at all doses. Thiamin loss was increased at higher doses (≥ 4.5 kGy), whereas riboflavin was not affected. α - and γ -tocopherols of tilapia and α -, β -, γ -, and δ -tocopherols of Spanish mackerel decreased with increased dose and continued to decrease during 20 days of storage.

Icekson et al. (1996) performed experiments using ionizing radiation to prolong the shelf life of two groups of refrigerated fish (*Cyprinus carpio*) stored at 0 – 2°C . Non-irradiated fish reached the nonacceptability point in 16 days and irradiated fish reached that point in 31 days, based on sensory evaluation. No difference was found in the shelf life of whole or eviscerated fish. If fish

were immediately cooled to 0°C after death, their shelf life was prolonged considerably. From this study, it is clear that chemical tests of freshness, such as TVB-N and *K* value determination, are not appropriate for the study of irradiated fish.

A study of amino acid and protein changes of irradiated tilapia (*Tilapia nilotica* × *T. aurea*) and Spanish mackerel (*Scomberomorus commerson*) stored at 2 ± 2°C was performed by Al-Kahtani et al. (1998). The boxes containing the fish and ice were irradiated with a ⁶⁰Co source at 1.5, 3.0, 4.5, 6.0, and 10 kGy. Generally, amino acids of both fish increased or decreased with increasing irradiation dose, with no clear trend of the change. For tilapia, lysine and methionine (g/100 g protein) showed an increase as irradiation dose increased (2.0 ± 0.0, 2.4 ± 0.0, 2.3 ± 0.0, 2.0 ± 0.0, and 2.4 ± 0.14 for methionine and 3.7 ± 0.0, 4.1 ± 0.3, 3.8 ± 0.0, 5.3 ± 0.0, and 5.5 ± 0.1 for lysine at 1.5, 3.0, 4.5, 6.0, and 10 kGy, respectively, at the first day of storage). For Spanish mackerel stored up to 20 days, the high dose of 10.0 kGy contributed to a significant reduction in the amounts of all essential and nonessential amino acids except lysine.

Lakshmanan et al. (1999b) studied irradiated (2 kGy) anchovy (*Stolephorus commersonii*). Treatment resulted in a shelf life of 17 days for the nonpackaged fish when stored under melting ice at 13°C in comparison to a storage life of 13 days for the non-irradiated counterpart. Packaged irradiated fish had a longer shelf life of 20 days; packaging caused drip accumulation and poor appearance of the fish. The protein content decreased after 10 days of storage, giving values of 0.97 ± 0.5 and 0.77 ± 0.01 mg in the case of non-irradiated and irradiated samples, respectively. The protein values decreased even more to 0.21 ± 0.06 and 0.17 ± 0.06 mg, respectively, after 17 days of storage.

Figure 9.1 shows the effect of irradiation on the total viable count (TVC) of anchovy (*Stolephorus commersonii*), non-packaged, and threadfin bream (*Nemipterus japonicus*) aerobically packaged.

Bari et al. (2000) found that irradiation (5 kGy) of fish cutlets, prepared at the laboratory scale according to selected formulation, could extend the shelf life up to 5 weeks at room temperature. In commercially prepared fish cutlets, maximum shelf life extension observed was 14 days for samples treated with 5 kGy of irradiation and stored at ambient temperature on the basis of combined microbiological, chemical, and organoleptic evaluation. The microbiological quality of the commercially prepared fish cutlets revealed the unhygienic conditions of the place where the fish was prepared and the unhygienic storage conditions and temperatures.

Mendes et al. (2000) studied irradiated blue jack mackerel (*Trachurus picturatus*) stored at 3°C for 23 days. In the irradiated samples (1, 2, and 3 kGy), volatile basic nitrogen (VBN) contents increased more gradually with time and levels at the end of the ice storage were, in general, three times lower than in the 0 kGy lot. In these samples, the 30–40 mg/100 g VBN level was only attained in the 1 and 2 kGy lots, at the end of the storage period. No significant differences were determined among the VBN contents of the samples irradiated at different levels. After 23

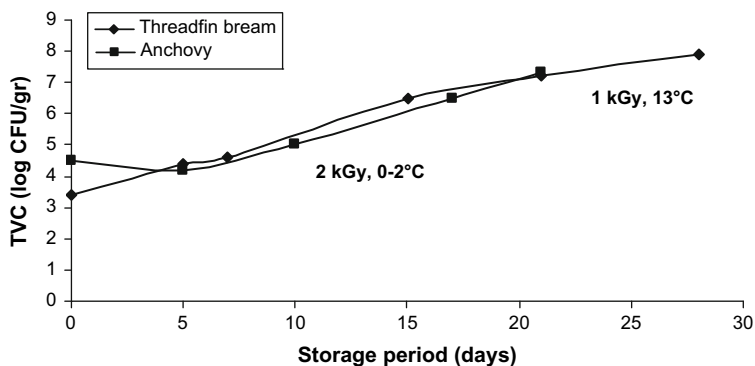


Figure 9.1: Effect of irradiation on the TVC of anchovy (*Stolephorus commersonii*), nonpackaged (Lakshmanan et al., 1999b), and threadfin bream (*Nemipterus japonicus*) aerobically packaged, under storage (Jeevanandam et al., 2001).

days of storage, the TMA content in the 1-, 2-, and 3-kGy samples was 18.9, 30.9, and 10.0 mg/100 g, respectively. The analysis of the results showed that irradiation of samples significantly decreased the contents of TMA.

Samples of tilapia nilotica (*Oreochromis niloticus*) irradiated with 0, 1.0, 2.2, and 5 kGy were stored at temperatures ranging from 0.5 to 2°C for 20 and 30 days. During storage, the level of moisture in the non-irradiated samples decreased and the levels of protein and lipid increased while the irradiated samples remained stable. The levels of TVB-N increased in the non-irradiated samples but tended to remain stable in the irradiated fish samples. The levels of amino acids in muscles and fatty acids in oil remained stable in the irradiated fish stored samples but decreased in the non-irradiated ones. Lipid oxidation showed a tendency to increase when irradiation dose increased (Cozzo-Siqueira et al., 2003).

Mendes et al. (2005) studied fresh Atlantic horse mackerel (*Trachurus trachurus*) γ -irradiated at 1 and 3 kGy and stored in ice for 23 days ($0 \pm 1^\circ\text{C}$). The non-irradiated samples had a sensory shelf life of 8 days, whereas those of the irradiated ones were extended by 4 days. TVCs and levels of amines increased in all samples with storage time, with their contents being significantly reduced by irradiation, even when the lower dose of irradiation (1 kGy) was used. Histamine in the irradiated lots was undetectable when the fish was spoiled at the end of 23 days, whereas in the control lot, the concentration did not exceed the maximum allowed in fresh fish (100 mg/kg). At the beginning of storage, no significant differences were determined between the control and the irradiated lots. However, lower sensory ratings were always ascribed from then onwards.

The impact of irradiation on TMA content of Atlantic horse mackerel (*Trachurus trachurus*) and sea bream (*Sparus aurata*) fillets vacuum packaged (VP), under storage, is shown in Figure 9.2.

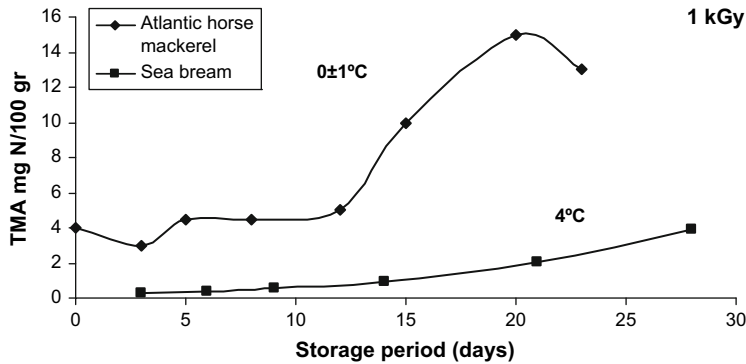


Figure 9.2: Effect of irradiation on TMA content of Atlantic horse mackerel (*Trachurus trachurus*) (Mendes et al., 2005) and sea bream (*Sparus aurata*) fillets VP, under storage (Chouliara et al., 2004).

Dvorak et al. (2005) investigated the effect of irradiated pieces of fish (*Oncorhynchus mykiss*) in relation to color changes. The parameters of color— L^* , a^* , and b^* —were determined. The change in L^* was identical for both irradiated (3 kGy) and non-irradiated samples. This change may be caused by maturation of fish flesh. a^* was identical and b^* decreased. The decrease of the pH was identical for both irradiated and non-irradiated samples. The reduction of the pH in fish flesh within 5 h *postmortem* corresponds with the curve of fish flesh maturation, and so it may be stated that the dose of 3 kGy did not affect the pH.

Silva et al. (2006) studied the effect of γ -radiation (1, 5, and 10 kGy) and post-irradiation ice storage ($2 \pm 0.5^\circ\text{C}$) on horse mackerel (*Trachurus trachurus*) muscle proteins. It was found that irradiation doses of 1 up to 10 kGy seemed to have no significant effect on the proteins of this species. The previous results indicate the possibility of irradiation treatment up to 10 kGy, if needed for extension of horse mackerel shelf life and safety.

The quality of non-irradiated and irradiated (2.5 and 5 kGy) sea bass (*Dicentrarchus labrax*) in ice conditions and stored at 4°C was investigated by Ozden et al. (2007). Among chemical indicators of spoilage, TVB-N values increased to 36.44 mg/100 g for non-irradiated sea bass during iced storage, whereas for irradiated fish lower values of 25.26 and 23.61 mg/100 g were recorded at 2.5 and 5 kGy, respectively (Day 17). Trimethylamine nitrogen (TMA-N) values and TBA values for irradiated samples were lower than those for non-irradiated samples. Sensory evaluation showed that odor, taste, and texture of cooked sea bass decreased with storage time.

Riebroy et al. (2007) irradiated samples of Som-fug (a Thai fermented fish mince) and found that they had higher thiobarbituric acid reactive substances (TBARS) values than that of the control. In general, the rate of increase in TBARS values was greater in samples irradiated with higher doses (6 kGy) during the first 25 days of storage than in control or samples irradiated at

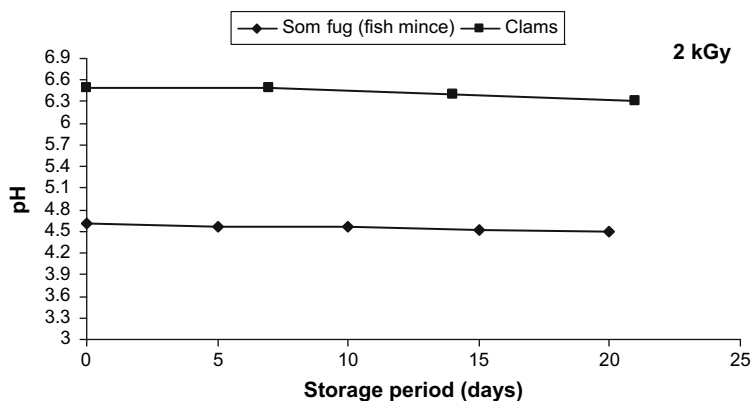


Figure 9.3: Effect of irradiation (2 kGy) on the pH of Som-fug (fish mince) (Riebroy et al., 2007) and homogenates of raw clams (*Gari solida*), under storage (Torres et al., 2001a).

2 kGy. The L^* value of all samples decreased, whereas a^* and b^* values increased throughout storage. Samples irradiated at 2 kGy had the smallest changes in a^* and b^* values. The pH values of all samples decreased gradually during the first 15 days of storage compared with those stored at Day 0.

The effect of irradiation (2 kGy) on the pH of Som-fug (fish mince) and homogenates of raw clams (*Gari solida*), under storage, is clearly shown in Figure 9.3.

Table 9.1 summarizes the quality parameters of irradiated fish and their shelf life extension.

9.2.2 Shellfish

Gardner and Watts (1957) treated oyster meats (*Crassostrea virginica* and *Crassostrea pacificus*) at 0.63, 0.83, and 3.5 kGy of ionizing irradiation and observed the development of undesirable odors. The odor of the raw irradiated oyster meats was described as “grassy” and for the cooked raw irradiated oyster meats the odor was described as “oxidized.” Moreover, they found that irradiation would not benefit preservation because enzyme action continues even at 3.5 kGy at 5°C.

Nickelson (1963) studied clam meats and found no detectable organoleptic differences between non-irradiated controls and clam meats irradiated at up to 8 kGy after 40 days of storage at 6°C. Connors and Steinberg (1964) determined that there is no significant difference between non-irradiated and irradiated samples of clam meats with doses from 2.5 to 5.5 kGy. Moreover, for clams (*Venerupis semidecus sata*) the optimum irradiation dose has been determined to be 1–4.5 kGy, yielding a shelf life of 4 weeks at 0–2°C.

Liuzzo et al. (1970) found that the optimum irradiation dose for shucked oyster meats, which would result in maximum shelf life of approximately 7 days, was 2.5 kGy. The organoleptic

TABLE 9.1 Quality of Irradiated Fish and Shelf Life Extension

| Species | Irradiation Type/Dose | Temperature | Shelf Life | Effect on Quality | References |
|--|-----------------------|---------------------|-------------|--|---|
| Ocean perch (<i>Sebastes alutus</i>) fillets | 1 2 kGy | 0.6°C | 25 28 days | — | Miyauchi et al., 1967; Teeny and Miyauchi, 1970 |
| European hake (<i>Merluccius merluccius</i>) | 1 1.5 kGy | 0.5°C | 24 28 days | — | de la Sierra Serrano, 1970 |
| Argentine whiting (<i>Merluccius hubsi</i>) | 5 kGy | 4°C | 48 days | — | Ritacco, 1976 |
| Channel catfish (<i>Ictalurus punctatus</i>) | 1 2 kGy | 0°C | 20 days | — | Emerson et al., 1964, 1965 |
| Lake trout (<i>Salvelinus namaycush</i>) | — | 0.6°C | 8 days | — | Graikowski et al., 1968 |
| | 3 kGy | 0.6°C | 26 days | The pigment in irradiated samples does not disappear until doses of 7 kGy are employed | |
| Mackerel (<i>Scomber scombrus</i>) | 2.5 kGy | 0.6°C | 30 35 days | — | Slavin et al., 1966 |
| Mackerel (<i>Rastrellinger kanagurta</i>) | 1.5 kGy | 0°C | 21 24 days | — | Ghadi et al., 1978; Hussain, 1980 |
| | 1.5 kGy | 7.8°C | 7 11 days | — | |
| Bombay duck (<i>Harpodon nehereus</i>) | — | Under refrigeration | ~5 7 days | — | Gore and Kumta, 1970; Kumta et al., 1973 |
| | 1.0 2.5 kGy | Under refrigeration | ~18 20 days | 5 kGy is the maximum acceptable dose for this fish because an off flavor develops at this dose but will subside after 4 days | |

(Continued)

TABLE 9.1 Quality of Irradiated Fish and Shelf Life Extension—cont'd

| Species | Irradiation Type/Dose | Temperature | Shelf Life | Effect on Quality | References |
|---|-----------------------|-------------|------------|---|--|
| White pomfret (<i>Stomateus cinereus</i>) | 1 kGy | 0–2°C | 4 weeks | — | Aiyar, 1976; Kumta and Sreenivasin, 1970 |
| Black pomfret (<i>Parastomatus niger</i>) | 1 kGy | 0–2°C | 10–16 days | — | |
| Gray sole (<i>Glyptocephalus cynoglossus</i>) fillets | 1–2 kGy | 0.6°C | 29 days | — | Miyachi et al., 1968 |
| | | 5.6°C | 10–11 days | — | |
| Haddock (<i>Melanogrammus aeglefinus</i>) fillets | 1.5–2.5 kGy | 5.6°C | 22–25 days | — | Rosnivali et al., 1968, 1970 |
| | | 0.6°C | 30–35 days | — | |
| Herring (<i>Clupea herring</i>) | — | 2°C | 10–14 days | The maximum acceptable dose was found to be less than 5 kGy, due to loss of color and natural flavor at 3 kGy and higher | Snauwert et al., 1977 |
| Kembung fish (<i>Rastrelliger neglectus</i>) | 1–2 kGy | 5°C | 12 days | Significant increase in TVB N and hypoxanthine, with a decrease in the specific activity of SH protease and acid phosphatase. However, lower TVB N values and hypoxanthine concentrations determined in samples irradiated at 2 kGy compared to those irradiated at 2 kGy after 7 days of storage | Sofyan, 1978 |

| | | | | | |
|---|--|---------------------|------------|---|--|
| Whitefish (<i>Coregonus clupeaformis</i>) | — | Under refrigeration | 12 15 days | — | Ostovar et al., 1967 |
| | 1.5 3 kGy | Under refrigeration | 15 29 days | — | |
| Ocean perch (<i>Sebastes marinus</i>) | 1.5 2.5 kGy | 0.6°C | 30 days | Doses higher than 1 kGy are not recommended because of sensory changes (off flavor) | Reinacher and Ehlermann, 1978; Ronsivalli and Slavin, 1965 |
| | 1.5 2.5 kGy | 7.8°C | 15 days | | |
| Kamaboko (fish paste) from Pollock and sardine | — | 1 4 and 10 12°C | 5 days | — | Kume et al., 1975; Oku, 1976, 1981; Oku and Kimura, 1975; Sasayama, 1972, 1973, 1977 |
| | 5 kGy | 1 4 and 10 12°C | 34 days | — | |
| Spanish mackerel (<i>Scomberomorus commerson</i>) | γ irradiation/1.5, 3, 4.5, 6, and 10 kGy | 2 ± 2°C | — | Amino acids increased or decreased with increasing irradiation dose with no clear trend of the change | Al Kahtani et al., 1998 |
| Tilapia (<i>Tilapia nilotica</i> x <i>T. aurea</i>) | γ irradiation/1.5, 3, 4.5, 6, and 10 kGy | 2 ± 2°C | — | | |
| Anchovy (<i>Stolephorus commersonii</i>) | — | 13°C | 13 days | The protein content decreased after 10 days of storage, giving values of 0.97 ± 0.5 mg. The protein values decreased further to 0.21 ± 0.06 mg after 17 days of storage. The protein content decreased after 10 days of storage, giving values of 0.77 ± 0.01 mg. The protein values decreased further to 0.17 ± 0.06 mg after 17 days of storage | Lakshmanan et al., 1999b |
| | γ irradiation/2 kGy | 13°C | 17 days | | |

(Continued)

TABLE 9.1 Quality of Irradiated Fish and Shelf Life Extension—cont'd

| Species | Irradiation Type/Dose | Temperature | Shelf Life | Effect on Quality | References |
|---|---------------------------------|---|------------|--|-------------------------|
| Pieces of rainbow trout (<i>Oncorhynchus mykiss</i>) | — | — | — | Some decrease for both irradiated and non irradiated samples | Dvorak et al., 2005 |
| | γ irradiation/3 kGy | — | — | Some change of L^* for both irradiated and non irradiated samples. This change may be due to maturation of fish flesh. a^* remained the same, whereas b^* decreased | |
| | — | — | — | | |
| Tilapia and Spanish mackerel | — | $2 \pm 2^\circ\text{C}$ up to 20 days storage | — | TVB N formation was lower in irradiated fish than in the non irradiated fish. Irradiation also caused a larger increase in TBA values during storage. Some fatty acids decreased by irradiation treatments at all doses Thiamin loss was more severe at higher doses (≥ 4.5 kGy), whereas riboflavin was not affected | Al Kahtani et al., 1996 |
| | γ irradiation/1.5–10 kGy | $2 \pm 2^\circ\text{C}$ at 20 days of storage | — | | |
| | — | $2 \pm 2^\circ\text{C}$ at 20 days storage | — | | |
| | γ irradiation/1.5–10 kGy | $2 \pm 2^\circ\text{C}$ at 20 days of storage | — | | |

| | | | | | |
|---|---------------------------|------------------------------|---------|---|-----------------------------|
| Sea bass (<i>Dicentrarchus labrax</i>) | — | 4°C | 13 days | TVB N values increased to 36.44 mg/100 g (Day 17) | Ozden et al., 2007 |
| | γ irradiation/ 2.5 kGy | 4°C | 15 days | TVB N values increased to 25.26 mg/100 g (day 17) | |
| | γ irradiation/5 kGy | 4°C | 17 days | TVB N values increased to 23.61 mg/100 g (Day 17) | |
| Tilapia nilotica (<i>Oreochromis niloticus</i>) | — | 0.5 °C for 20 and 30 days | — | During storage, moisture in the non irradiated samples decreased whereas protein and lipid increased. The levels of TVB N increased as well | Cozzo Siqueira et al., 2003 |
| | — | 0.5 °C for 20 and 30 days | — | During storage, the level of moisture, protein and lipid remained stable. The levels of TVB N remained stable. Lipid oxidation increased when the dose of irradiation increased | |
| | — | 0.5 °C for 20 and 30 days | — | | |
| | — | 0.5 °C for 20 and 30 days | — | | |
| Black bream (<i>Acanthopagrus australis</i>) | γ irradiation/1 kGy | 22°C | — | Although vitamin E loss was evident in some fillets but correlated with dosage treatments (0.246, 0.274, 0.253, 0.936, 0.512 and 0.510 mg/100 g) | Armstrong et al., 1994 |
| | γ irradiation/2 kGy | 22°C | — | | |
| | γ irradiation/6 kGy | 22°C | — | | |
| Redfish (<i>Centroberyx affinis</i>) | γ irradiation/1 kGy | 22°C | — | | |
| | γ irradiation/2 kGy | 22°C | — | | |
| | γ irradiation/6 kGy | 22°C | — | | |

(Continued)

TABLE 9.1 Quality of Irradiated Fish and Shelf Life Extension—cont'd

| Species | Irradiation Type/Dose | Temperature | Shelf Life | Effect on Quality | References |
|--|---------------------------------------|---------------------------|--|--|---------------------------------|
| Fish cutlets prepared at the laboratory scale | γ irradiation/5 kGy | Ambient temperature | 5 weeks | — | Bari et al., 2000 |
| | | | 14 days | — | |
| Horse mackerel (<i>Trachurus trachurus</i>) | γ irradiation/1, 5, and 10 kGy | $2 \pm 0.5^\circ\text{C}$ | — | No effect on the proteins of this species. | Silva et al., 2006 |
| Whitefish (<i>Coregonus clupeaformis</i>) | — | 3°C | 7.8 ± 1 days average shelf life | TBA for unirradiated samples remained low and almost unchanged throughout the study | Chuaqui Offermanns et al., 1988 |
| | γ irradiation/0.82 kGy | 3°C | 16.4 ± 3.6 days average shelf life | TBA values increased with storage | |
| | γ irradiation/1.22 kGy | 3°C | 20.9 ± 3.9 days average shelf life | TBA values increased with storage | |
| Som fug (bigeye snapper, <i>Priacanthus tayenus</i>), a Thai fermented fish mince | — | 4°C | — | L^* value of all samples decreased, whereas a^* and b^* values increased throughout storage. pH values of all samples decreased gradually. | Riebroy et al., 2007 |

| | | | | |
|--|----------------------------|-------|---------|---|
| Som fug (bigeye snapper, <i>Priacanthus tayenus</i>), a Thai fermented fish mince | γ irradiation/2 kGy | 4°C | — | <p>L^* value of all samples decreased, whereas a^* and b^* increased with storage. The smallest changes were in a^* and b^*. TBARS values greater in samples irradiated with 6 kGy. pH of all samples decreased gradually</p> <p>L^* of all samples decreased, whereas a^* and b^* increased throughout storage. TBARS dropped in samples irradiated with 2 kGy. pH values of all samples decreased gradually</p> |
| | γ irradiation/6 kGy | 4°C | — | |
| Refrigerated fish (<i>Cyprinus carpio</i>) | No data | 0 2°C | 16 days | <p>Chemical tests of freshness such as TVB N and K value not appropriate for irradiated fish identification. Organoleptic estimations and a new odor concentration meter fit best the objective determination of freshness</p> |

(Continued)

TABLE 9.1 Quality of Irradiated Fish and Shelf Life Extension—cont'd

| Species | Irradiation Type/Dose | Temperature | Shelf Life | Effect on Quality | References |
|---|-------------------------|-----------------|----------------------|---|---------------------|
| Blue jack mackerel (<i>Trachurus picturatus</i>) | — | 3°C for 23 days | Between 3 and 4 days | The VBN values of the 0 kGy meat exceeded the acceptable level (30–40 mg/100 g) after the fourth day | Mendes et al., 2000 |
| | γ irradiation/ 1 kGy | 3°C for 23 days | 8 days | VBN contents increased more gradually with time, and levels at the end of the ice storage were three times lower. After 23 days of storage, the TMA content was 18.9 mg/100 g | |
| | γ irradiation/ 2 kGy | | | VBN contents increased with time, and levels at the end of the ice storage were, in general, three times lower. After 23 days of storage, the TMA content was 30.9 mg/100 g | |
| | γ irradiation/ 3 kGy | | | VBN contents increased with time, and levels at the end of the ice storage were, in general, three times lower. After 23 days of storage, the TMA content was 10.0 mg/100 g | |

quality was not decreased until after 7 days storage on ice. Moreover, it was found that irradiation doses higher than 1 kGy altered the retention of B vitamins, the percentage moisture, glycogen content, and the soluble sugar content of oyster meats.

Poole et al. (1990) treated chilled saucer scallops (*Amusium balloti*) with 0.5, 1.5, and 3 kGy, yielding a shelf life of 28 days (raw) and 43 days (cooked), compared to 13–17 days for the non-irradiated meats. Doses of 1.5 kGy and higher resulted in a soft, spongy, mushy texture.

A sensory evaluation was performed for irradiated “choro” mussels (*Aulacome ater*), “abanico” clams (*Argopecten purpuratus*), and common clams (*Gari solida*). Choro mussels, raw or cooked, irradiated at 1.0 kGy were acceptable in appearance, odor, flavor (cooked only), and texture well beyond the experimental period of 21 days at 0–2°C so that there was no need for higher doses. For common clams, a dose of 2.0 kGy was optimal. With regard to abanico clams, cooked samples were acceptable in appearance, flavor, and texture when treated at either 1.0 or 2.0 kGy, but even 2.0 kGy did not provide acceptable scores beyond 14 days at 0–2°C because of poor initial quality of the samples (Torres et al., 2001a).

9.2.3 Crustaceans

Scholz et al. (1962) found that Pacific shrimp (*Pandalus jordani*) irradiated with 5 kGy yields a shelf life of 3 weeks at 3°C with no noticeable off-flavors. The optimum dose for raw, beheaded, tropical shrimps (*Penaeus* spp.) has been found to be 1.5–2 kGy, yielding a shelf life of approximately 42 days at 3°C. However, if a 4-min blanching is employed prior to 1.5–2 kGy, the shelf life is extended to 130 days (Gueavara et al., 1965; Kumta et al., 1970). The optimum dose for peeled European brown shrimp (*Crangon vulgaris* and *Crangon crangon*) is 1.5 kGy, which yields a shelf life of 23 days at 2°C, compared to 9–16 days for non-irradiated shrimp (Vyncke et al., 1976). According to many studies (Ehlermann, 1976; Ehlermann and Diehl, 1977; Ehlermann and Muenzer, 1976), the removal of oxygen from the environment also helps in maximizing the irradiation effects.

In a study by K. H. Lee et al. (2002), shrimp (*Acetes chinensis*) were sliced, washed, and then salted with 15 and 20% (w/w) sodium chloride. Salted shrimp was irradiated with 0, 5, and 10 kGy at two different stages—immediately after processing salted shrimp and at the optimum fermentation period—and fermented at 15°C for 10 weeks. Non-irradiated shrimp with 30% salt were also prepared as a control. Irradiated shrimp were not different in proximate composition, salinity, and water activity from nonirradiated shrimp with the same salt addition and the same irradiation time. During fermentation, VBN contents increased as the salt concentration and irradiation dose decreased. The results of sensory analysis, total bacterial count and pH, revealed that the combination of low salt concentration (15 or 20%) and γ -irradiation (5 or 10 kGy) was effective in processing low-salted and fermented shrimp. The findings revealed no adverse sensory quality and improved microbial shelf stability compared to control samples (30% of salt addition).

Sinanoglou et al. (2007) investigated frozen and irradiated mollusks (squid, octopuses, and cuttlefish) and crustaceans (shrimp). Total lipids of the cephalopod mollusk *Todorodes sagittatus* (squid), *Octopus vulgaris* (octopus), and *Sepia officinalis* (cuttlefish) non-irradiated mantle constituted 1.80, 2.32, and 1.55% of the wet tissue, respectively. The lipid content of *Penaeus monodon* non-irradiated muscle and cephalothorax was 1.30 and 2.75%, respectively. At doses of 4.7 kGy, mollusk mantle showed a loss of the total lipid content of 4.5–6.9%, and in shrimp muscle and cephalothorax the decrease was 6.2 and 5.8%, respectively, in comparison with the non-irradiated samples, but all changes were not statistically significant. The total fatty acid content and the ω -3: ω -6 fatty acid ration was not affected. A dose-dependent significant decrease in the ratio of polyunsaturated fatty acids:saturated fatty acids was observed. With the increase in radiation dose, redness (*a*) and yellowness (*b*) values showed variation, whereas the lightness (*L*) value was significantly decreased in mollusk mantles and shrimp muscle and increased in shrimp cephalothorax. Color changes increased as the dose increased.

Sharma et al. (2007) examined the influence of γ -irradiation on the volatile compounds profile of shrimp (*Solenocera choprii*). The whole shrimp, head, or muscle portions were separately irradiated at a dose of 2 kGy. The volatile components from non-irradiated and irradiated portions were isolated. Quantitative analysis of the data revealed that the overall effect of irradiation on volatile flavor compounds of the whole shrimp or fractions was not significant, suggesting that the sensory value of shrimp muscle or shell waste was not affected by γ -irradiation.

The quality parameters of irradiated shellfish and crustaceans and shelf life extension are given in Table 9.2.

9.3 The Microflora of Irradiated Fishery Products

9.3.1 Fish

Kazanas et al. (1966) studied the effects of irradiation on yellow perch fillets (*Perca flavescens*). The samples were irradiated with 3 and 6 kGy and stored at 1 or 6°C. Total plate counts (TPC) prior to irradiation did not exceed 8.7×10^5 per gram of sample. This count was reduced nearly 100% by irradiation with either 3 or 6 kGy. Progressively lower maximal bacterial populations and lengthened lag phases were obtained as more radiation was used. The growth rate of the population did not appear to decrease significantly. The shelf life of non-irradiated fillets at 1°C was found to be approximately 9–13 days, which was extended 3.6- and 5-fold by doses of 3 and 6 kGy, respectively. Increasing the storage temperature to 6°C decreased the lag phase and greatly accelerated spoilage compared with irradiated fillets stored at 1°C. The shelf life of non-irradiated samples stored at 6°C was approximately 6 days; this was extended 3- and 3.5-fold by irradiation to 3 and 6 kGy, respectively.

TABLE 9.2 Quality of Irradiated Shellfish and Crustaceans and Shelf Life Extension

| Species | Irradiation Type/Dose | Temperature | Shelf Life | Quality | Reference |
|---|----------------------------------|-------------|------------|---|----------------------|
| Pacific shrimp (<i>Pandalus jordani</i>) | 5 kGy | 3°C | 3 weeks | No noticeable off flavors | Scholz et al., 1962 |
| Clam meats | — | 6°C | 40 days | No detectable organoleptic differences | Nickelson, 1963 |
| | up to 8 kGy | 6°C | 40 days | No detectable organoleptic differences | |
| Peeled European brown shrimp (<i>Crangon vulgaris</i> and <i>Crangon crangon</i>) | — | 2°C | 9–16 days | — | Vyncke et al., 1976 |
| | 1.5 kGy | 2°C | 23 days | — | |
| Raw or cooked “choro” mussels (<i>Aulacome ater</i>) | γ irradiation/ 1 kGy | 0–2°C | — | Acceptable in appearance, odor, flavor (cooked only), and texture well beyond the experimental period of 21 days | Torres et al., 2001a |
| Cooked “abanico” clams (<i>Argopecten purpuratus</i>) | γ irradiation/ 1.0 or 2.0 kGy | 0–2°C | — | Acceptable in appearance, flavor, and texture when treated at either 1.0 or 2.0 kGy, irradiation 2.0 kGy gave no acceptable scores beyond 14 days at 0–2°C due to poor initial quality of the samples | |
| Shrimp head or muscle portions (<i>Solenocera choprii</i>) | γ irradiation/ 2 kGy | — | — | The sensory value of shrimp muscle or shell waste was not affected by irradiation | Sharma et al., 2007 |

Kazanas and Emerson (1968) studied irradiated (1 and 2 kGy) and non-irradiated yellow perch fillets (*Perca flavescens*) stored at 1°C. Organisms initially isolated from the non-irradiated fillets, in order of decreasing number, consisted of *Flavobacterium*, *Micrococcus-Sarcina*, *Achromobacter-Alcaligenes-Mima*, *Pseudomonas*, *Microbacterium*, *Vibrio*, *Bacillus*, *Corynebacterium*, *Lactobacillus*, *Brevibacterium*, and *Aeromonas*. Plate counts for fish prior to irradiation showed the presence of approximately 10^6 organisms/g of sample. Irradiation to 1 and 2 kGy produced 1.4 and 3 log reductions of the initial count, respectively. Irradiation to 1 and 2 kGy increased shelf life from 10 days for the control to 18 days, whereas irradiation of samples to 3 and 6 kGy resulted in an extension of shelf life to approximately 43 and 55 days, respectively.

In their experiments, Laycock and Regier (1970) used haddock (*Melanogrammus aeglefinus*) that was filleted after 2, 5, and 9 days in ice. Henceforth, it will be referred to as 2-, 5-, and 9-day fish. Irradiation (1 kGy) reduced the total bacterial count (TBC) by approximately 1 log order. *Achromobacter* was also reduced in numbers by approximately 1 log order by 1 kGy irradiation. *Pseudomonads*, isolated immediately after irradiation from fillets of 5- and 9-day fish, seem to have been reduced between 2 and 3 log orders. The storage life (3°C) of the non-irradiated fillets was determined by sensory analysis to be 9 days for the 2-day fish, 7 days for the 5-day fish, and 5 days for the 9-day fish. The irradiated samples (3°C) were judged spoiled after approximately 18 days of storage for 2- and 5-day samples and after approximately 13 days of storage for 9-day samples.

Clostridium botulinum type E was inoculated into haddock fillets at 10^4 spores/g and irradiated at 1 and 2 kGy. Those irradiated at 1 kGy were acceptable because spoilage occurred before toxin production was noticed. However, the 2-kGy exposure resulted in haddock fillets that had toxin present prior to spoilage developing (Eklund, 1982). Non-inoculated, naturally contaminated cod and haddock did not form toxins at doses as high as 2 kGy and stored at 10°C (Nickerson and Goldblith, 1969/1971).

Kamaboko is a fish paste (from pollock and sardine), a favorite product in Japan. Samples of Kamaboko were irradiated with doses up to 5 kGy and stored at 1–4 and 10–12°C. Shelf life was extended from approximately 5 days (non-irradiated samples) up to 34 days for samples irradiated with 5 kGy. The highest dose used (5 kGy) resulted in the survival only of the genus *Bacillus*. However, minor effects on flavor were observed, and it was concluded that the optimum dose is 3 kGy; at 10–12°C the shelf life extension was from 14 to 42 days (Oku, 1976, 1981; Oku and Kimura, 1975; Sasayama, 1972, 1973, 1977; Kume et al. 1975).

“Screening” packs comprising 10 lots each of codfish cake, with each lot containing approximately 10^6 spores of a different strain (5 type A and 5 type B) of *Clostridium botulinum* per can, were irradiated at $30 \pm 10^\circ\text{C}$ with a series of increasing doses (20 replicate cans/dose) of γ -irradiation. These packs were incubated for 6 months at 30°C. Results indicated that the experimental sterilizing dose (ESD) for codfish cake was $27.5 < \text{ESD} < 30$ kGy (Anellis et al. 1972).

Hussain et al. (1985) irradiated Indian mackerel (*Rastrellinger kanagurta*) at 0–3 kGy and stored them at 1–3°C. The bacterial load was 1×10^5 at Day 0 and increased to only 2.5×10^7 in 28 days. *Pseudomonas* and *Proteus* spp. were the predominant genera in the controls, whereas *Acromobacter*, *Flavobacterium*, *Bacillus*, and *Micrococcus* dominated in the irradiated fillets. It was determined that a pretreatment with a dip in 10% sodium polyphosphate decreased the associated drip loss. Optimal conditions were maintained for 3 weeks at 1.5 kGy with a pre-dip in 10% sodium polyphosphate.

In a study by Ogbadu (1988), smoked dried fish were inoculated with spores of *Aspergillus flavus* (U.I. 81) and irradiated with doses of 0.625, 1.26, 2.60, and 6.00 kGy of γ -irradiation. The effect on aflatoxin B₁ production on subsequent incubation for 8 days as stationary cultures was measured. The amount of aflatoxin B₁ produced was found to decrease with increased γ -irradiation dose levels (4.73, 2.45, 1.90, 0.80, and 0.51 mg/kg for 0, 0.625, 1.26, 2.60, and 6.00 kGy, respectively), whereas the non-irradiated control produced significantly greater amounts of aflatoxin B₁ compared to the treated cultures.

Chuaqui-Offermans et al. (1988) investigated the effects of irradiation on whitefish (*Coregonus clupeaformis*) at 3°C storage. The non-irradiated samples had an initial count of 1.1×10^5 microorganisms/g. In samples irradiated to 0.82 and 1.22 kGy, the initial bacterial count was reduced to 4.1×10^2 and 1.0×10^2 organisms/g, respectively. Psychrotrophs were also reduced by 2 and 3 orders of magnitude, and pseudomonads were not detected immediately after irradiation. By Day 7, non-irradiated fish had a very high standard plate count (SPC), and by Day 10 the count exceeded 10^7 /g. A maximum tolerable SPC for fish of 10^7 /g was suggested by the Canadian Food Products Development Centre based on guidelines by Agriculture Canada (1982) for red meats and poultry. Fish samples irradiated at 0.82 and 1.22 kGy did not reach SPC levels of 10^7 /g until Days 20 and 28, respectively. The pseudomonad count in irradiated samples remained quite low during the storage period. The psychrotroph count became quite high on Day 13 (10^8 /g); however, psychrotrophs are not related to spoilage. The shelf life of samples based only on microbiologic analyses, irradiated at 0.0, 0.82, and 1.22 kGy, was 7, 20, and 20–28 days, respectively.

Valdes and Szeinfeld (1989) found that hake fillets (*Merluccius merluccius hubsi*) irradiated with a 2-kGy dose showed a 1-log cycle reduction in bacterial number versus the controls, whereas a 3-log cycle reduction was observed at 6–10 kGy. A 6-kGy exposure was determined to be optimal. Washed red hake fish mince (*Urophycis chuss*) was irradiated at 0.66 and 1.31 kGy and then stored aerobically at 3.3°C. Total aerobic plate counts (TAPC) were monitored and found to be less than 10^6 CFU/g for 4, 10, and 17 days after irradiation at all doses. Sensory evaluation showed that irradiated samples were superior for 12–18 days longer than the non-irradiated controls, as well as microbiologically for 6–13 days longer than the non-irradiated ones (Dymsza et al., 1990).

Smoked salmon fillets were irradiated with 2 and 4 kGy. The main quality that was lost during the 4-kGy irradiation was the normal cherry-red color associated with smoked salmon. Color loss was not observed in samples irradiated with 2 kGy. Both doses were effective in reducing the number of microorganisms in samples, but the 4-kGy dose eliminated all coliforms, fecal streptococci, and *Staphylococcus aureus*. The non-irradiated samples reached an unacceptable plate count after 1 month of refrigerated storage, whereas the microbiological quality was maintained for 3 and 4 months at 2 and 4 kGy, respectively (Hammad and El-Mongy, 1992).

Cho et al. (1992) studied dried fish powders inoculated with mesophilic aerobic bacteria, molds, and coliforms at 10^3 – 10^7 , 10^2 – 10^3 , and 10^2 – 10^6 CFU/g, respectively. It was determined that if the samples were irradiated with 5–10 kGy, all molds and coliforms were eliminated but the mesophilic plate counts were reduced only to $<10^3$ CFU/g.

Abu-Tarboush et al. (1996) studied tilapia (*Tilapia nilotica* × *T. aurea*) and Spanish mackerel (*Scomberomorus commerson*) that were subjected to γ -irradiation doses of 1.5, 3.0, 4.5, 6, and 10 kGy. The irradiated and non-irradiated fish were stored at $2 \pm 2^\circ\text{C}$. Doses of 3.0 and/or 4.5 kGy extended the sensory acceptability (appearance, odor, texture, and taste) and the microbial quality (total count and coliforms) by 8 days compared to the non-irradiated controls. H_2S -producing bacteria were low in both types of fish, and a dose of 1.5 kGy kept their population at low levels throughout the storage period. *Yersinia* and *Campylobacter* species were effectively eliminated by doses of 1.5 and 3 kGy. Furthermore, this dose level was also sufficient to eliminate *Salmonella* spp. from both fish. Doses of 6 and 10 kGy caused a reduction in psychrotrophic counts but were detrimental to the quality of both species.

Studies were carried out to evaluate the microbiological profile, shelf life, and quality of γ -irradiated Nagli fish (*Sillago sihama*). Non-irradiated samples had a shelf life of 7 or 8 days of storage at 1 – 2°C , whereas irradiated samples (2 and 3 kGy) were acceptable up to 19 days. *Salmonella* sp. was not detected in 3-kGy irradiated samples, whereas 2 kGy destroyed *Vibrio parahaemolyticus* and *Staphylococcus aureus*. *Listeria monocytogenes* and *Yersinia enterocolitica* were not detected, but nonpathogenic species such as *Listeria grayi*, *Listeria murrayi*, and *Y. tuberculosis* were present in the fish prior to irradiation. Irradiation doses of 2 and 3 kGy destroyed *Yersinia* sp. and *Listeria* sp., respectively (Ahmed et al., 1997).

Kamat and Thomas (1998) investigated the influence of low (0.39–1.1%), medium (4.25%), and high (7.1–32.5%) fat levels in fish on irradiation inactivation of foodborne pathogens. Cells of *Listeria monocytogenes* 036, *Yersinia enterocolitica* F5692, *Bacillus cereus*, and *Salmonella typhimurium* at logarithmic phase were inoculated in 10% fish homogenates and subjected to γ -irradiation at ice temperature (0 – 1°C) with doses ranging from 0.05 to 0.08 kGy. The D_{10} values were 0.2–0.3, 0.15–0.25, 0.1–0.15, and 0.09–0.1 kGy for *Listeria monocytogenes* 036, *Bacillus cereus*, *Salmonella typhimurium*, and *Yersinia enterocolitica* F5692, respectively. It was concluded that the irradiation resistance of each organism was not affected by the fat content of the fish.

Lakshmanan et al. (1999b) determined that the initial bacterial load of anchovy (*Stolephorus commersonii*), which was approximately 10^4 CFU/g, increased during storage. During the entire storage period of more than 20 days, the CFU levels of irradiated, nonpackaged samples were 1 ± 2 log cycles less than those of the non-irradiated, nonpackaged control samples. Packaged, irradiated samples had lower CFU scores compared with packaged, non-irradiated samples. The increase in CFU levels in packaged samples was lower than that of the respective nonpackaged samples. Packaged irradiated samples had a longer shelf life of 20 days compared to a storage life of 13 days for the non-irradiated counterpart.

Mendes et al. (2000) found that irradiation of samples at different levels resulted in a proportional reduction in the number of bacteria in blue jack mackerel (*Trachurus picturatus*) stored at 3°C. Therefore, lower values were determined in the 3-kGy lot and bacterial counts were progressively higher in the 1-, 2-, and 0-kGy samples. At spoilage, the non-irradiated 13-day-old fish samples had 5–10 times as many bacteria as the irradiated counterparts on the same day. The storage life of non-irradiated fish (0-kGy lot) was found to be 3 or 4 days. Irradiation of the samples at the tested doses extended the storage life by 4 or 5 days, with the fish being unacceptable after 8 days. Moreover, sensory evaluation data showed that whereas non-irradiated fish tended to deteriorate in quality fairly rapidly, the irradiated samples appeared to remain at borderline quality prior to becoming unacceptable, for a longer time.

The D_{10} value of toxinogenic *Vibrio cholerae* O1 El Tor, Inaba was determined *in vitro* to be 0.13 kGy and in inoculated fresh fillets of saurel (*Trachurus picturatus murphyi*) to be 0.12 kGy. In another Pacific fish species known in Peru as “lisa,” *Mugil cephalus*, the D_{10} value was 0.13 kGy. A dose of 1.0 kGy doubled the microbiological shelf life of fish fillets during post-irradiation storage at 0–1°C to approximately 30 days. This dose was also deemed optimal for preserving all sensory characteristics evaluated except appearance, due to a darkening of fillets. According to Cozzo-Siqueira et al. (2003), irradiated (1, 2.2, and 5 kGy) samples of tilapia nilotica (*Oreochromis niloticus*) stored at temperatures ranging from 0.5 to 2°C for 20 and 30 days had a microbiological content below the levels established by the Brazilian seafood legislation, whereas the non-irradiated samples had a higher microbiological content and were not in conformity with the officially permitted levels.

Jaczynski and Park (2003) investigated electron penetration and microbial inactivation by electron beam (e-beam) in surimi seafood. Dose map revealed that one- and two-sided e-beam could efficiently penetrate 33- and 82-mm-thick surimi seafood, respectively. Modeling of microbial inactivation by e-beam demonstrated that two-sided e-beam may control *Staphylococcus aureus* if the surimi seafood package is thinner than 82 mm. The $D_{e\text{ beam}}$ value for *Staphylococcus aureus* was 0.34 kGy. An e-beam dose of 4 kGy resulted in a minimum of a 7-log and most likely a 12-log reduction of *Staphylococcus aureus*. Microbial inactivation was slower when frozen samples were subjected to e-beam.

Jo et al. (2005) investigated the effects of irradiation for eliminating *Salmonella typhimurium*, *Escherichia coli*, *Staphylococcus aureus*, and *Listeria ivanovii* on three prepared seafood products that are used to make a laver (dried seaweed) roll. The radiation sensitivity (D_{10} values) of these organisms ranged from 0.23 to 0.62 kGy in imitation crab leg, 0.31 to 0.44 kGy in surimi gel, and 0.27 to 0.44 kGy in dried seaweed. The growth of all four test organisms inoculated (10^8 CFU/g) into these foods was inhibited by irradiation during 24 h of post-irradiation storage regardless of the temperature (10, 20, and 30°C). *Listeria ivanovii* was not detected after a 3-kGy treatment, but the other pathogens were not detected after irradiation at 2 kGy.

Ozden et al. (2007) studied non-irradiated and irradiated (2.5 and 5 kGy) sea bass (*Dicentrarchus labrax*) in ice conditions at 4°C and found that microbial counts (psychrotrophic bacteria, mesophilic aerobic bacteria, H₂S-producing bacteria, Enterobacteriaceae, and pseudomonads) for non-irradiated sea bass samples were higher than those for irradiated fish. The results showed that the shelf life of sea bass stored in ice is 13 days for non-irradiated sea bass and 15 days for 2.5-kGy irradiated and 17 days for 5-kGy irradiated sea bass.

Riebroy et al. (2007) investigated the effects of irradiation at different doses (0, 2, and 6 kGy) on Som-fug (bigeye snapper, *Priacanthus tayenus*), a Thai fermented fish mince. On Day 0, the control sample had a TVC of 2.9×10^8 CFU/g and lactic acid bacteria (LAB) of 2.8×10^8 CFU/g. LAB, yeast, and mould counts in samples irradiated at 6 kGy were not detectable throughout the storage of 30 days at 4°C, whereas no growth was found in the sample irradiated at 2 kGy within the first 10 days.

The impact of various irradiation doses on fish microflora and fish shelf life is given in Table 9.3.

9.3.2 Shellfish

Shiflett et al. (1966) identified the microorganisms in Dungeness crabmeat (*Cancer magister*) and Pacific oysters (*Crassostrea gigas*). The initial flora of the shellfish and the flora changed during storage at 7°C. The microbial flora shifts in both shellfish were also determined after irradiation at 1 and 4 kGy and during subsequent storage at 7°C. The *Achromobacter* species predominated in the initial flora of crabmeat (77.0%). The predominant position of this group increased to 99.2% after 1 kGy and to 100% after 4 kGy. A large percentage of *Lactobacillus* was detected in oysters (55.0%). The *Lactobacillus* species were predominant after 1 kGy (92.4%), but the predominant survivors after 4 kGy were the *Achromobacter* species (99.3 %).

Dixon (1992) irradiated Florida shellstock oysters. A 2- or 3-log cycle reduction in bacterial counts was observed at all doses immediately after irradiation. Although bacterial counts were significantly reduced in irradiated oysters and *Vibrio vulnificus* demonstrated a high radio-sensitivity, the shelf life of the irradiated shellfish was significantly reduced at doses higher than 1 kGy.

TABLE 9.3 The Microflora of Irradiated Fish

| Species | Irradiation Type/ Dose | Temperature | Shelf Life | Results | Reference |
|--|--|----------------------------|------------|---|-----------------------------|
| <i>Tilapia nilotica</i> (<i>Oreochromis niloticus</i>) | γ irradiation/1.0, 2.2, and 5 kGy | 0.5 2°C for 20 and 30 days | — | Irradiated samples had a microbiological content below the levels established by the Brazilian seafood legislation, whereas the non irradiated samples had a higher microbiological content and were not in conformity with the officially permitted levels | Cozzo Siqueira et al., 2003 |
| Golden anchovy (0.39% fat content) | γ irradiation/1 kGy | 0 1°C | — | <i>Listeria monocytogenes</i> 036, <i>Yersinia enterocolitica</i> F5692, <i>Bacillus cereus</i> , and <i>Salmonella typhimurium</i> showed no difference in their survival | Kamat and Thomas, 1998 |
| Indian sardine (7.1% fat content) | γ irradiation/1 kGy | 0 1°C | — | | |
| Golden anchovy (0.39% fat content) | γ irradiation/3 kGy | 0 1°C | — | | |
| Indian sardine (7.1% fat content) | γ irradiation/3 kGy | 0 1°C | — | | |
| Mullet (<i>Mugil nuema</i>) | 1 kGy (no irradiation type) | — | — | Motility decrease of <i>Phagicola longa</i> parasites from 100 to 15% | Antunes et al., 1993 |
| | 2 kGy (no irradiation type) | — | — | Motility decrease of <i>Phagicola longa</i> parasites from 100 to 17% | |
| | 4 kGy (no irradiation type) | — | — | <i>Phagicola longa</i> metacercaria inviability | |
| | 10 kGy (no irradiation type) | — | — | <i>Phagicola longa</i> metacercaria inviability | |
| Gray mullet (<i>Mugil plunus</i>) | 2.0, 2.5, 3.0, and 3.5 kGy (no irradiation type) | — | — | Motility decrease of <i>Phagicola longa</i> parasites from 56 to 31, 9, 18, and 5%, respectively | |
| | 4.0 kGy (no irradiation type) | — | — | Tending to be the control dose for <i>P. longa</i> | |

(Continued)

TABLE 9.3 The Microflora of Irradiated Fish—cont'd

| Species | Irradiation Type/ Dose | Temperature | Shelf Life | Results | Reference |
|--------------------------------------|------------------------------------|------------------|------------|---|--------------------|
| Imitation crab leg | γ irradiation/1 kGy | 10, 20, and 30°C | — | <i>Salmonella typhimurium</i> , <i>Escherichia coli</i> , and <i>Staphylococcus aureus</i> were not detected | Jo et al., 2005 |
| Surimi gel | γ irradiation/1 kGy | 10, 20, and 30°C | — | <i>Salmonella typhimurium</i> , <i>Escherichia coli</i> , and <i>Staphylococcus aureus</i> were not detected | |
| Dried seaweed | γ irradiation/1 kGy | 10, 20, and 30°C | — | <i>Salmonella typhimurium</i> , <i>Escherichia coli</i> , and <i>Staphylococcus aureus</i> were not detected | |
| Imitation crab leg | γ irradiation/3 kGy | 10, 20, and 30°C | — | <i>Listeria ivanovii</i> was not detected | |
| Surimi gel | γ irradiation/3 kGy | 10, 20, and 30°C | — | <i>Listeria ivanovii</i> was not detected | |
| Dried seaweed | γ irradiation/3 kGy | 10, 20, and 30°C | — | <i>Listeria ivanovii</i> was not detected | |
| Nagli fish (<i>Sillago sihama</i>) | — | 1 2°C | 7 8 days | — | Ahmed et al., 1997 |
| | γ irradiation/2 kGy | 1 2°C | 19 days | Elimination of <i>Vibrio parahaemolyticus</i> and <i>Staphylococcus aureus</i> . Elimination of <i>Yersinia</i> sp. | |
| Nagli fish (<i>Sillago sihama</i>) | γ irradiation/3 kGy | 1 2°C | 19 days | <i>Salmonella</i> sp. were not detected Elimination of <i>Listeria</i> sp. | |
| Smoked dried fish | — | — | — | 4.73 mg/kg aflatoxin B ₁ | Ogbadu, 1988 |
| | γ irradiation/ 0.625 kGy | — | — | 2.45 mg/kg aflatoxin B ₁ | |
| | γ irradiation/ 1.26 kGy | — | — | 1.90 mg/kg aflatoxin B ₁ | |
| | γ irradiation/ 2.60 kGy | — | — | 0.80 mg/kg aflatoxin B ₁ | |
| | γ irradiation/ 6.00 kGy | — | — | 0.51 mg/kg aflatoxin B ₁ | |

| | | | | | |
|---|---------------------------------|---------|--|--|---------------------------------|
| Tilapia (<i>Tilapia nilotica</i> × <i>T. aurea</i>) and Spanish mackerel (<i>Scomberomorus commerson</i>) | — | 2 ± 2°C | — | — | Abu Tarboush et al., 1996 |
| | 1.5 kGy | 2 ± 2°C | — | The population of H ₂ S producing bacteria remained low throughout the storage period. Elimination of <i>Yersinia</i> and <i>Salmonella</i> spp. | |
| | 3.0 kGy | 2 ± 2°C | 8 day shelf life extension compared to untreated samples | Elimination of <i>Campylobacter</i> | |
| | 4.5 kGy | 2 ± 2°C | 8 day shelf life extension compared to untreated samples | — | |
| | 6 and 10 kGy | 2 ± 2°C | — | Reduction in psychrotrophic counts. Detrimental effects to the quality of both species of fish | |
| Whitefish (<i>Coregonus clupeaformis</i>) | — | 3°C | 7 days based only on microbiological data | Initial count of 1.1 × 10 ⁵ microorganisms/g | Chuaqui Offermanns et al., 1988 |
| | γ irradiation/0.82 and 1.22 kGy | 3°C | 20 days based only on microbiological data | Reduced to 4.1 × 10 ² organisms/g Psychrotrophs were also reduced by 2 orders of magnitude Pseudomonads were not detected immediately after irradiation | |
| | γ irradiation/0.82 and 1.22 kGy | 3°C | 20 28 days based only on microbiological data | Reduced to 1.0 × 10 ² organisms/g Psychrotrophs were also reduced by 3 orders of magnitude Pseudomonads were not detected immediately after irradiation | |

(Continued)

TABLE 9.3 The Microflora of Irradiated Fish—cont'd

| Species | Irradiation Type/ Dose | Temperature | Shelf Life | Results | Reference |
|--|----------------------------|-------------|------------|--|---------------------------|
| Yellow perch fillets (<i>Perca flavescens</i>) | — | 1°C | 10 days | Approximately 10^6 organisms/g | Kazanas and Emerson, 1968 |
| | γ irradiation/1 kGy | 1°C | 18 days | 1.4 log reduction of the initial count | |
| | γ irradiation/2 kGy | 1°C | 18 days | 3 log reduction of the initial count | |
| | γ irradiation/3 kGy | 1°C | 43 days | — | |
| | γ irradiation/6 kGy | 1°C | 55 days | — | |
| Som fug (bigeye snapper, <i>Priacanthus tayenus</i>), a Thai fermented fish mince | — | 4°C | — | TVC of 2.9×10^8 CFU/g and LAB of 2.8×10^8 CFU/g | Riebroy et al., 2007 |
| | γ irradiation/2 kGy | 4°C | — | No LAB; yeast and mould counts growth was found in the sample irradiated at 2 kGy within the first 10 days | |
| | γ irradiation/6 kGy | 4°C | — | LAB; yeast and mould counts in samples irradiated at 6 kGy were not detectable throughout the storage of 30 days | |

| | | | | | |
|--|--|------------------|-------------------------------|--|----------------------|
| Yellow perch fillets (<i>Perca flavescens</i>) | — | 1°C | 9 13 days | Initial total counts ranged from 0.93×10^5 to 8.62×10^5 per gram | Kazanas et al., 1966 |
| | — | 6°C | 6 days | | |
| | γ irradiation/3 kGy | 1°C | 3.6 fold shelf life extension | Nearly 100% reduction of microbial count | |
| | γ irradiation/6 kGy | 1°C | 5 fold shelf life extension | Nearly 100% reduction of microbial count. Progressively lower maximal bacterial populations and lengthened lag phases were obtained as more radiation was used | |
| | γ irradiation/3 kGy | 6°C | 3 fold shelf life extension | Nearly 100% reduction of microbial count | |
| | γ irradiation/6 kGy | 6°C | 3.5 fold shelf life extension | Nearly 100% reduction of microbial count. Progressively lower maximal bacterial populations and lengthened lag phases were obtained as more radiation was used | |
| Codfish cake approximately 10^6 spores of a different strain (five type A and five type B) of <i>Clostridium botulinum</i> per can | A series of increasing doses (20 replicate cans/dose) of γ irradiation | 6 months at 30°C | — | Experimental sterilizing dose (ESD) was $27.5 < \text{ESD} < 30$ kGy | Anellis et al., 1972 |

(Continued)

TABLE 9.3 The Microflora of Irradiated Fish—cont'd

| Species | Irradiation Type/ Dose | Temperature | Shelf Life | Results | Reference |
|---|----------------------------|-------------|------------|---|----------------------------|
| Haddock (<i>Melanogrammus aeglefinus</i>) that filleted after 2 days in ice | — | 3°C | 9 days | <i>Pseudomonas</i> and, to a lesser extent, <i>Achromobacter</i> predominated throughout storage | Laycock and Regier, 1970 |
| Haddock (<i>Melanogrammus aeglefinus</i>) that filleted after 5 days in ice | — | | 7 days | | |
| Haddock (<i>Melanogrammus aeglefinus</i>) that filleted after 9 days in ice | — | | 5 days | | |
| Haddock (<i>Melanogrammus aeglefinus</i>) filleted after 2 days in ice | γ irradiation/1 kGy | | 18 days | Irradiation (1 kGy) reduced the total bacterial count by approximately 1 log order <i>Achromobacter</i> was also reduced in numbers by approximately 1 log order by 1 kGy irradiation | |
| Haddock (<i>Melanogrammus aeglefinus</i>) filleted after 5 days in ice | γ irradiation/1 kGy | | 13 days | Irradiation (1 kGy) reduced the total bacterial count by approximately 1 log order | |
| | | | 9 days | <i>Achromobacter</i> was also reduced in numbers by approximately 1 log order by 1 kGy irradiation <i>Pseudomonads</i> , which were isolated immediately after irradiation from fillets of 5 and 9 day fish, seem to have been reduced by between 2 and 3 log orders | |
| Hake fillets (<i>Merluccius merluccius hubsi</i>) | γ irradiation/2 kGy | — | — | 1 log cycle reduction in bacterial number versus the controls. | Valdes and Szeinfeld, 1989 |
| | γ irradiation/ 6 10 kGy | — | — | 3 log cycle reduction in bacterial number versus the controls | |

| | | | | | |
|---|---|-------------------|--|---|----------------------|
| Washed red hake fish mince (<i>Urophycis chuss</i>) | γ irradiation/0.66 and 1.31 kGy | 3.3°C | Microbiologi- cally superior for 6–13 days longer than the non- irradiated samples | TAPC were monitored and found to be less than 10^6 CFU/g for 4, 10, and 17 days after irradiation at all doses | Dymsza et al., 1990 |
| Dried fish powders inoculated with mesophilic aerobic bacteria, molds, and coliforms at 10^3 , 10^7 , 10^2 , 10^3 , and 10^2 10^6 CFU/g, respectively | 5–10 kGy | — | — | All molds and coliforms were eliminated, but the mesophilic plate counts were reduced only to < 10^3 CFU/g | Cho et al., 1992 |
| “Lisa” (<i>Mugil cephalus</i>) | γ irradiation/ 1.0 kGy | 0–1°C | Approx- imately 30 days | A dose of 1.0 kGy would be sufficient to ensure inactivation of 107 CFU/g of the pathogen in these products, making them cholera safe even if consumed raw | Torres et al., 2001b |
| Blue jack mackerel | — γ irradiation/1, 2, and 3 kGy | 3°C 3°C | Between 3 and 4 days 8 days | Irradiation of samples at different levels resulted in a proportional reduction in the number of bacteria. At spoilage, the non- irradiated 13 day old fish samples had 5–10 times as many bacteria as the irradiated counterparts on the same day | Mendes et al., 2000 |
| Sea bass (<i>Dicentrarchus labrax</i>) | — γ irradiation/2.5 kGy γ irradiation/5 kGy | 4°C 4°C 4°C | 13 days 15 days 17 days | The higher the irradiation dose, the lower the population of psychrotrophic bacteria, mesophilic aerobic bacteria, H ₂ S producing bacteria, Enterobacteriaceae, and Pseudomonads. Acceptability scores for odor, taste, and texture of cooked sea bass decreased with storage time | Ozden et al., 2007 |

According to Gelli et al. (1999), doses lower than 3 kGy in oysters may achieve reasonable safety levels even against *Salmonella enteritidis*, assuming that the number of potential *Salmonella enteritidis* viable cells is as low as it should be if good primary production practices and Hazard Analysis and Critical Control Point guidelines are observed.

Oysters (*Crassostrea virginica*) collected on the Cuban coast were examined for contamination with *Vibrio cholerae* and other potentially pathogenic *Vibrio* species. All oyster samples tested were positive for Vibrionaceae, and 50% of samples contained non-O1 strains of *Vibrio cholerae*. The *Vibrio* species most often isolated were *V. cholerae*, *V. parahaemolyticus*, and *V. Alginolyticus*. The results of γ -irradiation treatment of artificially contaminated oysters confirmed that a dose of 1.2 kGy would be appropriate to eliminate numbers as high as 10^7 CFU/g *Vibrio* spp. in oysters (Cisneros Despaigne et al., 2001).

Gelli et al. (2001) conducted *in vitro* studies to evaluate the effects of ionizing radiation on various biotypes and serotypes of *Vibrio cholerae*, *V. parahaemolyticus*, *V. vulnificus*, *V. fluvialis*, *Aeromonas hydrophila*, *Plesiomonas shigelloides*; *Salmonella typhi*, *S. enteritidis*, *S. typhimurium*, *Shigella flexneri*, and *Escherichia coli* O157:H7. *In vivo* tests were also conducted in oysters allowed to self-contaminate with *V. cholerae* and *S. enteritidis* cultures in seawater tanks. The oyster samples used in this study were found to be free of pathogenic microorganisms. The Vibrionaceae were more radiation sensitive than the Enterobacteriaceae. Whereas a dose of 1.5 kGy was enough to eliminate an initial contamination of 10^{10} CFU/ml in pure culture suspensions of *Vibrio* spp., 2.5 kGy was necessary to achieve similar reductions in Enterobacteriaceae cultures. *Salmonella enteritidis* surviving cells were found in culture suspensions irradiated at doses as high as 2.0 kGy. In contrast, a dose of 3.0 kGy was needed to ensure complete elimination of 10^6 CFU/g *S. enteritidis* similarly inoculated into oysters. In conclusion, an irradiation dose of 1.5 kGy is sufficient to ensure the safety of raw *Crassostrea brasiliensis* against pathogenic Vibrionaceae, including *V. cholerae*, as well as against *Aeromonas hydrophila*, *Plesiomonas shigelloides*, *Shigella flexneri*, and *Escherichia coli* O157:H7, but it may not ensure elimination of *Salmonella typhi*, *S. enteritidis*, or *S. typhimurium* if initial contamination is high (10^8 – 10^{10} CFU/g).

The D_{10} values for *Vibrio cholerae* O1 biotype El Tor inoculated through the natural feeding system into three species of bivalve mollusks from the Peruvian Pacific coast—“choro” mussels (*Aulacome ater*), “abanico” clams (*Argopecten purpuratus*), and common clams (*Gari solida*)—were determined by Torres et al. (2001a). The D_{10} value *in vivo* for *Vibrio cholerae* O1 El Tor serotype Inaba inoculated into choros, abanico clams, and common clams is 0.14 kGy for all shellfish. Therefore, irradiation doses in the range 1.0–2.0 kGy would effectively eliminate the potential hazard posed by *Vibrio cholerae* in these mollusks when consumed raw. Although the initial microbiological quality of the selected shellfish, in general, and of the abanico clams, in particular, was low, irradiation at 1.0 kGy prolonged the shelf life of choros to

more than 21 days and that of the common clams to 14 days compared to the corresponding nonirradiated controls.

Figure 9.4 displays the impact of different irradiation doses on the mesophilic aerobic bacteria of sardines (*Sardina pilcard*), VP, and clams.

Lopez (2001) examined the presence of potentially pathogenic bacteria belonging to the Vibrionacea, especially *Vibrio cholerae*, and of *Salmonella* spp. in fresh Uruguayan mussels (*Mytilus* sp.) during two annual seasons. The radiation decimal reduction dose (D_{10}) of various toxigenic strains of *Vibrio cholerae* was determined to vary *in vitro* between 0.11 and 0.19 kGy. These findings and those from the examination of natural *Vibrio* spp. contamination in mussels were used to conclude that 1 kGy would be enough to render Uruguayan mussels safe from *Vibrio*. The radiation D_{10} value for toxigenic *Vibrio cholerae* O1 El Tor was found to be 0.13 kGy *in vitro* in artificially contaminated lisa (*Mugil cephalus*) fillets, and in saurel (*Trachurus picturatus murphyi*) fillets the D_{10} value was similar at 0.12 kGy. These results suggested that a dose of 1 kGy would be sufficient to ensure inactivation of 10^7 CFU/g of the pathogen in these products, making them cholera safe even if consumed raw, as these fish frequently are. A dose of 1 kGy doubled the microbiological shelf life of fish fillets during post-irradiation storage at $0-1^{\circ}\text{C}$ to approximately 30 days. This dose was also deemed optimal for preserving all sensory characteristics evaluated except appearance, due to a darkening of fillets (Torres et al., 2001b). Kilgen et al. (2001) suggested that low-dose irradiation at 0.5 or 1 kGy would be extremely effective and commercially feasible as a postharvest intervention method to control or eliminate *V. vulnificus* and to lower total aerobic plate counts in live, fresh shucked, or frozen oysters under commercial conditions, without killing the oysters.

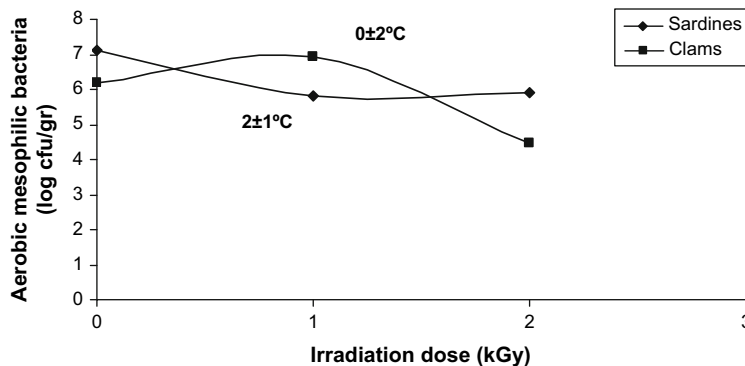


Figure 9.4: Effect of different irradiation doses on the mesophilic aerobic bacteria of sardines (*Sardina pilcardu*) vacuum packaged (Kasimoglu et al., 2003) and common clams (*Gari solida*) (Torres et al., 2001a).

Live oysters (*Crassostrea virginica*), with naturally incurred and artificially inoculated pathogenic vibrios, were treated with a 0- to 3-kGy dose of γ -radiation. *Vibrio vulnificus* (MO-624) was reduced from 10^6 CFU/g oyster meat to nondetectable levels with 0.75–1.0 kGy irradiation exposure. *Vibrio parahaemolyticus*, 03:K6 (TX-2103), required 1.0–1.5 kGy for reduction to nondetectable levels. Sensory panelists were unable to distinguish non-irradiated from irradiated oysters (1 kGy) (Andrews et al., 2003).

Jakabi et al. (2003) investigated the effect of a γ -radiation process on high levels of *Salmonella enteritidis*, *Salmonella infantis*, and *Vibrio parahaemolyticus* incorporated by oysters (*Crassostrea brasiliana*). The oysters were γ -irradiated in doses ranging from 0.5 to 3.0 kGy. A dose of 3.0 kGy was generally sufficient to reduce the level of *Salmonella* serotypes by 5 or 6 \log_{10} units. A dose of 1 kGy was sufficient to produce a 6- \log_{10} reduction in the level of *V. parahaemolyticus*. The highest irradiation dose did not kill the oysters or affect their sensory attributes.

Collins et al. (2005) determined the efficiency of e-beam irradiation on the viability of *Cryptosporidium parvum* oocysts in Eastern oysters (*Crassostrea virginica*), which were artificially infected with the Beltsville strain of *Cryptosporidium parvum*. The effects of the treatments were evaluated by oral feeding of the processed oyster tissues to neonatal mice. Significant reductions in infectivity were observed for in-shell and shucked oysters treated with e-beam irradiation at doses of 1.0, 1.5, or 2 kGy versus untreated controls. A dose of 2 kGy completely eliminated *Cryptosporidium parvum* infectivity and did not adversely affect the visual appearance of the oysters.

The effect of irradiation on shellfish microflora and its shelf life is summarized in Table 9.4.

9.3.3 Crustaceans and Cephalopods

Grodner and Hinton (1986) inoculated *Vibrio cholera* into crabmeat (*Callinectes sapidus*) 10^7 CFU/g homogenate. A dose of 0.25 kGy was effective in reducing *Vibrio cholera* greater than 3 log cycles, whereas 0.5 and 1 kGy completely eliminated all *Vibrio cholera* from the samples.

Irradiated freshwater prawns (*Macrobrachium rosenbergii*) at 1.45 and 2.3 kGy were studied by Angel et al. (1986). A 1 to 2 log cycle reduction in total numbers of bacteria was observed across the doses. After 28 days of storage, total counts increased approximately 2 to 3 log cycles.

Chen et al. (1996) investigated the microbial and sensory quality characteristics of irradiated (2 kGy or less) crab products (white lump, claw, and fingers) through 14 days of ice storage. Irradiation effectively reduced spoilage bacteria, extending shelf life by more than 3 days beyond that of control samples. At storage, fresh crab odor and flavor were similar for treated and control samples, whereas off-flavors and odors developed more rapidly in controls.

TABLE 9.4 The Microflora of Irradiated Shellfish

| Species | Irradiation Type/Dose | Temperature | Shelf Life | Results | Reference |
|--|-------------------------------|-------------|------------|--|---------------------------------|
| Pacific oysters (<i>Crassostrea gigas</i>) | — | 7°C | 2 days | A large percentage of <i>Lactobacillus</i> was detected in oysters (55.0%) | Shiflett et al., 1966 |
| | γ irradiation/ 1 kGy | 7°C | — | The <i>Lactobacillus</i> species were the predominant survivors (92.4%) | |
| | γ irradiation/ 4 kGy | 7°C | — | The predominant survivors were <i>Achromobacter</i> species (99.3 %) | |
| Oysters (<i>Crassostrea virginica</i>) | γ irradiation/ 1.2 kGy | — | — | The results of γ irradiation treatment of oysters confirmed that a dose of 1.2 kGy would be appropriate to eliminate numbers as high as 10 ⁷ CFU/g <i>Vibrio</i> spp. | Cisneros Despaigne et al., 2001 |
| Oysters | γ irradiation/ 1.5 kGy | — | — | An irradiation dose of 1.5 kGy is sufficient to ensure the safety of raw <i>Crassostrea brasiliensis</i> against pathogenic <i>Vibrionaceae</i> , including <i>V. cholerae</i> , as well as against <i>Aeromonas hydrophila</i> , <i>Plesiomonas shigelloides</i> , <i>Shigella flexneri</i> , and <i>Escherichia coli</i> O157:H7 | Gelli et al., 2001 |
| “Choro” mussels (<i>Aulacomya ater</i>), “abanico” clams (<i>Argopecten purpuratus</i>), and common clams (<i>Gari solida</i>) | γ irradiation/ 1.0 2.0 kGy | — | — | Effective elimination of the potential hazard posed by <i>Vibrio cholerae</i> in these samples | Torres et al., 2001a |

(Continued)

TABLE 9.4 The Microflora of Irradiated Shellfish—cont'd

| Species | Irradiation Type/Dose | Temperature | Shelf Life | Results | Reference |
|---|---------------------------------------|-------------|------------|--|----------------------|
| Lisa (<i>Mugil cephalus</i>) fillets, was in saurel (<i>Trachurus picturatus murphyi</i>) | γ irradiation/ 1 kGy | 0 1°C | 30 days | Sufficient to ensure inactivation of 10^7 CFU/g of the <i>Vibrio cholerae</i> O1 El Tor in these products | Torres et al., 2001b |
| Live oysters (<i>Crassostrea brasiliana</i>) | γ irradiation/ 1 kGy | — | — | 6 log ₁₀ reduction of <i>V. parahaemolyticus</i> | Jakabi et al., 2003 |
| | γ irradiation/ 3 kGy | — | — | Reduction of <i>Salmonella</i> serotypes by 5 to 6 log ₁₀ units | |
| Live oysters (<i>Crassostrea virginica</i>) | γ irradiation/ 0.75 1.0 kGy | — | — | <i>Vibrio vulnificus</i> (MO 624) was reduced from 10^6 CFU/g oyster meat to nondetectable levels (<3 MPN/g oyster meat) | Andrews et al., 2003 |
| | γ irradiation/ 1.0 1.5 kGy | — | — | <i>Vibrio parahaemolyticus</i> , 03:K6 (TX 2103), was reduced to nondetectable levels | |
| Eastern oysters (<i>Crassostrea virginica</i>) | E beam irradiation/ 2 kGy | — | — | Complete elimination of <i>C. parvum</i> infectivity | Collins et al., 2005 |

Furthermore, the overall acceptability scores for irradiated crab samples were higher than those for control samples throughout 14 days of ice storage.

Grass prawns (*Penaeus monodon*) were surface inoculated with *Vibrio cholera*, *Staphylococcus aureus*, *Escherichia coli*, and *Salmonella enteritidis* and irradiated at doses of 0–10 kGy and stored for 48 days. A 2- to 3-log reduction in bacterial numbers was observed up to 7.5 kGy, and D_{10} values were found to be 0.11, 0.29, 0.39, and 0.48 kGy for *V. cholera*, *Staphylococcus aureus*, *E. coli*, and *S. enteritidis*, respectively. The effect of irradiation on nutrients was also examined, and it was observed that C20:5, C22:6, and thiamine levels were reduced by 22, 25, and 32%, respectively (Hau and Liew, 1993; Hau et al., 1992).

Rashid et al. (1992) and Ito et al. (1993) reported that a dose of 3 kGy was enough to reduce *Vibrio* spp. and *Aeromonas hydrophila* in frozen shrimp by 4 log cycles, whereas 3.5 kGy was needed to achieve similar reduction in numbers of *Listeria monocytogenes* or *Salmonella* spp.

Torres et al. (2001b) determined the D_{10} value in tails of the shrimp species *Penaeus vannamei* (0.13 kGy). Best results in shrimp tails were obtained using 2 kGy, which doubled their microbiological shelf life to 20 days at 0–1°C. Sinanoglou et al. (2007) determined the effects of γ -irradiation on the microbiologic quality of frozen mollusks (squid, octopus, and cuttlefish) and crustaceans (shrimp) at different doses. Irradiation of shrimp and squid with either 2.5 or 4.7 kGy reduced mesophilic bacteria contamination to low or nondetectable levels, respectively, whereas irradiation of octopus and cuttlefish with the same doses reduced the bacterial population.

The effect of irradiation on the microflora of crustaceans and cephalopods is displayed in Table 9.5.

9.4 Irradiation of Fish and Hurdle Technology

9.4.1 Fish

Slavin et al. (1966) found that the optimum dose for smoked chubs (*Coregonus* spp.) is 1 kGy, which yields a shelf life of approximately 42 days under refrigeration. The maximum acceptable dose is approximately 8 kGy. Frozen chubs can be irradiated at 8 kGy and then smoked to yield a highly acceptable product.

Vacuum-packed silver or sockeye salmon irradiated at 3 kGy becomes rancid immediately after irradiation, whereas king and pink salmon irradiated at 3 kGy become rancid after 7 days at 0.6°C. Salmon treated with 1.5 kGy has a shelf life of approximately 20 days when stored at 2.2–2.6°C. The optimal dose for salmon irradiation has been determined to be less than 1 kGy, with a similar dose reported for smoked salmon (Cornett and Vallet, 1989; Eukel and Huber, 1960; Metlitskii et al. 1968; Rhodes, 1964; Stansby and Kudo, 1964).

TABLE 9.5 The Microflora of Irradiated Crustaceans and Cephalopods

| Species | Irradiation Type/Dose | Temperature | Shelf Life | Organoleptic Changes | Results | References |
|--|-------------------------|-------------|------------|----------------------|--|---------------------------------------|
| Dungeness crabmeat (<i>Cancer magister</i>) | — | 7°C | 2 days | — | The <i>Achromobacter</i> species predominated in the initial flora of crabmeat (77.0%) | Shiflett et al., 1966 |
| | γ irradiation/ 1 kGy | 7°C | — | — | The predominant position of <i>Achromobacter</i> increased to 99.2% | |
| | γ irradiation/ 4 kGy | 7°C | — | — | The predominant position of <i>Achromobacter</i> increased to 100% | |
| Crabmeat (<i>Callinectes sapidus</i>) homogenate inoculated with 10 ⁷ CFU/g | 0.25 kGy | — | — | — | Reducing <i>Vibrio cholera</i> greater than 3 log cycles | Grodner and Hinton, 1986 |
| | 0.5 and 1 kGy | — | — | — | Complete elimination of <i>Vibrio cholera</i> from the samples | |
| Frozen shrimp | 3 kGy | — | — | — | Reduction of <i>Vibrio</i> spp. and <i>Aeromonas hydrophila</i> by 4 log cycles | Ito et al., 1993; Rashid et al., 1992 |
| | 3.5 kGy | — | — | — | Similar reduction of <i>Listeria monocytogenes</i> or <i>Salmonella</i> spp. | |

| | | | | | | |
|---|-------------------------------------|-------------------------|--|---|--|--------------------------------------|
| Squid | γ irradiation/2.5 or 4.7 kGy | — | — | — | Reduced mesophilic bacteria contamination to low or nondetectable levels | Sinanoglou et al., 2007 |
| Octopus | γ irradiation/2.5 or 4.7 kGy | — | — | — | Reduction of the bacterial population | |
| Cuttlefish | γ irradiation/2.5 or 4.7 kGy | — | — | — | Reduction of the bacterial population | |
| Shrimp | γ irradiation/2.5 or 4.7 kGy | — | — | — | Reduced mesophilic bacteria contamination to low or nondetectable levels | |
| Crab products (white lump, claw, and fingers) | — | Ice storage for 14 days | 3 day shelf life extension compared to control samples | During storage, fresh crab odor and flavor were similar for treated and control samples, whereas off flavors and odors developed more rapidly in controls | — | Chen et al., 1996 |
| | γ irradiation/2 kGy or less | Ice storage for 14 days | — | — | Irradiation effectively reduced spoilage | |
| Grass prawns (<i>Penaeus monodon</i>) inoculated with <i>V. cholera</i> , <i>Staphylococcus aureus</i> , <i>E. coli</i> , and <i>S. enteritidis</i> | up to 7.5 kGy | — | — | — | A 2 to 3 log reduction in bacterial numbers | Hau and Liew, 1993; Hau et al., 1992 |

According to Hashish et al. (1966), the optimum dose for air-packed sablefish is 3 kGy, with rancidity occurring after 7 days at 0.6°C (Stansby and Kudo, 1964). Moreover, the optimum irradiation dose for sardines (*Sardinella melanura*) is 0.23 kGy, which triples the shelf life at 1°C. The optimum and maximum irradiation dose for VP silver hake (*Merluccius bilinearis*) was found to be 1.2 kGy, but this can be increased twofold with blanching prior to irradiation. Others have reported maximum doses of 2 up to 4.5 kGy; however, off-odors have been reported at doses higher than 3 kGy (Brooke and Steinberg, 1964; Massa et al., 1964). The optimum dose for VP halibut (*Hippoglossus hippoglossus*) steaks is 2–3 kGy, with a shelf life of 20 days at 5.6°C and greater than 30 days at 0°C. A maximum acceptable dose was found to be 5 kGy (Rhodes, 1964; Sieling, 1961). The optimum irradiation dose for vacuum-packed halibut (*Paralichthys californicus*) steaks is 2 kGy, yielding a shelf life of 14–21 days at 5.6°C and greater than 21–42 days at 0.6°C. The maximum acceptable dose was found to be 5 kGy (Slavin et al., 1966; Stienberg, 1965). The VP fillets of sole (*Eopsetta jordani*) had an optimum dose of 2–3 kGy, yielding a shelf life of 28–49 days at 0.6°C and 14–21 days at 5.6°C. No maximum dose has been clearly established; however, at 3 kGy significant odor and flavor changes occur (Spinelli et al., 1965).

The optimum dose for whole eviscerated, scaled gwyniad (*Coregonus wartmanni* Bloch) packed under vacuum in plastic films impermeable to water and oxygen was 1 kGy. The shelf life of 9 days on ice increased to 23 days. Higher doses resulted in even longer shelf life; however, they caused off-flavor (Ehlermann and Muenzer, 1970). The optimum dose for VP rockfish (*Sebastes* spp.) was found to be between 1.25 and 2.5 kGy. The refrigerated shelf life of rockfish irradiated at 2.5 kGy was 20 days (Miyachi, 1970).

Kennedy and Ley (1971) investigated the effect of irradiation (6 kGy) and cooking on niacin, riboflavin, and thiamin in cod fish fillets and concluded that irradiation followed by cooking produced a total loss that was the sum of the losses produced by each treatment. According to Loaharanu et al. (1972), shucked mussel meats, air packed, present an optimum dose of 1.5–2.5 kGy, which yields a shelf life of 6 weeks at 3°C compared to 3 weeks for the non-irradiated mussels.

According to Jo et al. (2004), in order to develop a lower salt traditional seafood product, frozen intestines of *Theragra chalcogramma* (Alaska pollock) were thawed, washed, fermented, and then seasoned to make Changran Jeotkal. The final salt content of the product was adjusted to 5% and the product was irradiated to absorbed doses of 0, 2.5, 5.0, and 10 kGy using γ -rays. Volatile basic nitrogen and amino nitrogen content and sensory evaluation indicated that 2.5-kGy treatment of the low-salt (5%) product was applicable to industry without adverse effect on the quality.

Quaranta et al. (1984) studied 4-day-old frozen tuna loins (*Thunnus obesus*) packed in polyethylene PE bags and irradiated by an X-ray machine at a dose of 2.2 kGy. Sensory panelists determined the non-irradiated control samples to be acceptable 15 days in comparison to 25 days observed for the irradiated samples.

Doke et al. (1976) prepared laminated films of Bombay duck (*Harpodon nehereus*). Fish fillets packaged in PE bags and irradiated at 2.5 kGy were acceptable for up to 20–22 days (0–2°C) in comparison to non-irradiated samples that had a shelf life of 5 days. According to the results, the dehydrated laminates irradiated with 2.5 kGy reached a shelf life of 4 months at ambient temperature.

Dogfish (*Squalus acanthias*) fillets were irradiated in nylon–PVDC–surlyn bags, under air. The maximum and optimum dose was determined to be 2 kGy, yielding a shelf life of 7 days at 8°C (Licciardelo et al., 1984a). Licciardelo et al. (1984b) studied cod fillets VP or packed in a 60% CO₂:40% air atmosphere in barrier bags followed by treatment with 1 kGy γ -irradiation and subsequent storage on ice. The 60%CO₂:40% packed, irradiated cod fillets retained quality attributes longer than the VP product, which retained its quality longer than air-packed fillets.

Venugopal et al. (1987) examined the storage stability of eviscerated Indian mackerel (*Rastrelliger kanagurta*) irradiated at a dose of 1.5 kGy and held under melting ice. A shelf life of 25 days was obtained when packaging in PE pouches prior to irradiation was employed, whereas nonpackaged, irradiated fish remained in acceptable condition up to 20 days. The nonpackaged irradiated fish has less irradiation odor and better appearance compared to the packaged irradiated fish during the course of ice storage. The shelf life of non-irradiated and nonpackaged mackerel kept in ice was only 14 days.

Przybylski et al. (1989) studied commercially cultured channel catfish (*Ictalurus punctatus*) packed in PE bags with atmospheres of 100% air, 100% CO₂, or 80% CO₂ and 20% air and were treated with 0, 0.5, or 1.0 kGy of γ -irradiation. The packaged samples were stored at 0–2°C for up to 30 days. The lowest psychotrophic plate counts were obtained with 100% CO₂ atmosphere. Increased radiation doses decreased the microbial population in fish sampled after 20 days of storage.

Fresh and frozen fillets of Atlantic cod (*Gadus morhua*) were packed in PE bags and irradiated at 1–5 kGy. The samples were stored at 4°C for 28 days and were analyzed for odor, hypoxanthine, TVA, and TVB-N. Irradiation was shown to be quite effective in delaying deterioration in these cod fillets, and 2–3 kGy was determined to be the optimum dose (Thibault and Charbonneau, 1991).

Monk et al. (1995) observed a doubling of the shelf life of Dover sole when 0.19% sodium benzoate was added to samples before irradiation. Kwon and Byun (1995) combined γ -irradiation with air-tight packaging to preserve and improve the quality of boiled-dried anchovies (*Engraulis encrasicolus*). Immediately after irradiation, the contents of polyunsaturated fatty acids decreased by approximately 5%, whereas saturated fatty acids contents slightly increased. The overall quantity of total and free amino acids was slightly decreased with the storage time. In sensory evaluation, γ -irradiation at or below 5 kGy did not induce significant changes in appearance, rancid flavor, and palatability of the rumples immediately

after treatment. Prepackaging with air-tight laminated film (nylon 15 μm /PE 100 μm) and irradiation (5 kGy) were effective for maintaining the marketable quality during 6 months of storage at ambient temperature and more than 1 year at cooling temperature (5–10°C). [Kwon and Byun \(1995\)](#) reported that the radiosensitivity (D_{10} value) of aerobic bacteria in air-tight packaged, boiled-dried anchovies (*Engraulis encrasicolus*) was 1.33 kGy and for yeasts and molds was 2.02 kGy. Microbes were particularly sensitive to irradiation, being easily destroyed at less than 5 kGy. As a result, irradiation at 5 kGy was enough to control microorganisms, and its combination with air-tight packaging in a laminated film (nylon 15 μm /PE 100 μm) was effective for maintaining the microbiological quality of the stored sample for 6 months at ambient temperature and more than 1 year at 5–10°C.

The effects of irradiation on brook charr (*Salvelinius fontinalis*) flesh irradiated at 1 and 3 kGy, vacuum packaged, and stored at 1°C during 14 days were determined by [Paradis and Adam-bounou \(1996\)](#). Microbiological quality of brook charr stored at 1°C was extended by irradiation treatment. Total plate count was decreased by irradiation treatment, and the effect was more accentuated at 3 kGy than at 1 kGy. However, the color of flesh was affected negatively by irradiation, and the effect was more important for the 3-kGy than for the 1-kGy treatment. Sensory evaluation confirmed the discoloration effect of irradiation on brook charr flesh and revealed that texture tends to be firmer at the end of storage in irradiated samples. However, flavor of flesh was not affected by irradiation.

[Hussain et al. \(1977\)](#) studied trout fillets inoculated and vacuum packed (0.75-mm PE film) with 10^5 *Clostridium botulinum* type E Beluga spores/g of fish and subjected them to irradiation with electrons (10 MeV) at doses of 0, 1, and 2 kGy. No toxin formation was observed at 0°C, and the fish became toxic long after spoilage had occurred at 5°C. At 10°C, irradiated (1 and 2 kGy) fillets became toxic before spoilage was observed, whereas non-irradiated fillets spoiled before they became toxic. In this case, irradiation increased the hazard potential of the VP fillets stored at 10°C.

[Jeevanandam et al. \(2001\)](#) studied fresh, eviscerated threadfin bream (*Nemipterus japonicus*) packaged in PE pouches that were dipped in 10% (w/w) sodium chloride for 1 h and subjected to γ -irradiation at 0, 1, or 2 kGy at ice temperature. The unsalted and non-irradiated fish was acceptable for up to 8 days, compared to a storage life of 12 and 22 days for the unsalted fish irradiated at 1 and 2 kGy, respectively. Salting prior to irradiation at 0, 1, or 2 kGy gave a shelf life of 9, 14, and 28 days, respectively. Salting gave a firmer texture to the fish and prevented drip formation in the pouches during storage. The microbial count of unsalted and non-irradiated fish increased from 4.4×10^4 per gram to 4.0×10^8 within 20 days of storage. Irradiation at 1 and 2 kGy decreased the initial counts to 2.3×10^3 and 5.7×10^2 per gram, respectively. After storage for 30 days, the microbial counts reached 8.0×10^7 and 1.0×10^7 per gram in the fish samples irradiated at 1 and 2 kGy, respectively. The initial microbial load of salted fish was 2.2×10^4 per gram, which increased to 5.6×10^7 per gram within 22 days of storage on ice.

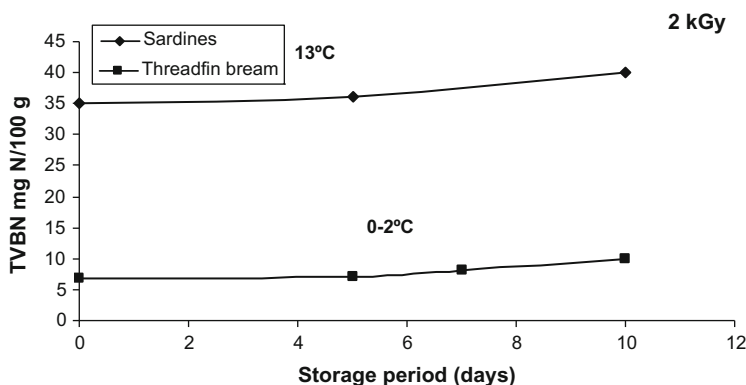


Figure 9.5: Effect of irradiation on TVB-N content of sardines vacuum packaged (Lakshmanan et al., 1999b) and threadfin bream (*Nemipterus japonicus*), under storage (Jeevanandam et al., 2001).

Irradiation at 1 and 2 kGy decreased the initial value to 9.5×10^2 and 4.7×10^2 per gram. Both irradiation and salt treatment caused lipid oxidation, as indicated by the TBA number, and irradiation also suppressed the formation of TVB-N and TVA.

Figure 9.5 displays the impact of irradiation on aerobic mesophilic bacteria of VP sardines (*Sardina pilcardu*) and clams.

Chawla et al. (2003) investigated radiation sensitivity of *Staphylococcus aureus*, *Bacillus cereus*, *Salmonella typhimurium*, and *Escherichia coli* in kwamegi (semi-dried raw Pacific saury). The growth of all four test organisms inoculated into these foods during 4 weeks of storage at an ambient winter temperature (ranging from 5 to 5°C) was recorded. All four pathogens (inoculated at 10^6 CFU/g) were eliminated by irradiation at 4 kGy. In the samples stored at 5°C, the counts remained almost constant. When stored at 5°C, in non-irradiated samples, viable counts increased by approximately 2 log cycles during the storage period of 4 weeks. In irradiated samples immediately after irradiation, there was a dose-dependent reduction in viable cells. During storage, viable counts increased in samples irradiated up to 2 kGy. However, in the sample irradiated at 3 kGy, surviving cells lost viability during storage. These studies demonstrate that irradiation, with a combination of low water activity and low temperature, could ensure the safety of kwamegi.

Lee et al. (2002) investigated the effects of irradiation (0, 3, 5, 7, or 10 kGy) on VP kwamegi, prepared from semi-dried Pacific saury (*Cololabis seira*) flesh. The total aerobic bacterial load of the control (0 kGy) was 2.8×10^4 at Day 0, which increased to 7.1×10^7 CFU/g following 20-day storage at 5°C. Microorganisms were not observed in 7- and 10-kGy irradiated kwamegi in initial storage. Microbial load of 7-kGy irradiated kwamegi in 60-day storage was 4.7×10^4 CFU/g. The D_{10} value of total aerobic bacteria on irradiation was approximately 2.37 kGy. For radappertization of kwamegi, irradiation doses higher than 10 kGy were necessary. In all

samples, TBA values increased during storage, regardless of radiation dose. Panelists found that the odor of irradiated kwamegi was better than that of the control and indicated that a unique fishy off-odor of the saury decreased in irradiated samples.

Savvaidis et al. (2002) studied the effect of γ -irradiation on the natural microflora of whole salted VP trout at 4 and 10°C. Moreover, the effectiveness of γ -irradiation in controlling *Listeria monocytogenes* inoculated into trout was investigated. Irradiation at doses of 0.5 and 2 kGy affected populations of *Pseudomonas* spp., *Brochothrix thermosfacta*, lactic acid bacteria (LAB), H₂S-producing bacteria typical of *Shewanella putrefaciens*, and Enterobacteriaceae, at both 4 and 10°C. This effect was more pronounced at the higher dose (2 kGy) and the lower temperature (4°C). Pseudomonads, H₂S-producing bacteria typical of *S. putrefaciens*, and Enterobacteriaceae showed higher sensitivity to γ -irradiation than did the rest of the microbial species. On the basis of sensory odor scores, a shelf life of 28 days (2 kGy, 4°C) was obtained for salted VP freshwater trout, compared with a shelf life of 7 days for the non-irradiated sample. Under the same conditions, the growth of *L. monocytogenes* inoculated into the samples was suppressed by 2 log cycles after irradiation (2 kGy) and storage for up to 18 days at 4°C.

Panchavarnama et al. (2003) described a process to enhance shelf life of freshwater fish, rohu (*Labeo rohita*), on ice using a combination treatment of coating the fish steaks with gel dispersion from the same fish and low-dose γ -irradiation. Coating of fresh rohu steaks by dipping in the dispersion for 1 h or γ -irradiation at 1 kGy gave a shelf life of 32 days in ice compared to 20 days for the untreated steaks. Irradiation at 1 kGy of the dispersion-coated steaks enhanced their shelf life to 42 days. Bleaching of the pink color of the steaks by the treatment was prevented when either butylated hydroxy anisole or ascorbic acid was incorporated at 5 g/kg (w/v) in the dispersion.

Sardines (*Sardina pichardus*) were VP in PE bags and irradiated at 1, 2, and 3 kGy doses in a ⁶⁰Co δ -irradiator. All samples were stored at $2 \pm 1^\circ\text{C}$. Irradiation produced a reduction in initial bacterial counts. Using a total count of 10^7 as an index to mark the end of storage life, it appears from the data that an irradiation dose of 3 kGy would extend the shelf life of sardines, when stored in vacuum package at $2 \pm 1^\circ\text{C}$ for 11 days (reaching 21 days). The initial pH and TBA values were not significantly different between non-irradiated and irradiated treatments. For all treatments, TBA showed fluctuations. There was a significant difference in TMA-N values between non-irradiated and irradiated samples over the period of refrigerated storage, with irradiated samples presenting the lower values. Furthermore, results showed that irradiation produced a reduction in initial bacterial count that was proportional to the irradiation dose (Kasimoglu et al., 2003). The effect of irradiation on TVB-N content of sardines and threadfin bream VP is shown in Figure 9.6.

Su et al. (2004) studied e-beam irradiation to reduce spoilage bacteria and *Listeria monocytogenes* on cold-smoked salmon. Salmon fillets were inoculated with *L. monocytogenes*

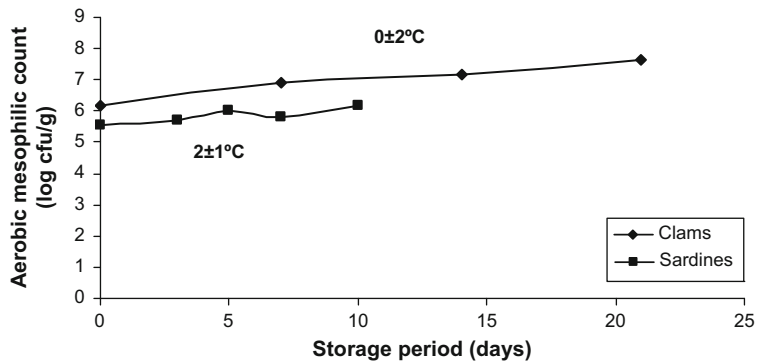


Figure 9.6: Effect of irradiation on aerobic mesophilic bacteria of vacuum-packaged sardines (*Sardina pilcardu*) (Kasimoglu et al., 2003) and clams (*Argopecten purpuratus*), under storage (Torres et al., 2001a).

(4.4×10^3 CFU/g) and exposed to e-beam radiation at doses of 1, 2, and 4 kGy. The e-beam irradiated samples were stored at 5°C and tested for psychrotrophs, mesophiles, and *L. monocytogenes* on Days 1, 8, and 28. Total bacterial populations on cold-smoked salmon were reduced by e-beam processing but increased during storage. *Listeria monocytogenes* cells (3.6 log CFU/g) on inoculated salmon were reduced by 2.5 log CFU/g with a low e-beam dose of 1.0 kGy and were completely eliminated by e-beam doses of 2.0 kGy and greater.

Chouliara et al. (2004) achieved a shelf-life of 27 or 28 days for VP, salted marine sea bream (*Sparus aurata*) fillets irradiated at 1 or 3 kGy under refrigeration ($4 \pm 1^\circ\text{C}$) compared to a shelf-life of 14 or 15 days for the non-irradiated VP, salted sea bream. Irradiation affected populations of *Pseudomonas* spp., H₂S-producing bacteria, *Brochothrix thermosphacta*, Enterobacteriaceae, and LAB. The effect was more pronounced at the higher dose (3 kGy) applied. Of the chemical indicators of spoilage, TMA values of non-irradiated, salted sea bream increased slowly to 8.87 mgN (100 g)⁻¹ flesh, whereas for irradiated, salted samples significantly lower values were obtained, reaching a final TMA value of 6.17 and 4.52 mgN (100 g)⁻¹ flesh at 1 and 3 kGy, respectively (Day 42). TVB-N values increased slowly, attaining a value of 60.52 mgN (100 g)⁻¹ for non-irradiated, salted sea bream during refrigerated storage, whereas for irradiated fish, lower values of 48.13 and 37.21 mgN (100 g)⁻¹ muscle were recorded at 1 and 3 kGy, respectively (Day 42). TBA values for irradiated, salted sea bream samples were higher than those for respective non-irradiated (salted) fish. Figure 9.7 shows the effect of irradiation on TBA content of sea bream fillets, vacuum packaged, and threadfin bream.

Jo et al. (2004) reported that irradiation at 2.5 kGy effectively controlled the microbial population during 12 weeks of refrigeration storage (10°C) of Changran Jeotkal, a low-salt traditional Korean seafood product, which is aged, fermented, and seasoned intestines of *Theragra chalcogramma* (Alaska pollock). The final level of microbial load in salted (5 and

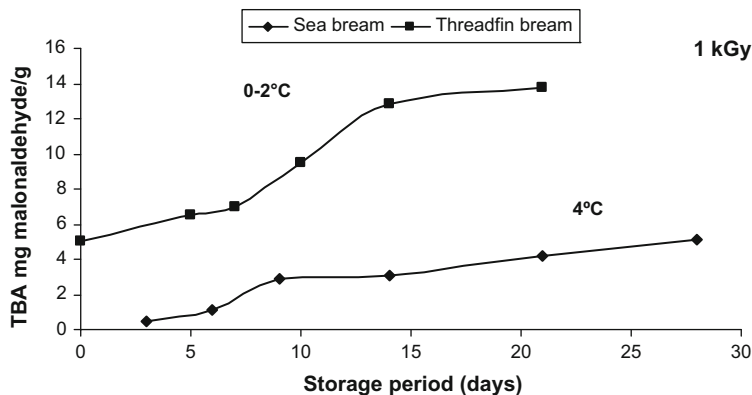


Figure 9.7: Effect of irradiation on TBA content of sea bream (*Sparus aurata*) fillets, vacuum packaged (Chouliara et al., 2004), and threadfin bream (*Nemipterus japonicus*) (Jeevanandam et al., 2001).

8%) and irradiated samples was less than 10^4 CFU/g. Samples that were salted (5%) but not irradiated reached a microbial load of greater than 10^4 CFU/g.

The effect of γ -irradiation (1.5 and 2 kGy) on the lipids of Indian mackerel (*Rastrelliger kanagurta*) aerobically packed in PE bags stored at 0–2°C was studied by Lakshmanan et al. (1999a). A higher carbonyl value was observed in irradiated samples (1.5 and 2 kGy) during initial phases of storage compared to that of the control sample. However, a progressive decrease in carbonyl values with storage at 0–2°C was found in irradiated samples. The variation in monosaturated fatty acids was 28.2–31.5% in the control, 30.7–34.4% in the irradiated (1.5 kGy), and 29.1–33.8% in the samples irradiated at 2 kGy during the course of chilled storage. Irradiation also had no adverse effect on the nutritionally important omega-3 polyunsaturated fatty acids (PUFAs) of the fish. Furthermore, the overall percentage of PUFAs remained constant.

Robertson et al. (2006) measured the effect of X-ray irradiation on reducing the population of *Listeria monocytogenes* on ready-to-eat, VP smoked mullet (*Mugil cephalus*). Smoked mullet was inoculated with a five-strain mixture of *L. monocytogenes* (10^4 CFU/g), vacuum packaged, and irradiated (0, 0.5, 1.0, 1.5, and 2.0 kGy). The packaged fish were then stored at 3 and 10°C for 90 and 17 days, respectively. Radiation doses of 0.5, 1.0, and 1.5 kGy reduced the initial population of *L. monocytogenes* by 1.1, 1.6, and 2.1 log CFU/g, respectively. The 2.0-kGy dose reduced *L. monocytogenes* to undetectable levels, with no recovery growth at either temperature. Compared to the control, irradiation at 1.5 kGy demonstrated 1.0 and 1.7 log CFU/g less growth at 3°C after 60 days and 10°C after 17 days, respectively. Sensory flavor analysis was conducted to determine if a difference existed between irradiated samples. Panelists indicated that there were no differences among treated and untreated samples.

Gamma irradiation in combination with packaging method was investigated with a view to extending the shelf life of processed shrimp. Seawater shrimps (*Penaeus* spp.) were washed, boiled in a salt solution, and dried, and the shells were removed and packed in plastic bags at ambient temperature. The final moisture content of semi-dried shrimp samples was approximately 35–37%, which was higher than that of the dried shrimp commercially sold in market (20–25%). Irradiation of semi-dried shrimp at 2 and 4 kGy could extend the shelf life to 35 and 49 days of storage compared to 10 days for control samples. During storage, TBA values, TVN values, and hardness increased. In addition, the redness of semi-dried shrimp decreased as time progressed due to oxidation of astaxanthin (Noomhorm et al., 2003).

The impact of irradiation on TBA content of rohu (*Labeo rohita*) (Panchavarnama et al., 2003) and semi-dried shrimp is displayed in Figure 9.8.

Luo et al. (2003) conducted a study to determine the minimum irradiation doses required to inactivate all spoilage nonspore and spore pathogenic microorganisms in semi-dried fish (name and species not mentioned) that have been vacuum packaged. The water activity (a_w) ranged between 0.918 and 0.934. The irradiation doses used in the study were 0, 1, 2, 2.5, 5, 7.5, 10, and 20 kGy. Results showed that the minimum irradiation dose required to inactivate all spoilage microorganisms in fish was 10 kGy. *Salmonella enteritidis* in semi-dried fish could be eliminated at a dose of 2.5 kGy. *Staphylococcus aureus* in semi-dried fish inactivated using a dose of 2 kGy was more resistant to irradiation. A dose of 7.5 kGy was required to inactivate *Bacillus cereus* in semi-dried fish.

Nketsia-Tabiri et al. (2003) studied ready-to-eat smoked sardines (*Sardinella* spp.) and a marinated fish (*Diplodus puntazzo*) product, packaged aerobically. The TVC was \log_{10} 6.74–8.96 and \log_{10} 2.6–7.2 CFU/g of fish, respectively. Although γ -irradiation

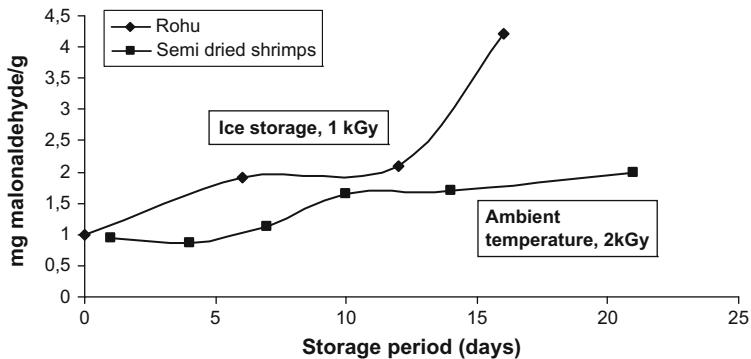


Figure 9.8: Effect of irradiation on TBA content of Rohu (*Labeo rohita*) (Panchavarnama et al., 2003) and semi-dried shrimps (*Penaeus* spp.) (Noomhorm et al. 2003), under storage.

(7–11 kGy) controlled microbial activity in some of the smoked sardines during a 12-week storage period, other sardines had unacceptable color, flavor, and texture. Regarding the marinated product, irradiation at 8–10 kGy substantially reduced the coliform count and extended the shelf life and overall acceptability of the product by 3 days.

The impact of irradiation in conjunction with hurdle technology on the sensory properties and shelf life of fish is given in [Table 9.6](#).

9.4.2 Shellfish

[Shiflett et al. \(1967\)](#) investigated the effects of sodium benzoate and potassium sorbate and irradiation on *Salmonella typhimurium* and *Salmonella enteritidis* inoculated into blended oysters (*Crassostrea gigas*), both raw and autoclaved, stored at 7°C. The oysters were treated with sodium benzoate (0.1%) or potassium sorbate (0.1%) and irradiated (1 kGy). In both non-irradiated and irradiated samples, greater numbers of *Salmonella* were recovered after storage at 7°C in the presence of sodium benzoate or potassium sorbate. The results of the autoclaved samples and studies in buffer indicated that this effect was not due to the reduction of competition from the natural flora when the additives were present.

[Novak et al. \(1966\)](#) irradiated oyster meats in cans in air at 2 kGy and stored them in ice for 23 days. The irradiated samples were found to be acceptable throughout the 23 days of storage, whereas the non-irradiated controls were spoiled by Day 7. [Carver et al. \(1967\)](#) reported that shucked surf clam meats (*Spisula solidissima*) air packed in plastic pouches have an optimum dose of 4.5 kGy, yielding a shelf life of 50 days at 0.6°C compared to 10 days for untreated surf clams. Also, doses of 1–2 kGy result in a shelf life of 40 days. In a study by [Ng et al. \(1987\)](#), cockles that had been treated with a combination of CO₂ (50–100%) atmosphere and γ -irradiation (2 kGy) and stored in melting ice showed an extended shelf life up to 18 days compared to 3 days for the untreated control.

[Table 9.7](#) shows the effect of irradiation and hurdle technology on shellfish parameters.

9.4.3 Crustaceans

The optimum irradiation dose for precooked crabmeat (*Cancer magister*) packed in cans or pouches is 2–2.5 kGy, yielding a shelf life of 28–42 days at 0.6°C and 14 days at 5.6°C. Non-irradiated samples had a shelf life of 6–14 days ([Scholz et al., 1962](#)). The optimum and maximum acceptable dose for cooked, VP king crab meat (*Paralithides camtschatica*) is 2 kGy, which yields a shelf life of 35 days at 0.6°C and 14 days at 5.6°C, compared to 5–9 days at 0.6°C, for non-irradiated samples. Above this dose, off-odors and -flavors predominate ([Miyachi et al., 1966](#)). Blanched tails of the Norwegian lobster (*Nephrops norvegicus*) have an optimum irradiation dose of 2–3 kGy, which results in a shelf life of 5 or 6 weeks at 0–1°C

TABLE 9.6 Irradiation of Fish and Hurdle Technology

| Species | Irradiation Type/Dose | Additional Hurdles | Temperature | Shelf Life | Organoleptic Changes | Results | References |
|---|-------------------------|---|---------------------|------------------------------|--|---|---|
| Halibut (<i>Paralichthys californicus</i>) stakes | 2 kGy | VP | 5.6°C | 14–21 days | — | — | Slavin et al., 1966; Stienberg, 1965 |
| | 2 kGy | | 0.6°C | More than 21–42 days | — | — | |
| Rockfish (<i>Sebastes</i> spp.) | 1.25–2.5 kGy | VP | Under refrigeration | 20 days | — | — | Miyauchi, 1970 |
| Sablefish | 3 kGy | Air packed | 0.6°C | 7 days | — | — | Stansby and Kudo, 1964 |
| Cod fish fillets | γ irradiation/ 6 kGy | Cooking | — | — | — | The two processes produced a total loss that was the sum of the losses produced by each process regarding niacin, riboflavin, and thiamin | Kennedy and Ley, 1971 |
| Sole (<i>Eopsetta jordani</i>) | 2–3 kGy | VP | 0.6°C | 28–49 days | At 3 kGy, significant odor and flavor changes occur | — | Spinelli et al., 1965 |
| Sole (<i>Eopsetta jordani</i>) | 2–3 kGy | VP | 5.6°C | 14–21 days | — | — | |
| Whole eviscerated, scaled gwyniad (<i>Coregonus wartmanni</i> Bloch) | 1 kGy | Under vacuum in plastic films impermeable to water and oxygen | — | 23 days (from 9 days on ice) | Higher doses resulted in even longer shelf life; however, they caused off flavor | — | Ehlermann and Muenzer, 1976 |

(Continued)

TABLE 9.6 Irradiation of Fish and Hurdle Technology—cont'd

| Species | Irradiation Type/Dose | Additional Hurdles | Temperature | Shelf Life | Organoleptic Changes | Results | References |
|--|-----------------------|---|-------------------------------|------------|----------------------|---|--------------------------------|
| Atlantic cod (<i>Gadus morhua</i>) fillets | 1.5 kGy | Packed in polyethylene bags | 4°C for 28 days | — | — | Results indicated that irradiation was quite effective in delaying deterioration in these cod fillets, and 2 to 3 kGy was determined to be the optimum dose | Thibault and Charbonneau, 1991 |
| Dogfish (<i>Squalus acanthias</i>) fillets | 2 kGy | Packed in nylon PVDC surlyn bags, under air | 8°C | 7 days | — | — | Licciardello et al., 1984a |
| Dover sole | No data | 0.19% sodium benzoate | — | — | — | — | Monk et al., 1995 |
| Kwamegi (semi dried raw Pacific saury) | — | Low water activity (0.90–0.95) and VP | 5°C storage period of 4 weeks | — | — | Viable counts of <i>S. aureus</i> , <i>B. cereus</i> , <i>Salmonella typhimurium</i> , and <i>E. coli</i> remained almost constant | Chawla et al., 2003 |
| | γ irradiation/ 2 kGy | Low water activity (0.90–0.95) and VP | 5°C storage period of 4 weeks | — | — | Viable counts of <i>S. aureus</i> , <i>B. cereus</i> , <i>Salmonella typhimurium</i> , and <i>E. coli</i> increased in samples irradiated up to 2 kGy | |
| | γ irradiation/ 3 kGy | Low water activity (0.90–0.95) and VP | 5°C storage period of 4 weeks | — | — | Surviving cells <i>S. aureus</i> , <i>B. cereus</i> , <i>Salmonella typhimurium</i> , and <i>E. coli</i> lost viability during storage | |
| | γ irradiation/ 4 kGy | Low water activity (0.90–0.95) and VP | 5°C storage period of 4 weeks | — | — | <i>S. aureus</i> , <i>B. cereus</i> , <i>Salmonella typhimurium</i> , and <i>E. coli</i> were eliminated | |

| | | | | | | | |
|--|----------------------|---------------------------------------|-------------------------------|---------|---|---|---------------------|
| Kwamegi (semi dried raw Pacific saury) | — | Low water activity (0.90 0.95) and VP | 5°C storage period of 4 weeks | — | — | Viable counts of <i>S. aureus</i> , <i>B. cereus</i> , <i>Salmonella typhimurium</i> , and <i>E. coli</i> increased by approximately 2 log cycles during the storage period of 4 weeks. Viable counts of <i>S. aureus</i> , <i>B. cereus</i> , <i>Salmonella typhimurium</i> , and <i>E. coli</i> increased in samples irradiated up to 2 kGy. Surviving cells lost viability during storage. <i>S. aureus</i> , <i>B. cereus</i> , <i>Salmonella typhimurium</i> , and <i>E. coli</i> were eliminated. | |
| | γ irradiation/ 2 kGy | Low water activity (0.90 0.95) and VP | 5°C storage period of 4 weeks | — | — | | |
| | γ irradiation/ 3 kGy | Low water activity (0.90 0.95) and VP | 5°C storage period of 4 weeks | — | — | | |
| | γ irradiation/ 4 kGy | Low water activity (0.90 0.95) and VP | 5°C storage period of 4 weeks | — | — | | |
| Atlantic horse mackerel (<i>Trachurus trachurus</i>) | — | — | 0 ± 1°C | 8 days | At the beginning, no significant differences were determined between the control and the irradiated lots. | TVCs and levels of amines increased in all samples with storage time. Histamine concentration did not exceed the maximum allowed in fresh fish. TVCs and amines levels were reduced by irradiation, even when the lower level (1 kGy) was used. Histamine in the irradiated lots was undetectable. | Mendes et al., 2005 |
| | γ irradiation/ 1 kGy | — | 0 ± 1°C | 12 days | Lower sensory ratings were, | | |
| | γ irradiation/ 3 kGy | — | 0 ± 1°C | 12 days | however, always ascribed from then onwards. | | |

(Continued)

TABLE 9.6 Irradiation of Fish and Hurdle Technology—cont'd

| Species | Irradiation Type/Dose | Additional Hurdles | Temperature | Shelf Life | Organoleptic Changes | Results | References |
|--|------------------------------------|--------------------|---------------------|------------|--|---|------------------------|
| Smoked mullet | — | VP | 3 and 10°C | — | Panelists indicated that there were no differences among treated and untreated samples. | — | Robertson et al., 2006 |
| | X ray irradiation/ 0.5 kGy | | | — | | Reduced the initial population of <i>L. monocytogenes</i> by 1.1 log. | |
| | X ray irradiation/ 1.0 kGy | | | — | | Reduced the initial population of <i>L. monocytogenes</i> by 1.6 log. | |
| | X ray irradiation/ 1.5 kGy | | | — | | Reduced the initial population of <i>L. monocytogenes</i> by 2.1 log. | |
| | X ray irradiation/ 2.0 kGy | | | — | Reduced <i>L. monocytogenes</i> to undetectable levels with no recovery growth at either temperature | | |
| Cold smoked salmon fillets | E beam irradiation/1, 2, and 4 kGy | — | 5°C | — | — | <i>Listeria monocytogenes</i> cells (3.6 log CFU/g) on inoculated salmon were reduced by 2.5 log CFU/g. | Su et al., 2004 |
| | E beam irradiation/2 kGy | — | | — | — | <i>Listeria monocytogenes</i> cells were completely eliminated. | |
| | E beam irradiation/4 kGy | — | | — | — | <i>Listeria monocytogenes</i> cells were completely eliminated | |
| Boiled dried anchovies Boiled dried anchovies (<i>Engraulis encrasicolus</i>) | γ irradiation/ 5 kGy | Air tight packaged | Ambient temperature | 6 months | γ irradiation at or below 5 kGy did not induce significant changes in appearance, rancid flavor, and palatability of the rumples immediately after treatment | D_{10} values for aerobic bacteria yeasts and molds were 1.33 and 2.02 kGy, respectively. Microbes were easily destroyed with 5 kGy | Kwon and Byun, 1995 |
| | | Air tight packaged | 5–10°C | 1 year | | | |

| | | | | | | | | |
|---|----------------------------------|--|-------------------|---------|---|---|--|------------------------------|
| Brook charr (<i>Salvelinius fontinalis</i>) | γ irradiation/1 and 3 kGy | VP | 1°C for 14 days — | — | — | Sensory evaluation confirmed the discoloration effect of irradiation on brook charr flesh and revealed that texture tends to be firmer at the end of storage in irradiated samples. The flavor of flesh was not affected by irradiation | Total plate count was decreased by irradiation treatment. Total plate count was decreased and the effect was more accentuated at 3 than at 1 kGy | Paradis and Adambounou, 1996 |
| | | | 1°C for 14 days — | | | | | |
| Freshwater fish, rohu (steaks) (<i>Labeo rohita</i>) | — | — | — | 20 days | — | — | — | Panchavarama et al., 2003 |
| | γ irradiation/1 kGy | — | — | 32 days | — | — | — | |
| | — | Coating (gel dispersion from the same fish) | — | 32 days | — | — | Bleaching of the pink color of the steaks by the treatment was prevented when either butylated hydroxy anisole or ascorbic acid was incorporated at 5 g/kg (w/v) in the dispersion | |
| | γ irradiation/1 kGy | Coating (gel dispersion from the same fish) | — | 42 days | — | — | — | |
| Cod fillets | — | Air packed | — | — | — | — | The CO ₂ packed, irradiated cod fillets retained quality attributes longer than the VP product, which retained their quality longer than air packed fillets | Licciardello et al., 1984b |
| | — | VP | — | — | — | — | | |
| | 1 | Packaged in a 60% CO ₂ , 40% air atmosphere | — | — | — | — | | |

(Continued)

TABLE 9.6 Irradiation of Fish and Hurdle Technology—cont'd

| Species | Irradiation Type/Dose | Additional Hurdles | Temperature | Shelf Life | Organoleptic Changes | Results | References |
|---|---------------------------------------|---|-------------------------|------------|----------------------|--|-------------------------|
| Cultured channel catfish (<i>Ictalurus punctatus</i>) | 0, 0.5, or 1.0 kGy | 100% air PE bags | 0 2°C for up to 30 days | — | — | The lowest psychotrophic plate counts were obtained with 100% CO ₂ atmosphere. Increased radiation doses decrease the microbial population in fish sampled after 20 days of storage | Przybylski et al., 1989 |
| | 0, 0.5, or 1.0 kGy | 100% CO ₂ PE bags | 0 2°C for up to 30 days | — | — | | |
| | E beam irradiation/0, 0.5, or 1.0 kGy | 80% CO ₂ and 20% air PE bags | 0 2°C for up to 30 days | — | — | | |
| Trout fillets inoculated with 10 ⁵ <i>Clostridium botulinum</i> type E | — | VP on 0.75 mm PE film | — | — | — | Fillets spoiled before they became toxic | Hussain et al., 1977 |
| | E beam irradiation/0, 0.5, or 1.0 kGy | VP on 0.75 mm PE film | 0°C | — | — | No toxin formation was observed from <i>Clostridium botulinum</i> | |
| | E beam irradiation/0, 0.5, or 1.0 kGy | VP on 0.75 mm PE film | 5°C | — | — | The fish became toxic long after spoilage occurred | |
| | E beam irradiation/0, 0.5, or 1.0 kGy | VP on 0.75 mm PE film | 5°C | — | — | Fillets became toxic before spoilage was observed | |

| | | | | | | | |
|--|---------------------------|---------------------|---------|------------|--|--|------------------------|
| Salted sea bream (<i>Sparus aurata</i>) fillets | — | VP | 4 ± 1°C | 14 15 days | Sensory evaluation (taste) showed a reasonably good correlation with bacterial populations | TMA values reached 8.87mgN (100 g) ⁻¹ flesh. Total volatile base nitrogen values reached 60.52 mgN (100 g) ⁻¹ | Chouliara et al., 2004 |
| | γ irradiation/ 1 kGy | | | 27 28 days | | TMA value reached 6.17 mgN (100 g) ⁻¹ flesh. Total volatile base nitrogen values reached 48.13 mgN (100 g) ⁻¹ muscle. Irradiation affected populations of <i>Pseudomonas</i> spp., H ₂ S producing bacteria, <i>Brochothrix thermosphacta</i> , Enterobacteriaceae, and LAB. | |
| | γ irradiation/ 3 kGy | | | 27 28 days | | TMA value reached 4.52 mgN (100 g) ⁻¹ . Total volatile base nitrogen values reached 37.21 mgN (100 g) ⁻¹ muscle. Irradiation affected populations of <i>Pseudomonas</i> spp., H ₂ S producing bacteria, <i>Brochothrix thermosphacta</i> , Enterobacteriaceae, and LAB. The effect was more pronounced at 3 kGy | |
| Changran Jeotkal (Korean seafood product, which is aged, fermented, and seasoned intestines of <i>Theragra chalcogramma</i> [Alaska pollock]) | — | Low salt (5%) | 10°C | — | — | Samples that were salted (5%) but not irradiated reached a microbial load of >10 ⁴ CFU/g. | Jo et al., 2004 |
| | γ irradiation/ 2.5 kGy | Low salt (5 and 8%) | 10°C | 12 weeks | — | Final level of microbial load in salted (5 and 8%) and irradiated samples was less than 10 ⁴ CFU/g | |

(Continued)

TABLE 9.6 Irradiation of Fish and Hurdle Technology—cont'd

| Species | Irradiation Type/Dose | Additional Hurdles | Temperature | Shelf Life | Organoleptic Changes | Results | References |
|--|------------------------------|------------------------|-------------|------------|---|--|--------------------------|
| Kwamegi, prepared from semi dried Pacific saury (<i>Cololabis seira</i>) flesh | — | VP | 5°C | — | Panelists found that the odor of irradiated kwamegi was better than that of the control and indicated that a unique fishy off odor of the saury decreased in irradiated samples | Total aerobic bacterial load reached 7.1×10^7 CFU/g (at Day 20). | Lee et al., 2002a |
| | γ irradiation/ 3 kGy | VP | — | — | | 1.2×10^4 (at Day 20) | |
| | γ irradiation/ 5 kGy | VP | — | — | | 8.5×10^2 (at Day 20) | |
| | γ irradiation/ 7 kGy | VP | — | — | | 3.3×10^1 (at Day 20) | |
| | γ irradiation/ 10 kGy | VP | — | — | | No growth observed | |
| Threadfin bream (<i>Nemipterus japonicus</i>) | — | Packaged in PE pouches | — | 8 days | Salting resulted in a firmer texture. The appearance of | The microbial count was 4.4×10^4 | Jeevanandam et al., 2001 |
| | 1 kGy | Packaged in PE pouches | — | 12 days | salted and irradiated fish was affected presumably by some bleaching of the pigments, whereas the appearance was | Irradiation and salt treatment caused lipid oxidation, as indicated by the TBA number, and irradiation also suppressed the formation of TVB N and TVA. There was a decrease of the initial counts. | |
| | 2 kGy | Packaged in PE pouches | — | 22 days | unaffected in the case of unsalted and irradiated fish during ice storage. However, in both unsalted and salted fish, there was no irradiation odor even at 2 kGy | Irradiation and salt treatment caused lipid oxidation, as indicated by the TBA number, and irradiation also suppressed the formation of TVB N and TVA. There was a decrease of the initial counts | |

| | | | | | |
|--|-------|--|---|---------|--|
| Threadfin bream (<i>Nemipterus japonicus</i>) | — | Packaged in PE pouches and dipped in 10% (w/w) sodium chloride | — | 9 days | The initial count was 2.2×10^4 per gram |
| | 1 kGy | Packaged in PE pouches and dipped in 10% (w/w) sodium chloride | — | 14 days | Irradiation and salt treatment caused lipid oxidation, as indicated by the TBA number, and irradiation also suppressed the formation of TVB N and TVA. |
| | 2 kGy | Packaged in PE pouches and dipped in 10% (w/w) sodium chloride | — | 28 days | |

(Continued)

TABLE 9.6 Irradiation of Fish and Hurdle Technology—cont'd

| Species | Irradiation Type/Dose | Additional Hurdles | Temperature | Shelf Life | Organoleptic Changes | Results | References |
|--|---------------------------|---|-------------|------------|----------------------|---|--|
| Indian mackerel (<i>Rastrelliger kanagurta</i>) | — | Aerobically packaged in polyethylene bags | 0 2°C | — | — | Variation in monosaturated fatty acids was 28.2 3 1.5% | Lakshmanan et al., 1999a |
| | γ irradiation/ 1.5 kGy | | 0 2°C | — | — | Variation in monosaturated fatty acids was 30.7 34.4%. A higher carbonyl value was observed in irradiated samples during initial phases of storage. Irradiation also had no adverse effect on the nutritionally important omega 3 polyunsaturated fatty acids (PUFA) of the fish. | |
| | γ irradiation/ 2 kGy | | 0 2°C | — | — | Variation in monosaturated fatty acids was 29.1 33.8%. A higher carbonyl value was observed in irradiated samples during initial phases of storage. Irradiation also had no adverse effect on the nutritionally important omega 3 PUFA of the fish | |

| | | | | | | | | |
|--------------|---------------------------|----|------|---------|---|---|--|-----------------------|
| Salted trout | — | VP | — | 7 days | — | — | Irradiation affected populations of <i>Pseudomonas</i> spp., <i>Brochothrix thermosfacta</i> , lactic acid bacteria, H ₂ S producing bacteria typical of <i>Shewanella putrefaciens</i> , and Enterobacteriaceae. The growth of <i>L. monocytogenes</i> was suppressed by 2 log cycles for up to 18 days. Irradiation affected populations of <i>Pseudomonas</i> spp., <i>Brochothrix thermosfacta</i> , lactic acid bacteria, H ₂ S producing bacteria typical of <i>Shewanella putrefaciens</i> , and Enterobacteriaceae. Irradiation affected populations of <i>Pseudomonas</i> spp., <i>Brochothrix thermosfacta</i> , lactic acid bacteria, H ₂ S producing bacteria typical of <i>Shewanella putrefaciens</i> , and Enterobacteriaceae. | Sawaidis et al., 2002 |
| | γ irradiation/ 0.5 kGy | | 4°C | — | — | | | |
| | γ irradiation/ 2 kGy | VP | 4°C | 28 days | — | | | |
| | γ irradiation/ 0.5 kGy | VP | 10°C | — | — | | | |
| | γ irradiation/ 2 kGy | VP | 10°C | — | — | | | |

(Continued)

TABLE 9.6 Irradiation of Fish and Hurdle Technology—cont'd

| Species | Irradiation Type/Dose | Additional Hurdles | Temperature | Shelf Life | Organoleptic Changes | Results | References |
|---|------------------------|-----------------------------------|---------------------|-------------------|---|---------|-----------------------------|
| Eviscerated Indian mackerel (<i>Rastrelliger kanagurta</i>) | — | — | Ice storage | 14 days | — | — | Venugopal et al., 1987 |
| | γ irradiation/ 1.5 kGy | — | Ice storage | 20 days | The nonpackaged irradiated fish has less irradiation odor and better appearance compared with packaged irradiated fish during the course of ice storage | — | |
| | γ irradiation/ 1.5 kGy | Packaging in polyethylene pouches | Ice storage | 25 days | | — | |
| Laminated films of Bombay duck (<i>Harpodon nehereus</i>) | — | Packaged in polyethylene bags | 0 2°C | 5 days | — | — | Doke et al., 1976 |
| | 2.5 kGy | Packaged in polyethylene bags | 0 2°C | 20 22 days | — | — | |
| | 2.5 kGy | Dehydrated laminates | Ambient temperature | 4 months | — | — | |
| Halibut (<i>Hippoglossus hippoglossus</i>) steaks | 2 3 kGy | VP | 5.6°C | 20 days | — | — | Rhodes, 1964; Sieling, 1961 |
| | 2 3 kGy | VP | 0°C | More than 30 days | — | — | |

| | | | | | | | |
|--|-----------------------------|----------------------------|---------------------|----------|--|--|---------------------------|
| Smoked salmon fillets | — | — | Under refrigeration | 1 month | — | — | Hammad and El Mongy, 1992 |
| | 2 kGy | — | Under refrigeration | 3 months | Color loss was not observed in samples irradiated with 2 kGy. | Reduced the number of microorganisms in samples | |
| | 4 kGy | — | Under refrigeration | 4 months | Color loss of normal cherry red color | Elimination of all coliforms, fecal streptococci, and <i>Staphylococcus aureus</i> | |
| Anchovy (<i>Stolephorus commersonii</i>) | γ irradiation/ 2 kGy | Packaged polyethylene bags | 13°C | 20 days | Packaging caused drip accumulation and poor appearance of the fish | — | Lakshmanan et al., 1999b |
| Sardines (<i>Sardina pichardus</i>) | — | VP in polyethylene bags | 2 ± 1°C | 10 days | — | The initial pH and TBA values were not significantly different between unirradiated and irradiated treatments. For all treatments, TBA showed fluctuations. There were higher TMA N values in comparison to unirradiated samples. | Kasimoglu et al., 2003 |
| | γ irradiation/ 3 kGy | VP in polyethylene bags | 2 ± 1°C | 21 days | — | The initial pH and TBA values were not significantly different between non irradiated and irradiated treatments. For all treatments, TBA showed fluctuations. There were lower TMA N values in comparison to non irradiated samples. Irradiation produced a reduction in initial bacterial count | |

TABLE 9.7 Effect of Irradiation and Hurdle Technology on Shellfish Parameters

| Species | Irradiation Type/Dose | Additional Hurdles | Temperature | Shelf Life | Results | Reference | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|-------------------------|--|---------------------|------------|---|------------------------|---|---|-------------------------------|-------|---------|---|---------------------|---------|-------------------------------|-------|---------|---|---------|-------------------------------|-------|---------|---|----------------------|---|------------|-----|---------|---|------------------------|-------------|------------|-----|---------|---|---------|-------------------------|--------------------------------------|----------------|--------|---|-----------------|-------------------------|--------------------------------------|----------------|---------|---|--------------------------------|---|-----------------------|---------------------|---------|---|-----------------------|-------------------------|-----------------------|---------------------|---------|--|-------------------------|
| Oysters (<i>Crassostrea gigas</i>) both raw and autoclaved | — | Sodium benzoate (0.1%) or potassium sorbate (0.1%) | 7°C | — | In both non irradiated and irradiated samples, greater numbers of <i>Salmonella</i> were recovered after storage at 7°C in the presence of sodium benzoate or potassium sorbate | Shiflett et al., 1967 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | γ irradiation/ 1 kGy | Sodium benzoate (0.1%) or potassium sorbate (0.1%) | 7°C | — | | | Shucked surf clam meats (<i>Spisula solidissima</i>) | — | Air packed in plastic pouches | 0.6°C | 10 days | — | Carver et al., 1967 | 1 2 kGy | Air packed in plastic pouches | 0.6°C | 40 days | — | 4.5 kGy | Air packed in plastic pouches | 0.6°C | 50 days | — | Shucked mussel meats | — | Air packed | 3°C | 3 weeks | — | Loaharanu et al., 1972 | 1.5 2.5 kGy | Air packed | 3°C | 6 weeks | — | Cockles | γ irradiation/ 2 kGy | CO ₂ (50 100%) atmosphere | In melting ice | 3 days | — | Ng et al., 1987 | γ irradiation/ 2 kGy | CO ₂ (50 100%) atmosphere | In melting ice | 18 days | — | Shrimps (<i>Penaeus</i> spp.) | — | Packed in plastic bag | Ambient temperature | 10 days | — | Noomhorm et al., 2003 | γ irradiation/ 2 kGy | Packed in plastic bag | Ambient temperature | 35 days | During storage, TBA values, total volatile nitrogen values, and hardness increased | γ irradiation/ 4 kGy |
| Shucked surf clam meats (<i>Spisula solidissima</i>) | — | Air packed in plastic pouches | 0.6°C | 10 days | — | Carver et al., 1967 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 1 2 kGy | Air packed in plastic pouches | 0.6°C | 40 days | — | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 4.5 kGy | Air packed in plastic pouches | 0.6°C | 50 days | — | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Shucked mussel meats | — | Air packed | 3°C | 3 weeks | — | Loaharanu et al., 1972 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 1.5 2.5 kGy | Air packed | 3°C | 6 weeks | — | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Cockles | γ irradiation/ 2 kGy | CO ₂ (50 100%) atmosphere | In melting ice | 3 days | — | Ng et al., 1987 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | γ irradiation/ 2 kGy | CO ₂ (50 100%) atmosphere | In melting ice | 18 days | — | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Shrimps (<i>Penaeus</i> spp.) | — | Packed in plastic bag | Ambient temperature | 10 days | — | Noomhorm et al., 2003 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | γ irradiation/ 2 kGy | Packed in plastic bag | Ambient temperature | 35 days | During storage, TBA values, total volatile nitrogen values, and hardness increased | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | γ irradiation/ 4 kGy | Packed in plastic bag | — | 49 days | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

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|--|--|----------------------|---|---|--|-----------------------------|
| Semi dried fish (name and species not mentioned) | γ irradiation/ 0, 1, 2, 2.5, 5, 7.5, 10, and 20 kGy | VP | — | — | <i>S. enteritidis</i> in semi dried fish could be eliminated at a dose of 2.5 kGy. <i>S. aureus</i> in semi dried fish inactivated using a dose of 2 kGy was more resistant to irradiation. A dose of 7.5 kGy was required to inactivate <i>B. cereus</i> in semi dried fish | Luo et al., 2003 |
| Ready to eat smoked sardines (<i>Sardinella</i> spp.) | γ irradiation/ 7 11 kGy | Packaged aerobically | — | — | Controlled microbial activity in some of the smoked sardines during a 12 week storage period; others had unacceptable color, flavor, and texture. | Nketsia Tabiri et al., 2003 |
| Ready to eat marinated fish (<i>Diplodus puntazzo</i>) product | γ irradiation/ 8 10 kGy | Packaged aerobically | — | — | Reduced the coliform count and extended the shelf life and overall acceptability of the product by 3 days | |

compared to 5 or 6 days for untreated tails and 4 weeks for blanched and non-irradiated tails (Hannesson and Dagbjartsson, 1970).

Loaharanu et al. (1972) reported that precooked crabmeat (*Portunus pelagicus*), air packed in plastic bags, has an optimum dose of 2 kGy, which yields a shelf life of 28 days at 3°C compared to 7 days for non-irradiated samples. Dagbjartsson and Solberg (1973) found that precooked lobster meat, air packed in plastic bags, is optimally irradiated at 0.75 kGy, yielding a shelf life extension of 14 days. Higher doses result in significant off-flavors and -odors. Furthermore, for the European lobster (*Homarus gammarus*), Rhodes (1964) found that its optimum irradiation dose is 1–3 kGy, but this finding is based only on appearance and odor.

Morais (1984) studied deep-sea shrimp (*Pandalus borealis*) and found that it has an optimum irradiation dose of less than 2 kGy. The development of black spot or melanosis is enhanced by irradiation; however, if blanching is employed prior to irradiation, it can be controlled. Five minutes of blanching in combination with 2-kGy irradiation results in an acceptable product that has a shelf life of 41 days at 0–1°C.

Kanatt et al. (2006) studied cooked marinated shrimp (*Penaeus indicus*) with reduced water activity (0.85 ± 0.02), packaged in low-density polyethylene bags, γ -irradiated, and stored at ambient temperature ($25 \pm 3^\circ\text{C}$). The total viable bacterial count, *Staphylococcus* species count, and aerobic spore count in the non-irradiated samples were 10^1 – 10^3 , 10^0 – 10^1 , and 10^1 – 10^2 CFU/g, respectively. Irradiation at 1 kGy decreased the TVC by 1 log cycle, whereas at 2.5 kGy there were approximately 3 log cycle reductions. Coliforms were not detected in any of the shrimp samples. The non-irradiated samples showed visible mold growth within 2 weeks of storage. Shrimp irradiated at 1 kGy showed visible mold growth within 30 days, but a dose of 2.5 kGy completely inhibited mold growth. However, non-irradiated control samples showed lower lipid oxidation (lower TBARS values) than irradiated samples. The TBA value of irradiated (2.5 kGy) shrimp after 2 months of storage was 2.73 mg malonaldehyde/kg. Sensory panelists were not able to detect changes in appearance, odor, and taste as affected by γ -irradiation.

The effect of irradiation in conjunction with hurdle technology on crustaceans is summarized in Table 9.8.

9.5 Conclusions

Gamma irradiation of 2–7 kGy is considered an interesting method of preservation to extend the shelf life of fish and also reduce qualitatively and quantitatively the microbial population (*Salmonella*, *Listeria*, and *Vibrio* spp. as well as many fish-specific spoilers such as Pseudomonaceae and Enterobacteriaceae) in fish and fish products. The shelf life of non-irradiated perch fillets stored at 6°C was approximately 6 days, but this was extended 3- and 3.5-fold by irradiation to 3 and 6 kGy, respectively. It was shown that the optimum dose for vacuum-packed halibut (*Hippoglossus hippoglossus*) steaks is 2–3 kGy, with a shelf life of 20 days at 5.6°C and

TABLE 9.8 Impact of Irradiation in Conjunction with Hurdle Technology on Crustaceans

| Species | Irradiation Type/Dose | Additional Hurdles | Temperature | Shelf Life | Results | References |
|---|-----------------------|--------------------------------------|-------------|------------|---------|---|
| Precooked crabmeat (<i>Cancer magister</i>) | 2 2.5 kGy | Packed in a can or pouches | 0.6°C | 28 42 days | — | Scholz et al., 1962 |
| | | Packed in a can or pouches | 5.6°C | 14 days | — | |
| Beheaded, tropical shrimps (<i>Penaeus</i> spp.) | 1.5 2 kGy | — | 3°C | 42 days | — | Gueavara et al., 1965; Kumta et al., 1970 |
| | | 4 min blanching prior to irradiation | 3°C | 130 days | — | |
| Cooked king crab meat (<i>Paralithides camtschatica</i>) | — | VP | 0.6°C | 5 9 days | — | Miyachi et al., 1966 |
| | 2 kGy | VP | 0.6°C | 35 days | — | |
| | | VP | 5.6°C | 14 days | — | |
| Precooked crabmeat (<i>Portunus pelagicus</i>) | — | Air packed in plastic bags | 3°C | 7 days | — | Loaharanu et al., 1972 |
| | 2 kGy | Air packed in plastic bags | 3°C | 28 days | — | |
| Norwegian lobster (<i>Nephrops norvegicus</i>) tails | — | — | 0 1°C | 5 6 days | — | Hannesson and Dagbjartsson, 1970 |
| | — | Blanched | 0 1°C | 4 weeks | — | |
| | 2 3 kGy | Blanched | 0 1°C | 5 6 weeks | — | |

(Continued)

TABLE 9.8 Impact of Irradiation in Conjunction with Hurdle Technology on Crustaceans—cont'd

| Species | Irradiation Type/Dose | Additional Hurdles | Temperature | Shelf Life | Results | References |
|---|---------------------------|---|--------------------------------|------------|---|---------------------|
| Cooked marinated shrimp (<i>Penaeus indicus</i>) | — | Water activity (0.85 ± 0.02) and packaging (in low density polyethylene bags) | Ambient temperature (25 ± 3°C) | — | The total viable bacterial count, <i>Staphylococcus</i> species, and aerobic spore counts in the non irradiated samples were in the range of 10 ¹ 10 ³ , 10 ⁰ 10 ¹ , and 10 ¹ 10 ² CFU/g, respectively. There was visible mold growth within 2 weeks. | Kanatt et al., 2006 |
| | γ irradiation/ 1 kGy | Water activity (0.85 ± 0.02) and packaging (in low density polyethylene bags) | Ambient temperature (25 ± 3°C) | — | Decreased TVC by 1 log cycle. Decreased the visible mold growth within 30 days | |
| | γ irradiation/ 2.5 kGy | Water activity (0.85 ± 0.02) and packaging (in low density polyethylene bags) | Ambient temperature (25 ± 3°C) | — | Decreased TVC approximately 3 log cycle reduction. Inhibition of mold growth | |

more than 30 days at 0°C. Gamma irradiation (0.5 and 2 kGy) of natural microflora of whole salted vacuum-packaged trout at 4 and 10°C was very effective in controlling *Listeria monocytogenes* inoculated into trout. It also affected the populations of *Pseudomonas* spp., *Brochothrix thermosfacta*, lactic acid bacteria, and H₂S-producing bacteria typical of *Shewanella putrefaciens* of inoculated trout.

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Proteins

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10.1 Introduction

Food irradiation is the process of exposing food to carefully controlled amounts of ionizing energy. “Irradiation is commended as a safe and effective food processing method that can reduce the risk of food poisoning and preserve foods without detriment to health and with minimum effect on nutritional quality” (Kouba, 2003). It can be used to reduce insect infestation of grain, dried spices, and dried or fresh fruits and vegetables; inhibit sprouting in tubers and bulbs; retard postharvest ripening of fruits; inactivate parasites in meats and fish; eliminate spoilage microbes from fresh fruits and vegetables; extend the shelf life of poultry, meats, fish, and shellfish; decontaminate poultry and beef; and sterilize foods and feeds (Shea et al., 2000). Four criteria are generally recognized as necessary for an irradiated food to be considered wholesome: (1) the absence of induced radioactivity; (2) the absence of viable pathogens or their toxins; (3) the absence of excessive loss of nutrients; and (4) the absence of toxic, mutagenic, or carcinogenic radiolytic products (Thayer, 1990).

The use of ionizing radiation to preserve foods was first proposed in 1896 when Minsch published the first article suggesting the use of ionizing radiation to destroy spoilage organisms in food. In 1905, patents were filed in the United States and in the United Kingdom to use irradiation to improve the condition of food (Brewer, 2004; O’Byrne et al., 2008).

The forms of ionizing energy (ionizing radiation) that may be used in food processing include gamma rays (from cobalt-60 or cesium-137), X-rays, and accelerated electrons (electron beam) (Kader, 1986).

Treating foods with ionizing irradiation results in a major reduction in microbial contamination and insect pests but only minor changes in the food components responsible for their nutritional value (Delincée, 1998). Ionizing radiations (γ and e-beams) and UV light can inactivate foodborne microorganisms without substantially heating the food (Lado and Yousef, 2002).

The use of γ -irradiation to enhance the shelf life of minimally processed fruits and vegetables and to ensure the microbiological safety is increasing because it appears to be effective both on cells and on spores. On the other hand, UV light has been used to treat fruit-based products or juices (e.g., apple juice and cider) (Corbo et al., 2009). UV light is effective against microorganisms, and studies have shown that a treatment of less than 1 s is sufficient to kill molds and spores. Topics of discussion are the process validation (e.g., lamp performance degradation) and the shadowing effects (Mittendorfer et al., 2002).

10.2 Proteins

Proteins are important components in food for both their nutritional and their functional values. Dietary proteins provide amino acids and nitrogen necessary for organisms. Proteins are believed to be largely responsible for functional properties, such as foaming, emulsification, nitrogen solubility, and oil and water absorption, whereas viscosity and swelling characteristics are starch related (Maity et al., 2009). Furthermore, it is believed that they have other specific functions due to the presence of bioactive peptides in their primary sequences making them potential health-promoting ingredients. Moreover, protein components play an important role in determining the sensory and textural characteristics of food (Léonil et al., 2000). The radiation-chemical changes in proteins depend strongly on irradiation conditions. Therefore, irradiation treatment can increase the cohesive strength of proteins by the formation of cross-links (Lacroix et al., 1998). If proteins are irradiated in the solid state and in a clear chemical form, the absorption of radiation energy gives rise to free radicals (Grolichova et al., 2004). In the irradiation of aqueous protein solutions, the radiation-chemical changes of amino acids will appear due to water radicals and radicals that arise from the individual mixture components and generate hydroxyl radicals (OH) that produce stable compounds such as bityrosine (Grolichova et al., 2004; Lacroix et al., 1998). Proteins in meat are a source of energy and essential amino acids (Stevenson, 1994).

10.2.1 Effect of γ -Irradiation on Proteins

Gamma irradiation affects proteins by causing conformational changes, oxidation of amino acids, scission of covalent bonds, and formation of protein-free radicals. Chemical changes of the proteins that are caused by γ -irradiation are fragmentation, cross-linking, aggregation, and oxidation by oxygen radicals that are generated in the radiolysis of water (Shawrang et al., 2008). Assuming that these changes occur simultaneously, their rates depend on the chemical nature of the protein, its physical state, and the irradiation conditions. The effect of γ -radiation on protein conformation appears to depend on several factors, such as protein concentration, the presence of oxygen, and the quaternary structure of proteins. The γ -irradiation was shown to affect the secondary structure rearrangement (Kojthung et al., 2008).

10.2.1.1 Egg proteins

The egg white proteins were reported to be aggregated by irradiation (Kume et al., 1994). Increasing doses led to an increase of the yolk and a decrease of white egg viscosimetry. Low and high doses of irradiation (0.5 and 5 kGy) do not seem to affect the viscosity of yolk egg products, but results indicated that viscosity decreased with a 2-kGy irradiation.

Albumin

Gamma irradiation of bovine serum albumin (BSA) protein solutions caused the disruption of the ordered structure of protein molecules as well as degradation, cross-linking, and aggregation of the polypeptide chains due to oxygen radicals generated by the radiolysis of water. It also altered the secondary structure, tertiary structure, and molecular weight profiles of BSA (Gaber, 2005). Irradiation of shell eggs seems to have no effect on the protein pattern of yolks, independent of the irradiation dose. With regard to the whites, there seems to be a slight degradation of the higher molecular-weight proteins with an irradiation dose of 5 kGy. However, there is no degradation of the major egg white protein (Pinto et al., 2004).

Lactalbumin appeared more easily protected from radiation-induced precipitation than either myoglobin or BSA. Approximately 75% of the lactalbumin could be recovered with sodium dodecyl sulfate–polyacrylamide gel electrophoresis (SDS-PAGE) after 6 months of frozen post-irradiation storage (Krumhar and Berry, 1990). At 0.13 and 0.41% of BSA concentration, only the aggregated pattern of protein bands remained. However, at 3.9% of concentration, irradiation did not significantly affect the molecular weight profile of proteins (Cho et al., 1999).

Hajós and co-workers (1990) reported that in the pattern of the irradiated fresh egg white, obtained with SDS-PAGE, only minor changes were recorded with regard to the molecular masses of protein zones. Therefore, according to the protein structure investigation, γ -irradiation of egg white both in the frozen state and in powdered form could be strongly suggested for the preservation of the products.

Ovalbumin and ovomucoid

Fifty-eight percent of total protein in chicken egg white is ovalbumin and 10% is ovomucoid (Niciforovic et al., 1999). Circular dichroism (CD) showed that an increase of radiation decreased the ordered structure of proteins. Fluorescence spectroscopy indicated that irradiation quenched the emission intensity excited at 280 nm. SDS-PAGE indicated that radiation caused initial fragmentation of polypeptide chains and, as a result, subsequent aggregation. Gamma irradiation of protein solutions causes disruption of the ordered structure of protein molecules, as well as degradation and aggregation of the polypeptide chains, due to oxygen radicals generated by irradiation. It also alters the secondary structure, tertiary structure, and molecular weight profiles of ovalbumin and ovomucoid (Moon and Song, 2001). The amount of ovalbumin decreased almost linearly in the dose range 0–7.5 kGy (Niciforovic et al., 1999). Strong

precipitin arcs were also observed for egg-white proteins (ovalbumin and ovomucoid) in the egg irradiated at 10 kGy. The arc intensities, especially those of ovomucoid, decreased when subjected to 50 kGy irradiation (Kume et al., 1994).

10.2.1.2 Meat proteins

Camel meat proteins

The composition of camel meat varies based on several factors. Age is an important factor in determining meat quality and composition. The percentage of protein decreased with increasing camel age. No significant differences in protein of camel meat were observed due to irradiation. Crude protein was $23.69 \pm 0.06\%$ before the irradiation and $22.19 \pm 0.44\%$ after the 6-kGy dose of irradiation (Al-Bachir and Zeinou, 2009).

Chicken breast meat

Textural toughening of chicken breast meat can be the reason for the aggregation of meat protein (myofibril units, sarcomere) due to γ -irradiation. The appearance of high-molecular-weight protein bands and the decrease in protein solubility due to aggregation of proteins were observed in irradiated soybean protein (Yoon, 2003).

Gelatin

The viscosity of gelatin solutions was reduced as a consequence of both γ -irradiation and e-beam irradiation. In both cases, the irradiated samples underwent a decrease of 40–50% (5.2 and 4.2 cP for 50-kGy γ -irradiation and e-beam irradiation, respectively, compared to 8.9 cP for the 0-kGy dose) (Vieira and Del Mastro, 2002). Cross-linking of a fiber induced by 50 kGy γ -irradiation gave a high tensile strength (TS) equal to 151 MPa. A dose of 100 kGy resulted in a decrease of strength at 74 MPa (Fukae and Midorikawa, 2008).

Globulin

The effect of irradiation on bovine γ -globulins depends on the applied dose and, to some extent, on the dose rate used for irradiation. A significant decrease in denaturation enthalpy was reported in the case of bovine γ - and α -globulin due to irradiation. Broader endotherms observed at a lower temperature and in a wider temperature range compared to denaturation effects of the non-irradiated samples are probably associated with denaturation processes of the globulins' fraction (Ciesla et al., 2000).

Ground beef

Gamma irradiation and an edible coating film (calcium caseinate and whey protein isolate) containing natural antimicrobial compounds resulted in a significant reduction of bacterial growth in ground beef and stabilized the biochemical characteristics (Ouattara et al., 2002a). Lacroix et al. (2004) observed no significant difference between the control treatment group and ascorbic acid plus edible coating films for all the microorganisms determined.

Myoglobin

Grinding of meat accelerates the oxidation of myoglobin. Acidic conditions (pH 5 and 6) rather than neutral (pH 7) helped to keep myoglobin in solution after irradiation (0, 5, and 10 kGy) (Krumhar and Berry, 1990). Gamma irradiation of the myoglobin solutions caused disruption in the ordered structure of the protein molecules, as well as degradation, cross-linking, and aggregation of the polypeptide chains. The effect of irradiation on the myoglobin was more significant at a low protein concentration. The irradiated myoglobin could be differentiated from the native one by disruption of its heme group (Lee and Song, 2002). The addition of salt slowed the accumulation of metmyoglobin (MetMb) in raw beef patties. Salt is a powerful oxidant, and cooking greatly accelerates the oxidative changes in meat. Pre-rigor grinding and salting reduced the pH decline, leading to a lower content of MetMb (the ferric state) and higher ultimate pH (compared to the case of post-rigor samples). On the other hand, lipid oxidation occurred rapidly in the presence of a greater proportion of heme proteins in the reduced, ferrous state (Badr, 2007).

Myosin

Myosin is the major construction protein of chicken meat (Niciforovic et al., 1999). Myosin molecules suffered conformational changes by γ -irradiation. The changes were dependent on the morphological properties of myosin. By ionizing radiation, myosin head parts started to lose epitopes on the surface and myosin rods, LMM parts, were structurally released and better recognized by Ab at 3 kGy and below (Lee et al., 2000). Myosin dissociates to heavy (223 kDa) and light chains (18 and 22 kDa), and tropomyosin dissociated to 32-kDa subunit components. Tropomyosin was not significantly affected due to irradiation or because of thermal conditions (from 8.4 ± 0.4 at 0 kGy to 8.4 ± 0.3 at 7 kGy) (Niciforovic et al., 1999).

Porcine and bovine blood plasma proteins

An increase of γ -irradiation (1, 5, 7, and 10 kGy) decreased the ordered structure of plasma protein solutions and caused initial fragmentation of the polypeptide chains and subsequent aggregation. However, solubility and viscosity of the irradiated plasma protein powders, as well as the secondary structure and molecular weight profile, were not significantly changed with radiation dose (Lee et al., 2003).

10.2.1.3 Dairy proteins

β -Lactoglobulin

β -Lactoglobulin (β -Lg) irradiated in the solid state showed no significant structural changes compared to non-irradiated samples, except for a very small alteration in CD spectra of the samples irradiated at the highest dose. The changes observed on the β -Lg irradiated in solution, related to secondary and mainly to tertiary structure, explain, at least partially, the protein aggregation. These changes were more severe at low protein concentration and at high radiation dose (Hoz and Netto, 2008). For β -Lg at 0.1 and 0.35%, there were mostly aggregated

molecules. In contrast, at 0.72 and 4.05%, the major bands remained intact as the subunit molecular weight of a native β -Lg. An increase in protein concentration β -Lg revealed that the gel permeation chromatogram profile was similar to that of the control, which was not irradiated (Cho et al., 1999).

Caseinate films

Cross-linked caseinate films had improved resistance to microbiological degradation and were less soluble in water. The 4-kGy films readily dissolved within 24 h, whereas the 64-kGy films remained solid for more than 2 weeks. For the 64-kGy films, the bacterial population reached 10^9 CFU/ml on Day 28, whereas a comparable number of microorganisms had already been reached on Day 12 in the case of the 4-kGy film (Mezgheni et al., 2000). Gamma irradiation increased the puncture strength by more than 35% for calcium caseinate films (Ouattara, Sabato, et al., 2002b).

Casein

α_{S1} -Casein to total protein ratio in raw milk decreased from 19.63 to 8.64% by 10 kGy of γ -irradiation. The ratio of α_{S1} - to α_{S0} -casein also decreased from 1.38 to 0.53, thereby confirming that α_{S1} -casein is more susceptible to γ -irradiation than α_{S0} -casein. Similarly, α_{S1} -casein to total protein ratio in Queso Blanco cheese decreased from 17.48 to 7.82% and the ratio of α_{S1} - to α_{S0} -casein decreased from 1.16 to 0.43 by 10 kGy of γ -irradiation. A dose-dependent reduction of β_{A1} -casein was also reported. β_{A1} -Casein to total protein ratios in raw milk and Queso Blanco cheese decreased from 22.00 to 14.16% and from 21.96 to 13.89% after 10 kGy, respectively. The ratios of β_{A1} - to β_{A2} -casein decreased from 1.10 to 0.64 and from 0.93 to 0.57 in milk and Queso Blanco cheese, respectively (Ham et al., 2009).

Radiation treatment effectively reduces the numbers of microorganisms present in samples of industrial casein. For casein 30 mesh, total microflora declined from 6.04 log CFU/ml at 0 kGy to 1.30 log CFU/ml at 10 kGy, coliforms declined from 2.45 log CFU/ml at 0 kGy to less than 1 log CFU/ml at 10 kGy, and molds and yeasts declined from 3.40 log CFU/ml at 0 kGy to 1.48 log CFU/ml at 10 kGy. Proportional differences in the microbiological counts were noticed in casein 60 mesh and milk powder, respectively (Zegota and Malolepzy, 2008).

Milk protein (calcium caseinate and whey protein isolate)

The increase in solution viscosity of solutions after irradiation was closely associated to induction of cross-linking. Lower viscosity values were detected after heating solutions irradiated with a 32-kGy dose than after heating non-irradiated solutions. The milk protein films were characterized by improved barrier properties and mechanical resistance and higher rigidity than those prepared from the non-irradiated solutions (Ciesla et al., 2004).

Milk proteins [calcium caseinate and whey protein isolate (WPI)] were irradiated to improve the storage-keeping quality of strawberries (*Fragaria* spp.). In the first experiment, coating

formulation based on caseinate and/or strawberries were irradiated. Both γ -irradiation treatment and the edible coating process significantly delayed mold growth. The edible coating based on irradiated caseinate was found to be more effective than that of unirradiated caseinate. In the second experiment, the coating formulation based on 1:1 caseinate:whey was shown to be more effective than those based on calcium caseinate. The presence of whey proteins added further value to the resulting edible coating because it delayed the appearance of molds on strawberries (Vachon et al., 2003).

Whey protein

There was no significant change in the a^* value, whereas the b^* value increased with irradiation dose due to the formation of a yellow-brown color that increased as a result of irradiation of whey protein dispersion. L^* values decreased upon irradiation due to loss of lightness. A decrease in free amino acids and a significant dose-dependent decrease in the reducing sugar content were observed in irradiated whey protein dispersion, whereas β -carotene bleaching was inhibited in the presence of irradiated whey protein (Chawla et al., 2009).

10.2.1.4 Plant proteins

Albumin

The increase in extractable albumin proteins of wheat grain content from wheat grain was observed up to a 5-kGy dose. Among extracted proteins, the lowest numbers of wheat albumin protein bands were five and eight in grain samples treated at doses of 10 and 0.5 kGy, respectively (Gralic and Warchalewski, 2006).

Black truffles proteins

The most pronounced degradation phenomena were observed in the control, whereas they were not as evident in the treated samples, especially in the 1.5-kGy irradiated sample. In the third group, the 2.0-kGy treated sample showed decreasing values after 30 days of storage probably because of a greater degradation of protein with consequent release of peptides. In the 2.0-kGy irradiated samples, the protein profile was characterized by a 20-kDa polypeptide (Nazzaro et al., 2007).

Bombyx mori silk fibroin

The biodegradation of silk fibroin increased with increasing irradiation intensity. The intensity of protein bands (37 kDa) gradually increased as the irradiation concentration increased, thereby indicating a degree of linkage between polypeptides. The disappearance of low-molecular-weight protein in the PBS-treated condition was due to γ -radiation, which destroyed the hydrogen linkage of secondary structure and did not degrade the polypeptide chain. However, the presence of two low-molecular-weight proteins (37 and 33 kDa) in the protease solution confirmed the occurrence of enzymic activity on the silk fibroin, thereby resulting in a release of proteins into the solutions (Kojthung et al., 2008).

Cannabis sativa and Helianthus annuus proteins

There was no apparent change in the protein fraction, and the relative proportion of each major protein band (separated by molecular weight) did not change after the irradiation (Fisk et al., 2009).

Canola seed proteins

The two major protein components in canola seed are cruciferin (12S globulin) with four subunits and napin (2S albumin) with two subunits. Rumen degradability of napin was more than that of cruciferin (12S globulin), a globular protein rich in hydrophobic amino acid (methionine). Gamma irradiation decreased ruminal degradation of napin and cruciferin subunits. At doses higher than 15 kGy, cross-linked products of protein molecules that could not penetrate the running gel were identified (Ebrahimi et al., 2009).

Cry1Ab protein of transgenic rice

The relative content of Cry1Ab protein in the transgenic rice reached 0.16% but decreased to 0.04% after irradiation (0–7 kGy) with a 7-kGy dose. The higher doses of irradiation affected the Cry1Ab protein content similarly to thermal treatment. The amounts of Cry1Ab protein decreased significantly by the higher doses of 200 kGy (Wu et al., 2004).

Dry red kidney proteins

Gamma irradiation was found to affect the physicochemical properties of dry red kidney beans. The highest dose used (8 kGy) significantly modified the extent of deamidation, the number of sulfhydryl groups, as well as the solubility and the hydrophobicity of the protein. The deamidation increased (from $26.00 \pm 0.04\%$ to $65.89 \pm 0.05\%$), protein solubility increased (from $91.2 \pm 4.1\%$ to $92.0 \pm 0.9\%$), and hydrophobicity increased (from 3.3 ± 0.1 to 4.8 ± 0.2) with the irradiation dose, whereas the number of sulfhydryl groups was reduced (from 32.6 ± 0.6 mM/g to 23.1 ± 0.2 mM/g) by the treatment.

Gluten films

The γ -irradiation treatment of the gluten solutions caused the disruption of ordered structures of the protein molecules, increasing TS (TS value was 3.99 MPa at 50 kGy compared to 2.68 MPa for the control); percentage elongation (%E) decreased with increased irradiation dose (%E at 50 kGy was 108% compared to 282% for the control); and water vapor permeability (WVC) of gluten films decreased significantly when irradiated. At 50 kGy, WVP decreased by 29% compared to unirradiated samples (from ~ 7.8 to ~ 5.8 ng/m \cdot s \cdot Pa) (Lee et al., 2005a).

Gluten protein on wheat

Compared to non-irradiated wheat, the relative decline in total insoluble glutenin at the 20-kGy dosage ranged from 34 to 49%. Increasing levels of irradiation also progressively reduced the ratio of high molecular weight:low molecular weight to 13–15% at 20 kGy (Köksel et al.,

1998). The irradiation dose factor showed a highly significant effect on wet gluten content (WGC) and moisture of wet gluten content (MCGC) but no effect on dry gluten content (DGC). The values of WGC, DGC, and MCGC indices for non-irradiated wheat sample were 28.6, 10.2, and 180.4%, respectively. As the irradiation dose increased on wheat samples, decreases in WGC (3.2, 8.4, 14.4, and 17.1%) and MCGC (6.4, 14.4, 22.3, and 27.9%) were observed (Wang and Yu, 2009). The effect of γ -irradiation on the %E and TS of gluten, soy protein isolate (SPI), and zein films is shown in Figures 10.1 and 10.2. Both of them display an increase in %E with irradiation dose, although there is a threshold (25–35 kGy) above which a decrease in %E is observed (possibly due to cross-linking) and then, at higher doses (above 40 or 50 kGy) a further increase (attributed to loosening of structure) is recorded. In Figure 10.3, the effects of γ -irradiation dose on viscosity of gluten, SPI, and zein films are displayed.

Leaf protein in desi and kabuli chickpea

In kabuli chickpea, leaf protein contents slightly decreased after γ -irradiation (various doses) of seeds compared with non-irradiated seeds. However, in desi chickpea, the protein contents were lower after 0.1–0.8 kGy doses, whereas higher radiation doses (0.9 and 1 kGy) caused an increase in leaf protein contents in desi chickpea compared with control. A maximum decrease in protein content was reported after a dose of 0.8 kGy in desi as well as kabuli chickpea.

*Maize cultivars (*Zea mays*) and sorghum (*Sorghum bicolor*)*

For Maize 75 cultivars, no significant differences were observed in all fractions, except in prolamins and glutelins. For sorghum, significant increases in globulins, prolamins, and glutelins were observed (Hassan et al., 2009).

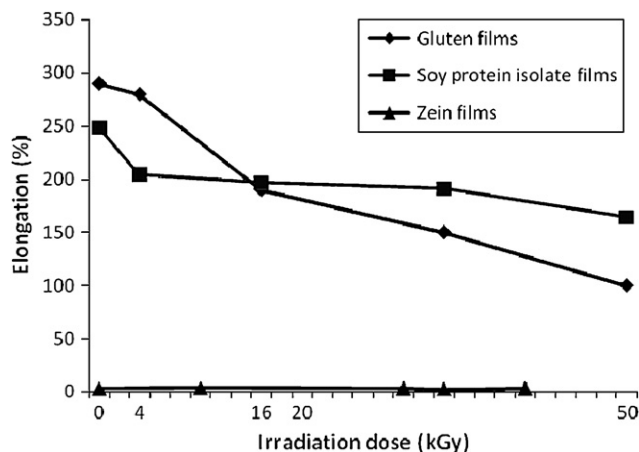


Figure 10.1: Effect of γ -irradiation on the percentage elongation of gluten (◆) (Lee et al., 2005a), soy protein isolate (■) (Lee et al., 2005b), and zein (▲) (Soliman and Furuta, 2009) films.

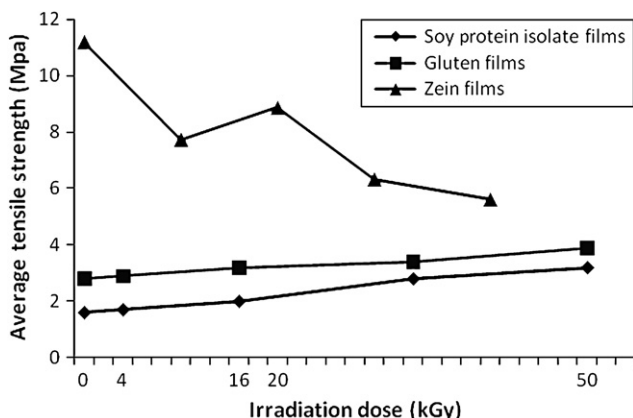


Figure 10.2: Effect of γ -irradiation on the tensile strength of gluten (■) (Lee et al., 2005a), soy protein isolate (Lee et al., 2005b) (◆), and zein (▲) (Soliman and Furuta, 2009) films.

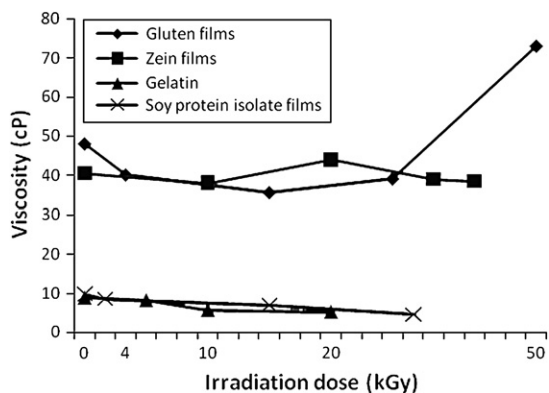


Figure 10.3: Effect of γ -irradiation on the viscosity of gluten (■) (Lee et al., 2005a), zein (■) (Soliman and Furuta, 2009), gelatin (▲) (Vieira and Del Mastro, 2002), and soy protein isolate (×) (Lee et al., 2005b) films.

Cauliflower membrane proteins

The protein content of the microsomal membranes was reduced by 15% in the controls during storage. The protein content was not immediately affected by irradiation, but approximately 50% of the membrane protein was lost during storage. The ratio of membrane lipid phosphate to protein, which remained constant in the controls during storage, increased markedly in the irradiated samples (Voisine et al., 1991).

Mushrooms proteins

Fruit bodies of *Pleurotus nebrodensis* contain substantial amounts of soluble protein (3.1–3.4 mg/g fresh weight) and, after harvesting, this served as a nutrient source to support continuing

metabolic activity. A decline in soluble protein concentration was considered to be an important indicator of tissue senescence (Xiong et al., 2009).

Oryza sativa L. Cv-Shankar and Cicer arietinum L. proteins

Soluble protein loss of 27% was observed in *Oryza sativa L. Cv-Shankar* when irradiated at 6 kGy. On the other hand, minimal loss of total soluble protein was reported in *Cicer arietinum L.*, which showed only 3% loss of protein when irradiated at 1 kGy and only 27% loss when irradiated at 6 kGy. The maximum loss of total protein in *O. sativa L. Cv-2233* (~30%) was observed at the higher dose (6 kGy). In *C. arietinum*, the effect of γ -rays was more pronounced on albumin and prolamin. However, a dose of 2 kGy resulted in loss of protein content in the range of 6–16% for all three seed types (Maity et al., 2009). Studies on the physicochemical properties of rice proved that apparent amylose content, gel consistency, and gelatinization temperature were all affected by γ -irradiation pretreatment, and these effects were closely related to the changes of starch structure. As a result, γ -irradiation could effectively improve the eating and cooking quality of rice (Yu and Wang, 2007).

Soya protein/soy protein isolate

The WVP of films based on SPI decreased when irradiated. Gamma irradiation was efficient for inducing cross-links in protein edible films and slowed the biodegradation of the material at 4 and 64 kGy (Lacroix et al., 2002). According to Lee et al. (2005b), γ -irradiation treatment of SPI solutions increased the viscosity, TS, and yellowness (b^*) of proteins but decreased the WVP. The viscosity value for 50 kGy was 3.92 cP compared with 9.31 cP for the control. The TS value was 3.24 MPa for 50 kGy compared with 1.59 MPa for the control. The WVP of SPI films significantly decreased when irradiated; at 50 kGy, WVP decreased by 13% compared to the control film. The yellowness value (b^*) at 50 kGy was 10.6 compared with 4.0 for the control film. However, the film thickness values were not significantly different among treatments.

Sunflower meal proteins

The combined effect of different methods revealed that irradiation alone had little effect on *in vitro* protein digestibility. Dry heating plus irradiation at 10 kGy increased the value by 3%, whereas heating plus irradiation at 20 kGy increased the value by 9%. Meanwhile, autoclaving plus irradiation at 10 kGy resulted in increased *in vitro* protein digestibility by 10% over the control (81.5%). In fact, the combined action of autoclaving plus irradiation (at 20 kGy) led to maximum digestibility (90.07%) (Diaa and El-Din Farag, 1999).

Ragi malt

The protein content of the ragi malt (control and irradiated) mixed with green gram malt at the 50% level (18.8 control and 18.9 irradiated), was found to be appreciably higher than that of the ragi malt mixed with green gram malt at the 30% level (14.6 control and 14.9 irradiated) (Pednekar et al., 2009).

Velvet bean seeds proteins

Gamma irradiation resulted in a significant increase in crude protein with all irradiated doses (control, 23.21%; 30 kGy, 31.06%). The *in vitro* protein digestibility (IVPD) of raw seeds (49.74%) was not significantly affected by γ -irradiation doses up to 15 kGy ($P > 0.05$). However, there was a significant increase in IVPD (59.41%) at 30 kGy ($P < 0.05$), which can be attributed to the degradation of proteins into fractions susceptible to enzymes or partial destruction of trypsin inhibitors (Bhat et al., 2008).

Zein

Soliman and Furuta (2009) showed that γ -irradiation treatment has a potential for modifying the physicochemical properties of zein-based films, particularly the color, appearance, and water barrier properties. The effects of γ -irradiation on gluten, zein, gelatin and SPI are shown in Figure 10.3. According to the figure, in most cases, there was either a slight or strong tendency upwards.

10.2.2 Effect of E-Beam Irradiation on Proteins

10.2.2.1 Egg proteins

The CD measurement of egg white protein indicated that even at 16 kGy, only limited changes in protein secondary structure were observed. On the other hand, the lipid content in egg yolk is high, and lipid—especially unsaturated lipid—is more reactive than protein, especially in radical-induced chain reactions. The lipid in egg yolk could act as a buffer for protein against radiation-induced reactions (Huang et al., 1997).

10.2.2.2 Meat proteins

Globin

The shift in color in cooked beef was caused by an oxidation/reduction reaction, in which irradiation caused the reduction of oxidized globin myohemichromagen to reduced globin myohemochromogen (loss of surface redness of non-irradiated control steaks; i.e., spontaneous oxidation of oxymyoglobin to metmyoglobin). Irradiation doses greater than 150 kRad (1.5 kGy) initiated a brown discoloration of meat exposed to air. However, in the absence of oxygen and at greater irradiation, a bright red color similar to oxymyoglobin was observed. Oxidation of oxymyoglobin, as measured by the change in surface redness on the sirloin steaks, was reduced by the presence of ginseng during storage. The production of water-soluble lipid peroxide can induce oxymyoglobin oxidation, thereby resulting in protection against peroxy radical-induced oxymyoglobin oxidation. Therefore, irradiation induced an oxymyoglobin-like pigment in pork, and both oxymyoglobin and metmyoglobin were developed in beef as a result of irradiation (Nanke et al., 1998). Moreover, the exposure of meat to irradiation can increase the production of water-soluble free radicals (e.g., hydroxyl

radical), thus promoting the oxidation of oxymyoglobin (Nanke et al., 1998; Wong and Kitts, 2002).

Turkey breast roll

The protein content of irradiated turkey breast rolls without plum extract was 23.91%, and that of irradiated turkey breast rolls with 3% plum extract was 23.92%. Therefore, there was no difference in protein content of irradiated turkey breast roll before and after the addition of plum extract (Lee and Ahn, 2004).

Sarcoplasmic and myofibrillar proteins

Total carbonyl content was higher in the sarcoplasmic proteins isolated from irradiated meat 0, 1, 3, and 7 days after irradiation than in sarcoplasmic proteins isolated from non-irradiated meat. Total carbonyl content was higher in myofibrillar proteins isolated from irradiated steaks than in myofibrillar proteins isolated from non-irradiated steaks at all time points (Rowe et al., 2004).

10.2.2.3 Fish proteins

Cold-smoked salmon protein structure

E-beam irradiation with 8 kGy modified the protein structure of cold-smoked salmon, namely decreasing the α -helix protein backbone arrangement and increasing the β -sheet, turns, and unordered structure. An absorbed irradiation dose ≥ 1 kGy produced a significant decrease of 1518 cm^{-1} band, which can be attributed to a decrease in carotenoid content in cold-smoked salmon (Herrero et al., 2009). The impact of γ -irradiation dose on the sensory score and thiobarbituric acid (TBA) of anchovy, threadfin bream, and sea bream is shown in

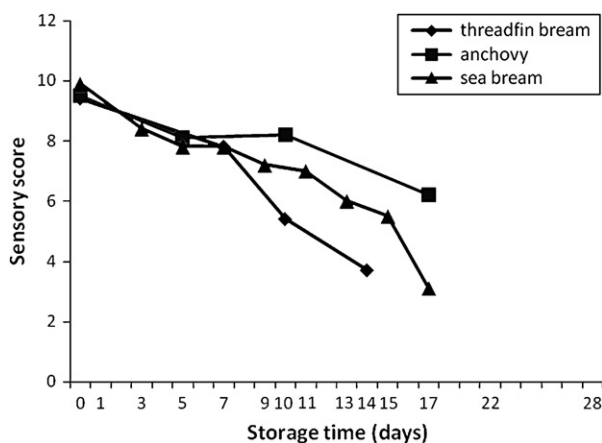


Figure 10.4: Effect of γ -irradiation on the sensory score of threadfin bream (◆) (Jeevanandam et al., 2001), anchovy (■) (Lakshmanan et al., 1999), and sea bream (▲) (Özden et al., 2007b).

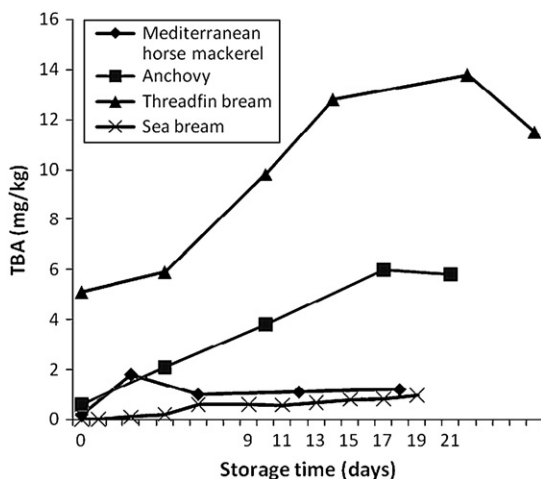


Figure 10.5: Effect of γ -irradiation on the thiobarbituric acid (TBA) of Mediterranean horse mackerel (◆) (Mbarki et al., 2009), threadfin bream (▲) (Jeevanandam et al., 2001), anchovy (■) (Lakshmanan et al., 1999), and sea bream (×) (Özden et al., 2007b) versus storage time.

Figures 10.4 and 10.5. The sensory score versus irradiation dose exhibited a gradual lowering trend, whereas in the case of TBA the values gradually increased. Such a result was anticipated because irradiation is considered to alter, at least to some extent, the sensory properties of food. On the other hand, irradiation triggered the increase in TBA similarly to a previous report on irradiated fatty acids emulsions by Iowa State University. The impact of storage time on the total volatile basic nitrogen (TVB-N) and trimethylamine (TMA) of γ -irradiated anchovy, Mediterranean horse mackerel, threadfin bream, and sea bream is displayed in Figures 10.6 and 10.7. TVB-N of γ -irradiated fish increased substantially only with long

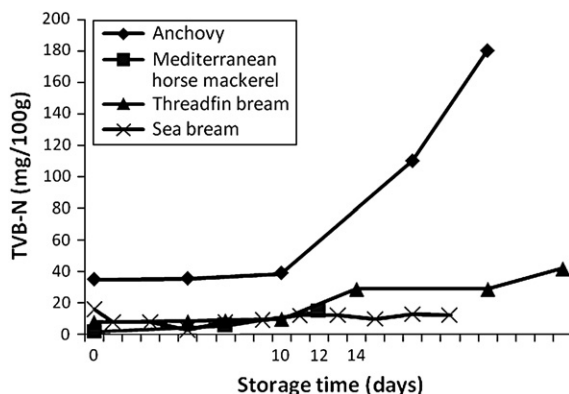


Figure 10.6: Effect of storage time on the total volatile basic nitrogen (TVB-N) of γ -irradiated anchovy (◆) (Lakshmanan et al., 1999), Mediterranean horse mackerel (■) (Mbarki et al., 2009), threadfin bream (▲) (Jeevanandam et al., 2001), and sea bream (×) (Özden et al., 2007b).

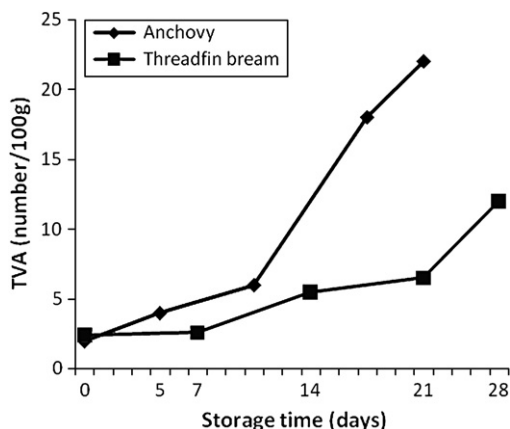


Figure 10.7: Effect of γ -irradiation on the TVA of anchovy (◆) (Lakshmanan et al., 1999) and threadfin bream (■) (Jeevanandam et al., 2001).

storage time, similar to results reported by Chauhan et al. (2009) and Alur et al. (2006). Figures 10.8 and 10.9 exhibit the effect of γ -irradiation on the H_2S -producing bacteria and TMA-N production of sea bream, sea bass, and Mediterranean horse mackerel. Both concentrations of H_2S and TMA-N increased considerably at higher irradiation doses. However, similar results were reported by Balamatsia et al. (2006) for chicken meat at even lower irradiation doses (e.g., 2 kGy). In fact, the authors reported that with regard to volatile amines, both TMA-N and TVB-N values for non-irradiated aerobically packaged chicken increased steeply, with final values of approximately 20.3 and 58.5 mg N/100 g of muscle, respectively. Irradiated aerobically packaged chicken samples had significantly lower TMA-N and TVB-N values ($P < 0.05$) of approximately 2.2–3.6 and 30.5–37.1 mg N/100 g of muscle, respectively, during refrigerated storage for 21 days (Balamatsia et al., 2006). The impact of γ -irradiation on the thiobarbituric acid reactive substances (TBARs) of Iberian dry-cured

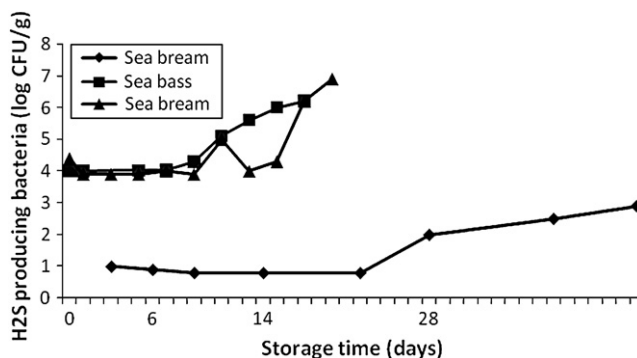


Figure 10.8: Effect of γ -irradiation on the H_2S -producing bacteria of sea bream (◆; 3 kGy) (Chouliara et al., 2003), sea bass (■) (Özden et al., 2007a), and sea bream (▲; 5 kGy) (Özden et al., 2007b).

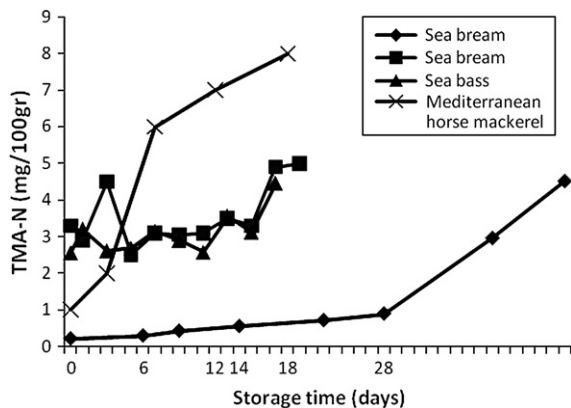


Figure 10.9: Effect of γ -irradiation on the TMA-N (mg/100 g) production of sea bream (◆; 3 kGy) (Chouliara et al., 2003), sea bream (■; 5 kGy) (Özden et al., 2007b), sea bass (▲) (Özden et al., 2007a), and Mediterranean horse mackerel (×) (Mbarki et al., 2009).

hams, raw beef patties, raw beef, and moist beef biltong is shown in Figure 10.10. TBARs (an indicator of oxidative rancidity) was found to increase from 20% to approximately 300% for processed meat and raw beef irradiated at 8 and 4 kGy, respectively.

10.2.2.4 Dairy proteins

Oil emulsion proteins

BSA, gelatin, and myofibrillar protein produced many benzene-containing compounds, but irradiation at the 2.5-kGy dose could not create these products except for benzaldehyde from BSA. There were no changes in organoleptic characteristics and chemical composition in

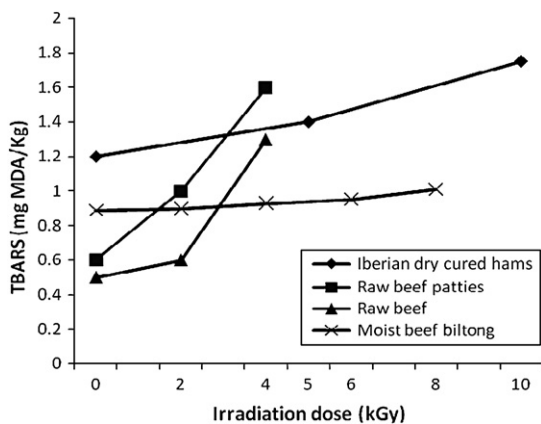


Figure 10.10: Effect of γ -irradiation on the TBARs of Iberian dry-cured hams (◆) (Cava et al., 2005), raw beef patties (■) (Badr, 2007), raw beef (▲) (Badr, 2007), and moist beef biltong (×) (Nortjé et al., 2005).

gelatin irradiated at the 5-kGy dose. Oil emulsion containing myofibrillar protein produced 3-methylbutanal and 2-methylbutanal, but the amounts of these compounds were not affected by irradiation doses between 0 and 10 kGy (Jo and Ahn, 2000).

The impact of γ - and e-beam irradiation on proteins of animal origin is summarized in Table 10.1.

10.2.2.5 Plant proteins

Globular proteins in almond (Prunus amygdalus)

Regarding protein content, there was a slight and nonsignificant decrease following the treatments for the three doses used; the values were 24.16–28.37 g/100 g for samples irradiated at 3 kGy, 21.58–25.88 g/100 g for those subjected to 7 kGy, and 21.87–25.09 g/100 g at 10 kGy, compared with 20.44–25.38 g/100 g for the control samples (Sánchez Bela et al., 2008).

Irradiation of seeds revealed a decrease in crude protein, which was not significant at any of the doses. Results of the protein solubility of lotus seeds, as a result of e-beam irradiation, showed significant increases from 5 kGy upwards (control, 45.7%; 5–30 kGy, 61.1–84.5%). Such increases due to irradiation can be attributed to higher protein extraction from the seed matrix (Bhat and Shridhar, 2008).

Table 10.2 provides a synopsis of the effects of γ - and e-beam irradiation on proteins of plant origin.

10.2.3 Effect of UV Irradiation on Proteins

Ionizing and UV radiation damage microbial DNA and, to a lesser extent, denature proteins (Lado and Yousef, 2002).

10.2.3.1 Egg albumin films

UV treatment increased TS and b^* values of albumin films. Small but significant decreases in total soluble matter were also reported for the UV-treated albumin films. UV irradiation also reduced the WVP of albumin films (Rhim et al., 1999).

10.2.3.2 Meat proteins

Collagen

Changes in collagen were found at all levels of the hierarchical structural organization. In general, the native collagen triple helix is most sensitive to UV 254 nm radiation. When irradiated collagen was present in its native conformation, the average line width was 117 ± 2.3 nm and the average height was 8.24 ± 0.3 nm. In contrast, when the native collagen films were irradiated with UV 254 nm for 80 h (187 J/cm^2), the average line height did not change significantly and was 7 ± 0.4 nm, whereas the average line width in the irradiated sample

TABLE 10.1 Effect of Irradiation on Proteins of Animal Origin

| Protein | Origin | Type/Dose of Irradiation | Other Technologies | Quality Parameters | Effect of Irradiation | Reference |
|---|-----------------------|---|--|---|--|---------------------|
| β Lactoglobulin (β Lg) | Commercial β Lg | γ irradiation/10, 25, or 50 kGy | The samples irradiated were stored at 4°C. | Solid state Water activity $a_w = 0.74$ Helix, 0 kGy = 14.4% Helix, 50 kGy = 15.3% The differences in β strands, turns, and unordered structure were not statistically significantly. Solution (10 mg/ml) β strands, 0 kGy = 35.0% β strands, 50 kGy = 32.9% Turns, 0 kGy = 12.0% Turns, 50 kGy = 13.1% | | Hoz and Netto, 2008 |
| Bovine serum albumin (BSA), gelatin, and myofibrillar | Oil emulsion | e beam irradiation/0, 2.5, 5.0, or 10.0 kGy | Irradiated samples were stored at 4°C. | Total ion counts = 10^3 BSA, 0 kGy = 583 BSA, 10 kGy = 1703 Gelatin, 0 kGy = 501 Gelatin, 10 kGy = 1176 | BSA Methylbenzene, 10 kGy = 137 Ethylbenzene, 0 kGy = 0 Ethylbenzene, 10 kGy = 148 Benzaldehyde, 0 kGy = 0 Benzaldehyde, 10 kGy = 117 Gelatin Benzaldehyde, 0 kGy = 0 Benzaldehyde, 10 kGy = 275 Myofibrillar Methylbenzene, 0 kGy = 0 Methylbenzene, 10 kGy = 227 Ethylbenzene, 0 kGy = 0 Ethylbenzene, 10 kGy = 199 | Jo and Ahn, 2000 |
| Sodium caseinate (SC) | Turkey breast rolls | e beam irradiation/0 or 3 kGy | Samples were transported to the irradiation facility in ice boxes containing ice to maintain the temperature of samples close to | RTE turkey breast roll with plum extract Protein, 0% = 23.91% Protein, 3% plum extract = 23.92% 9 Unit linear scales (1 = none; 9 = extremely; IRR, irradiated) Color, 0% plum extract, no IRR = 2.6 Color, 0% plum extract, IRR = 2.6 Color, 3% plum extract, No IRR = 7.6 | TBARS of RTE turkey 0 days Breast rolls, 0% plum extract, no IRR = 1.59 mg MDA kg/meat Breast rolls, 0% plum extract, IRR = 1.10 mg MDA kg/meat Breast rolls, 3% plum extract, no IRR = 1.36 mg MDA kg/meat | Lee and Ahn, 2004 |

| | | | | | | |
|---------|------------------------------------|--|---|--|---|---|
| | | 0°C in the dark. After irradiation, turkey hams were stored at 4°C. | Color, 3% plum extract, IRR = 7.3 Texture, 0% plum extract, no IRR = 5.8 Texture, 0% plum extract, IRR = 5.7 Texture, 3% plum extract, no IRR = 4.1 Texture, 3% plum extract, IRR = 3.8 | Breast rolls, 3% plum extract, IRR = 0.81 mg MDA kg/meat 7 day Breast rolls, 0% plum extract, no IRR = 1.19 mg MDA kg/meat Breast rolls, 0% plum extract, IRR = 0.95 mg MDA kg/meat Breast rolls, 3% plum extract, no IRR = 1.09 mg MDA kg/meat Breast rolls, 3% plum extract, IRR = 0.84 mg MDA kg/meat | | |
| Albumin | Chicken eggs and yolk | γ irradiation/0.5 up to 5 kGy at dose rate of 1.0 kGy/h | Pasteurization Package of yolk products was treated for 3 min at 64°C and package of whites was treated for 90 s at 57°C. | Asymptotic viscosity of pasteurized egg = ~ 0.1 Pa·s Asymptotic viscosity of pasteurized yolk = ~ 0.8 Pa·s | Asymptotic viscosity Eggs, 0 kGy = ~ 1.25 Pa·s Eggs, 5 kGy = ~ 0.1 Pa·s Yolks, 0 kGy = ~ 1.4 Pa·s Yolks, 5 kGy = ~ 1.9 Pa·s | Pinto et al., 2004 |
| | Mediterranean horse Mackerel | γ irradiation/1 and 2 kGy | Irradiated Mediterranean horse mackerel stored in ice ($2 \pm 1^\circ\text{C}$). | The total potential demerit points ranged from 0 (excellent quality) to 1 (extremely spoiled). 0 days Sensory evaluation, 0 kGy = ~ 0.05 Sensory evaluation, 2 kGy = ~ 0.05 18 days Sensory evaluation, 0 kGy = ~ 1 Sensory evaluation, 2 kGy = ~ 0.75 Fatty acid 1 day SFA, 0 kGy = $\sim 30.489 \pm 0.181$ SFA, 2 kGy = $\sim 27.709 \pm 0.276$ 18 days SFA, 0 kGy = $\sim 34.846 \pm 0.273$ SFA, 2 kGy = $\sim 31.858 \pm 0.173$ | The differences in TVB N and TMA on 0 days were not statistically significantly. 18 days TVB N, 0 kGy = ~ 40 mg/100g TVB N, 2 kGy = ~ 20 mg/100g TMA, 0 kGy = ~ 20 mg/100g TMA, 2 kGy = ~ 7 mg/100g 0 days TBA, 0 kGy = ~ 0.1 mg/kg lipid TBA, 2 kGy = ~ 4 mg/kg lipid 18 days TBA, 0 kGy = ~ 0.1 mg/kg lipid TBA, 2 kGy = ~ 1 mg/kg lipid 0 days Mesophiles, 0 kGy = ~ 4.30 log ₁₀ CFU/g Mesophiles, 2 kGy = ~ 3.30 log ₁₀ CFU/g 18 days | Mbarki et al., 2009 |

(Continued)

TABLE 10.1 Effect of Irradiation on Proteins of Animal Origin—cont'd

| Protein | Origin | Type/Dose of Irradiation | Other Technologies | Quality Parameters | Effect of Irradiation | Reference |
|--|---------------|--|---|---|--|---------------------------|
| | | | | | Mesophiles, 0 kGy = $\sim 6.30 \log_{10}$ CFU/g Mesophiles, 2 kGy = $\sim 4.30 \log_{10}$ CFU/g 0 days Total coliforms, 0 kGy = $\sim 1.47 \log_{10}$ CFU/g Total coliforms, 2 kGy = absent 18 days Total coliforms, 0 kGy = $>6 \log_{10}$ CFU/g Total coliforms, 2 kGy = absent | |
| Calcium caseinate and whey protein isolate (WPI) | Ground beef | γ irradiation/0, 1, 2, and 3 kGy | The protein based coating solution was cross linked by thermal treatment 90°C for 30 min. Film forming solutions were casted onto sterile petri plates (8.5 cm, ID) and dried overnight at 20 \pm 1°C in a climatic chamber. Irradiated samples were stored at 4 \pm 1°C in ascorbic acid (AA). | For total aerobic plate counts and for AA + coating, the differences were not statistically significant 0 days TBARS, 0 kGy = 5.28 ± 0.42 mg MDA/kg sample TBARS, 2 kGy = 7.34 ± 0.79 mg MDA/kg sample AA + coating, 0 kGy = not exist AA + coating, 2 kGy = 10.26 ± 4.72 8 days TBARS, 0 kGy = 8.10 ± 0.88 mg MDA/kg sample TBARS, 2 kGy = 21.08 ± 0.79 mg MDA/kg sample AA + coating, 0 kGy = not exist AA + coating, 2 kGy 14.01 ± 1.70 mg MDA/kg sample | Coliforms, 0 kGy = $\sim 4.8 \log_{10}$ CFU/g Coliforms, 3 kGy = $\sim 1 \log_{10}$ CFU/g Enterobacteriaceae, 0 kGy = $\sim 4.5 \log_{10}$ CFU/g Enterobacteriaceae, 3 kGy = $\sim 1 \log_{10}$ CFU/g <i>Pseudomonas</i> , 0 kGy = $\sim 8 \log_{10}$ CFU/g <i>Pseudomonas</i> , 3 kGy = $\sim 2.5 \log_{10}$ CFU/g Lactic acid bacteria (LAB), 0 kGy = $\sim 8 \log_{10}$ CFU/g LAB, 3 kGy = $\sim 7 \log_{10}$ CFU/g In AA + coating, the differences were not statistically significant for coliforms, Enterobacteriaceae, <i>Pseudomonas</i> , and LAB | Quatarra et al., 2002a |
| | Luncheon meat | γ irradiation/0, 1, 2, 3, and 4 kGy | Irradiated luncheon meat stored at 1 \pm 3°C for 14 weeks. | For taste and flavor on a 5 point scale (1 = very bad; 5 = very good) 0 weeks Taste, 0 kGy = 3.085 Taste, 4 kGy = 2.992 7 weeks Taste, 0 kGy = 2.825 | 0 weeks Microbial load of luncheon meat, 0 kGy = 2×10^3 CFU/g Microbial load of luncheon meat, 4 kGy = <10 CFU/g 14 weeks Microbial load of luncheon meat, 0 kGy = rejected | Al Bachir and Mehio, 2001 |

Taste, 2 kGy = 3.175
 0 weeks
 Flavor, 0 kGy = 3.423
 Flavor, 2 kGy = 3.308
 7 weeks
 Flavor, 0 kGy = 2.500
 Flavor, 2 kGy = 2.150

Microbial load of luncheon meat,
 4 kGy = 1×10^6 CFU/g
 0 weeks
 Lipid peroxide, 0 kGy = 413 mmol O₂/g
 Lipid peroxide, 4 kGy = 2.44 mmol O₂/g
 14 weeks
 Lipid peroxide, 0 kGy = rejected
 Lipid peroxide, 4 kGy = 1.14 mmol O₂/g
 Total acid (lactic acid [LA])
 0 weeks
 Volatile basic nitrogen (VBN), 0 kGy =
 0.024
 VBN, 4 kGy = 0.024
 14 weeks
 VBN, 0 kGy = rejected
 VBN, 4 kGy = 0.011

| | | | | | | | |
|--|------|--|--|---------|--|--|-------------------|
| Sarcoplasmic and myofibrillar proteins | Beef | e beam irradiation/ average dose 6.4 kGy | Vacuum packaged steaks irradiated from one side of each animal. After irradiation, all steaks were held at 4°C, vacuum packaged, and frozen at 20°C. | 0 days | <i>L*</i> , normal finishing diet (CON), 0 kGy = 32.6 ± 0.45 | Protein solubility | Rowe et al., 2004 |
| | | | | 14 days | <i>L*</i> (CON), 6.24 kGy = 29.7 ± 0.39 | 0 days Sarcoplasmic proteins, 0 kGy = ~54 mg protein/gtissue | |
| | | | | 14 days | <i>L*</i> (CON), 0 kGy = 37.4 ± 0.47 | Sarcoplasmic proteins, 6.24kGy = ~55 mg protein/gtissue | |
| | | | | 0 days | <i>L*</i> (CON), 6.24 kGy = 35.6 ± 0.51 | 14 days Sarcoplasmic proteins, 0 kGy= ~38 mg protein/gtissue | |
| | | | | 0 days | Finishing diet with vitamin E (VITE), 0 kGy = 33.1 ± 0.81 | Sarcoplasmic proteins, 6.24kGy = ~41 mg protein/gtissue | |
| | | | | 14 days | VITE, 6.24 kGy = 27.39 ± 0.39 | 0 days Carbonyl content of myofibrillar proteins, 0 kGy = ~5.8 nmol/mg protein | |
| | | | | | VITE, 0 kGy = 38.1 ± 0.47 | Myofibrillar proteins, 6.24 kGy = ~2 nmol/mg protein | |
| | | | | | VITE, 6.24 kGy = 37.1 ± 0.57 | | |

(Continued)

TABLE 10.1 Effect of Irradiation on Proteins of Animal Origin—cont'd

| Protein | Origin | Type/Dose of Irradiation | Other Technologies | Quality Parameters | Effect of Irradiation | Reference |
|---|------------|---|---|---|--|---------------------|
| | | | | 0 days a^* (CON), 0 kGy = 19.4 ± 0.41 a^* (CON), 6.24 kGy = 14.4 ± 0.25 | 14 days Myofibrillar proteins, 0 kGy = ~7 nmol/mg protein Myofibrillar proteins, 6.24 kGy = ~5 nmol/mg protein | |
| | | | | 14 days a^* (CON), 0 kGy = 19.8 ± 0.32 a^* (CON), 6.24 kGy = 14.4 ± 0.25 | 0 days Carbonyl content of Sarcoplasmic proteins, 0 kGy = ~6 nmol/mg protein Sarcoplasmic proteins, 6.24kGy = ~2.5 mg protein/gtissue | |
| | | | | 0 days VITE, 0 kGy = 19.2 ± 0.44 VITE, 6.24 kGy = 9.9 ± 0.72 | 14 days Sarcoplasmic proteins, 0 kGy = ~13.8 nmol/mg protein Sarcoplasmic proteins, 6.24kGy = ~12 nmol/mg protein | |
| | | | | 14 days VITE, 0 kGy = 19 ± 0.26 VITE, 6.24 kGy = 12.8 ± 0.46 | | |
| | | | | 0 days b^* (CON), 0 kGy = 17.4 ± 0.31 b^* (CON), 6.24 kGy = 13.3 ± 0.33 | | |
| | | | | 14 days b^* (CON), 0 kGy = 18.9 ± 0.32 b^* (CON), 6.24 kGy = 16.9 ± 0.23 | | |
| | | | | 0 days VITE, 0 kGy = 17.3 ± 0.36 VITE, 6.24 kGy = 13.2 ± 0.39 | | |
| | | | | 14 days VITE, 0 kGy = 19.0 ± 0.24 VITE, 6.24 kGy = 16.3 ± 0.4 | | |
| Calcium caseinate, whey isolate protein | Milk films | γ irradiation/dose of 32 kGy at a dose rate of 7 Gys ⁻¹ | Part of these solutions were used for viscosity studies, whereas the other parts were heated for 45 min in an immunological water bath at constant temperature of 90°C. | Tensile strength (TS), 0 kGy = 53.9 ± 2.6 Nmm ⁻¹ TS, 32 kGy = 77.4 ± 3.2 Nmm ⁻¹ Viscoelasticity coefficient, 0 kGy = 0.524 ± 0.01 Viscoelasticity coefficient, 32 kGy = 0.561 ± 0.01 Water vapor permeability(WVP), 0 kGy = $168.6 \pm 10.1 \times 10$ g mm/m ² day mmHg WVP, 32 kGy = $114.9 \pm 9.6 \times 10$ g mm/m ² day mmHg | Deformation, 0 kGy = 4.46 ± 0.29 mm Deformation, 32 kGy = 4.07 ± 0.35 mm | Ciesla et al., 2004 |

| | | | | | | |
|--|---|--|---|--|--|----------------------------|
| Bovine serum albumin | γ irradiation/0, 0.5, 1, and 5 kGy | Protein solutions were diluted to a suitable concentration with PBS buffer before irradiation. | | Optical anisotropy of BSA, 0 kGy = ~0.06 Optical anisotropy of BSA, 5 kGy = ~0.09 Molecular weight of BSA BSA, 0 kGy = ~70 kDa BSA, 5 kGy = ~40 kDa | Gaber, 2005 | |
| Hexanal, thiobarbituric acid reactive substances (TBARS) | Dry cured Iberian hams | γ beam irradiation/0, 5, and 10 kGy | Dry cured ham slices were VP in nylon/PE bags (9.3 ml O ₂ /m ² /24 h at 0°C). Following irradiation samples returned to cooler and color measured within 2h. Samples storage at 80°C till TBARS and hexanal measured. | L^* , 0 kGy = ~38 L^* , 10 kGy = ~40 a^* , 0 kGy = ~24 a^* , 10 kGy = ~30 b^* , 0 kGy = ~11 b^* , 10 kGy = ~12 | TBARS of dry cured Iberian hams TBARS, 0 kGy = ~1.25 mg MDA/kg sample TBARS, 10 kGy = ~1.75 mg MDA/kg sample Hexanal, 0 kGy = ~1.25 μ g hexanal/g sample Hexanal, 10 kGy = ~1.75 μ g hexanal/g sample | Cava et al., 2005 |
| Crude protein (Cp) | Camel meat | γ irradiation/0, 2, 4, and 6 kGy | For each treatment, 20 bags of camel meat were allocated and all were stored at 1 4°C. | Cp, 0 kGy = 23.69 \pm 0.06 Cp, 6 kGy = 22.19 \pm 0.44 0 days Free fatty acid (FFA) C:14, 0 kGy = 4.53 \pm 0.54% FFA C:14, 6 kGy, 3.86 \pm 0.10% 6 days FFA C:14, 0 kGy = rejected (the total microbial count exceeds 10 ⁷) FFA C:14, 6 kGy = 4.34 \pm 0.64% | 0 days Microbial load, 0 kGy, 6.01 \pm 0.20 log ₁₀ CFU/g Microbial load, 6 kGy = <1 log ₁₀ CFU/g 6 days Microbial load, 0 kGy = rejected Microbial load, 6 kGy = <1 log ₁₀ CFU/g 0 days Total coliforms, 0 kGy = 3.15 \pm 0.02 log ₁₀ CFU/g | Al Bachir and Zeinou, 2009 |

(Continued)

TABLE 10.1 Effect of Irradiation on Proteins of Animal Origin—cont'd

| Protein | Origin | Type/Dose of Irradiation | Other Technologies | Quality Parameters | Effect of Irradiation | Reference |
|---------|--------|--------------------------|--------------------|---|--|-----------|
| | | | | The differences in FFA C:16 at 0 days were not statistically significant. | Total coliforms, 6 kGy = <1 log ₁₀ CFU/g | |
| | | | | 6 days | 6 days | |
| | | | | FFA C:16, 0 kGy = rejected | Total coliforms, 0 kGy = rejected | |
| | | | | FFA C:16, 6 kGy = 30.57 ± 0.16% | Total coliforms, 6 kGy = <1 log ₁₀ CFU/g | |
| | | | | The differences in FFAC:18 at 0 days were not statistically significant. | Total acidity (% LA) | |
| | | | | 6 days | 0 days | |
| | | | | FFA C:18, 0 kGy, rejected | LA, 0 kGy = 0.38 ± 0.04% | |
| | | | | FFA C:18, 6 kGy, 25.81 ± 0.22% | LA, 6 kGy = 0.37 ± 0.05% | |
| | | | | Texture, 0 kGy = 3.72 ± 1.40 | 6 days | |
| | | | | Texture, 6 kGy = 3.60 ± 1.32 | LA, 0 kGy = rejected | |
| | | | | Flavor, 0 kGy = 3.52 ± 1.42 | LA, 6 kGy = 0.36 ± 0.04 | |
| | | | | Flavor, 6 kGy = 3.64 ± 1.55 | 0 days | |
| | | | | Color, 0 kGy = 4.00 ± 1.35 | Peroxide value, 0 kGy = 0.47 ± 0.10 mmol O ₂ /g | |
| | | | | Color, 2 kGy = 4.08 ± 1.1 | Peroxide value, 6 kGy = 0.21 ± 0.01 mmol O ₂ /g | |
| | | | | Taste, 0 kGy = 3.88 ± 1.17 | 6 days | |
| | | | | Taste, 6 kGy = 3.48 ± 1.19 | Peroxide value, 0 kGy = rejected | |
| | | | | | Peroxide value, 6 kGy = 0.20 ± 0.02 mmol O ₂ /g | |
| | | | | | TBA value 0.192 mg malonaldehyde per kilogram of camel meat remained stable at all doses for all 6 days except for Days 4 and 6 at 0 kGy, which rejected | |
| | | | | | 0 days | |
| | | | | | VBN, 0 kGy = 71.0 ± 10.0 ppm | |
| | | | | | VBN, 6 kGy, 173.67 ± 43.50 ppm | |
| | | | | | 6 days | |
| | | | | | VBN, 0 kGy = rejected | |
| | | | | | VBN, 6 kGy = 169.03 ± 5.51 ppm | |

| | | | | | | |
|---------------------|-------------|---|--|--|--|----------------------|
| Caseinate and WPI | Ground beef | γ irradiation/0, 1, 2, and 3 kGy | Samples were stored at 4 \pm 2°C Ascorbic acid | | TBARS, 0 kGy = 5.28 \pm 0.42 μ g/g TBARS, 2 kGy = 7.34 \pm 0.79 μ g/g Total aerobic plates (APCs), 0 kGy = \sim 6.5 log ₁₀ CFU/g APCs, 2 kGy = \sim 6.5 log ₁₀ CFU/g Ascorbic + films, 0 kGy = \sim 4 log ₁₀ CFU/g Ascorbic + films, 3 kGy = \sim 2.5 log ₁₀ CFU/g | Lacroix et al., 2004 |
| Thiobarbituric acid | Sea bass | γ irradiation/2.5 and 5 kGy | Fish samples were maintained at 2 \pm 2°C during irradiation by using sealed ice covering for the samples. | The differences in quality score after 17 days and texture, odor, and taste score at 0 days were not statistically different before and after IRR. 17 days Texture, 0 kGy = 3.0 \pm 0.3 Texture, 0 kGy = 3.8 \pm 0.4 Odor, 0 kGy = 2.4 \pm 0.3 Odor, 5 kGy = 3.5 \pm 0.3 Taste, 0 kGy = 2.6 \pm 0.5 Taste, 5 kGy = 3.9 \pm 0.3 The differences in microbiological populations (Enterobacteriaceae, psychrotrophic bacteria, mesophilic aerobic bacteria, H ₂ S producing bacteria, and <i>Pseudomonas</i>) were not statistically different before and after IRR | 0 day pH, 0 kGy = 6.71 \pm 0.02 pH, 5 kGy = 6.71 \pm 0.02 17 days pH, 0 kGy = 7.30 \pm 0.01 pH, 5 kGy = 6.91 \pm 0.01 The differences in TVB N, TMA N, and TBA at 0 days were not statistically different before and after IRR. 17 days TVB N, 0 kGy = 36.44 \pm 0.69 mg/100 g TVB N, 0 kGy = 23.61 \pm 0.75 mg/100 g TMA N, 0 kGy = 5.40 \pm 0.18 mg/100 g TMA N, 5 kGy = 4.46 \pm 0.09 mg/100 g TBA, 0 kGy = 0.005 \pm 0.00 mg MA/kg TBA, 5 kGy = 0.022 \pm 0.00 mg MA/kg | Ozden et al., 2007a |

(Continued)

TABLE 10.1 Effect of Irradiation on Proteins of Animal Origin—cont'd

| Protein | Origin | Type/Dose of Irradiation | Other Technologies | Quality Parameters | Effect of Irradiation | Reference |
|---|---------------------|---|---|--|---|----------------------|
| α Helix, β sheet | Cold smoked salmon | e beam irradiation/0, 1, 2, 3, 4, and 8 kGy | Experiments were performed at room temperature (18–20°C) by triplicate. The temperature increase during treatment was less than 2°C. After irradiation treatment, samples were stored at 4°C until analysis | Percentages of α helix, β sheet, turns, and unordered on protein secondary structures of cold smoked salmon analyzed. α Helix, 0 kGy = 62.6 ± 0.4 α Helix, 8 kGy = 55.2 ± 1.1 β Sheet, 0 kGy = 18.2 ± 1.1 β Sheet, 10 kGy = 20.2 ± 0.1 Turns, 0 kGy = 11.5 ± 0.9 Turns, 10 kGy = 14.7 ± 0.7 Unordered, 0 kGy = 7.7 ± 0.6 Unordered, 10 kGy = 9.8 ± 0.4 | Normalized intensities of the tyrosyl doublet (I_{850}/I_{830}), 0 kGy = $0.98 \pm 0.04 \text{ cm}^{-1}$ Tyrosyl doublet (I_{850}/I_{830}), 8 kGy = $1.11 \pm 0.08 \text{ cm}^{-1}$ Tyrosyl doublet (I_{1450}/I_{1003}), 0 kGy = $11.1 \pm 3.7 \text{ cm}^{-1}$ Tyrosyl doublet (I_{1450}/I_{1003}), 8 kGy = $5.1 \pm 0.8 \text{ cm}^{-1}$ Tyrosyl doublet (I_{2935}/I_{1003}), 0 kGy = $65.8 \pm 9.1 \text{ cm}^{-1}$ Tyrosyl doublet (I_{2935}/I_{1003}), 8 kGy = $60.6 \pm 3.5 \text{ cm}^{-1}$ | Herrero et al., 2009 |
| Nitrosoheme pigments (NO Mb), residual nitrite, <i>N</i> nitrosodi methylamine (NDMA) | Cooked pork sausage | γ irradiation/0 and 5 kGy | MAP The produced samples were then air, vacuum, and 100% CO ₂ , 100% N ₂ , or 25% CO ₂ /75% N ₂ gas packaged. All samples were stored at 4°C before irradiation. After irradiation, the analysis was performed and the remainder of the sample was immediately stored at 4°C for 4 weeks | Air 0 weeks <i>a</i> *, 0 kGy = 3 <i>a</i> *, 5 kGy = 2.6 4 weeks <i>a</i> *, 0 kGy = 2.8 <i>a</i> *, 5 kGy = 2.3 Vacuum 0 weeks <i>a</i> *, 0 kGy = 3.2 <i>a</i> *, 5 kGy = 2.9 4 weeks <i>a</i> *, 0 kGy = 3.1 <i>a</i> *, 5 kGy = 2.7 0 weeks CO ₂ , 0 kGy = 3.1 CO ₂ , 5 kGy = 2.7 4 weeks CO ₂ , 0 kGy = 3.3 CO ₂ , 5 kGy = 2.8 0 weeks N ₂ , 0 kGy = 3.2 N ₂ , 5 kGy = 2.6 | NO Mb Air 0 weeks NO Mb, 0 kGy = 52.3 ppm hematin NO Mb, 5 kGy = 41.2 ppm hematin 4 weeks NO Mb, 0 kGy = 40.2 ppm hematin NO Mb, 5 kGy = 37.3 ppm hematin Vacuum 0 weeks NO Mb, 0 kGy = 56.3 ppm hematin NO Mb, 5 kGy = 47 ppm hematin 4 weeks NO Mb, 0 kGy = 45.3 ppm hematin NO Mb, 5 kGy = 42.5 ppm hematin CO ₂ 0 weeks CO ₂ , 0 kGy = 59.4 ppm hematin CO ₂ , 5 kGy = 46.7 ppm hematin 4 weeks CO ₂ , 0 kGy = 49.5 ppm hematin CO ₂ , 5 kGy = 42.9 ppm hematin N ₂ | Ahn et al., 2004 |

4 weeks
N₂, 0 kGy = 3.0
N₂, 5 kGy = 2.6

0 weeks
N₂, 0 kGy = 58.7 ppm hematin
N₂, 5 kGy = 43.8 ppm hematin

4 weeks
N₂, 0 kGy = 44.8 ppm hematin
N₂, 5 kGy = 40.9 ppm hematin

Residual nitrite

Air

0 weeks
Residual nitrite, 0 kGy = 67.2 ppm
Residual nitrite, 5 kGy = 60.3 ppm

4 weeks
Residual nitrite, 0 kGy = 49.1 ppm
Residual nitrite, 5 kGy = 47.2 ppm

Vacuum

0 weeks
Residual nitrite, 0 kGy = 68.4 ppm
Residual nitrite, 5 kGy = 57.7 ppm

4 weeks
Residual nitrite, 0 kGy = 45.5 ppm
Residual nitrite, 5 kGy = 43.3 ppm

CO₂

0 weeks
CO₂, 0 kGy = 67.0 ppm
CO₂, 5 kGy = 53.8 ppm

4 weeks
CO₂, 0 kGy = 45.2 ppm
CO₂, 5 kGy = 42.7 ppm

N₂

0 weeks
N₂, 0 kGy = 69.3 ppm
N₂, 5 kGy = 62.8 ppm

4 weeks
N₂, 0 kGy = 46.3 ppm
N₂, 5 kGy = 45.3 ppm

(Continued)

TABLE 10.1 Effect of Irradiation on Proteins of Animal Origin—cont'd

| Protein | Origin | Type/Dose of Irradiation | Other Technologies | Quality Parameters | Effect of Irradiation | Reference |
|------------------------------|------------------------------|---|--|--|--|--------------------------------|
| | Poultry frankfurters | e beam irradiation/0, 1, 2, and 3 kGy | The irradiated samples were held overnight in a refrigerator at 4°C. | 32 days Appearance Red color, 0 kGy = 44 ± 3 Red color, 3 kGy = 43 ± 3 Brown color, 0 kGy = 71 ± 2 Brown color, 3 kGy = 71 ± 2 Total aroma, 0 kGy = 44 ± 4 Total aroma, 3 kGy = 44 ± 2 Texture attributes Overall hardness, 0 kGy = 54 ± 3 Overall hardness, 3 kGy = 53 ± 3 Total flavor, 0 kGy = 62 ± 7 Total flavor, 3 kGy = 61 ± 7 | | Johnson and Resurreccion, 2009 |
| α and β caseins | Milk and Queso Blanco cheese | γ irradiation/0, 1, 2, 3, 4, 5, and 10 kGy | Milk Samples were turned 360° continuously during the irradiation process and the non irradiated control was placed outside of the irradiation chamber to have the same temperature effect as the irradiating sample. The rectangular cheese was divided into 12 pieces and vacuum packaged. | Milk α_{s1} casein, 0 kGy = 19.63 ± 1.44% α_{s1} casein, 10 kGy = 8.64 ± 2.50% α_{s0} casein, 0 kGy = 14.23 ± 0.41% α_{s0} casein, 10 kGy = 16.42 ± 1.15% β_B casein, 0 kGy = 1.22 ± 0.27% β_B casein, 10 kGy = 2.37 ± 0.75% β_{A1} casein, 0 kGy = 22 ± 0.98% β_{A1} casein, 0 kGy = 14.16 ± 2.73% β_{A2} casein, 0 kGy = 19.94 ± 0.59% β_{A2} casein, 10 kGy = 22.06 ± 0.70% β_{A3} casein, 0 kGy = 6.91 ± 1.19% β_{A3} casein, 10 kGy = 13.63 ± 2.21% | Queso Blanco cheese α_{s1} casein, 0 kGy = 17.48 ± 1.82% α_{s1} casein, 10 kGy = 7.82 ± 0.31% α_{s0} casein, 0 kGy = 15.05 ± 0.68% α_{s0} casein, 10 kGy = 18.32 ± 0.10% β_B casein, 0 kGy = 1.88 ± 0.15% β_B casein, 10 kGy = 2.49 ± 0.75% β_{A1} casein, 0 kGy = 21.96 ± 1.49% β_{A1} casein, 0 kGy = 13.89 ± 0.28% β_{A2} casein, 0 kGy = 23.65 ± 0.27% β_{A2} casein, 10 kGy = 24.28 ± 0.77% β_{A3} casein, 0 kGy = 6.67 ± 1.71% β_{A3} casein, 10 kGy = 15.74 ± 0.27% | Ham et al., 2009 |

| | | | | | | |
|---------|---------------|---|---|---|--|------------------|
| Gelatin | Bovine powder | Comparison of γ irradiation and e beam irradiation/5, 10, 20, and 50 kGy | The radiation effects were measured following viscosity changes at 40°C of gelatin powder 10% aqueous solutions using a Brookfield viscometer, model DVIII, spindle SC4 18, with Rheocalc software. | Viscosity e beam irradiation, 0 kGy = ~8.9 cP γ irradiation, 0 kGy = ~8.9 cP e beam irradiation, 5 kGy = ~8.4 cP γ irradiation, 5 kGy = ~8.2 cP e beam irradiation, 10 kGy = ~6 cP γ irradiation, 10 kGy = ~5.7 cP e beam irradiation, 20 kGy = ~5.4 cP γ irradiation, 20 kGy = ~5.2 cP e beam irradiation, 50 kGy = ~4.2 cP γ irradiation, 50 kGy = ~4.1 cP | Vieira and Del Mastro, 2002 | |
| Myosin | Bovine | γ irradiation/0, 1, 3, 5, and 10 kGy | After irradiation, myosin solutions and beef cuts were stored at 4°C in low temperature incubator. | Anti myosin whole molecules IgG, 0 kGy = 98.50 ± 1.76 mg/ml Anti myosin whole molecules IgG, 10 kGy = 24.36 ± 3.62 mg/ml Heavy meromyosin S 1 IgG, 0 kGy = 102.10 ± 2.34 mg/ml Heavy meromyosin S 1 IgG, 10 kGy = 20.47 ± 3.24 mg/ml Anti light meromyosin, 0 kGy = 103.61 ± 3.87 mg/ml Anti light meromyosin, 10 kGy = 30.56 ± 2.56 mg/ml | Relative fluorescence intensity, 0 kGy = 1.95 ± 0.09 mg/ml Relative fluorescence intensity, 10 kGy = 3.64 ± 0.08 mg/ml OD value at 340 nm, 0 kGy = 0.88 ± 0.11 OD value at 340 nm, 10 kGy = 2.20 ± 0.12 | Lee et al., 2000 |

(Continued)

TABLE 10.1 Effect of Irradiation on Proteins of Animal Origin—cont'd

| Protein | Origin | Type/Dose of Irradiation | Other Technologies | Quality Parameters | Effect of Irradiation | Reference |
|----------------------------|--------------------|---|--|--|---|--------------------|
| Blood plasma protein | Bovine and porcine | γ irradiation/0, 1.5, 7, and 10 kGy | 2% trichloroacetic acid was added to precipitate the plasma protein. The plasma protein was then freeze dried. | <p>Bovine blood plasma protein, 0 kGy = 119.0 ± 1.3</p> <p>Bovine blood plasma protein, 10 kGy = 114.7 ± 3.9</p> <p>Porcine blood plasma protein, 0 kGy = 144.6 ± 2.2</p> <p>Porcine blood plasma protein, 10 kGy = 144.1 ± 3.2</p> | <p>Viscosity</p> <p>Bovine blood plasma protein, 0 kGy = 1.88 ± 0.01 cP</p> <p>Bovine blood plasma protein, 10 kGy = 1.86 ± 0.01 cP</p> <p>Porcine blood plasma protein, 0 kGy = 1.88 ± 0.01 cP</p> <p>Porcine blood plasma protein, 10 kGy = 1.85 ± 0.0 cP</p> | Lee et al., 2003 |
| Oxymyoglobin, metmyoglobin | Pork, beef, turkey | e beam irradiation/1.5, 3.0, 4.5, 7.5, and 10.5 kGy | The pork, beef, and turkey samples were vacuum packaged within 5 min of cutting using a rollstock Intact packaging machine quipped with a 6 mil barrier film. After packaging, the samples were transferred to a $0 \pm 2^\circ\text{C}$ cooler for overnight storage. | <p>Pork</p> <p>L^*, 0 kGy = 53.92</p> <p>L^*, 10.5 kGy = 56.36</p> <p>a^*, 0 kGy = 15.33</p> <p>a^*, 10.5 kGy = 25.91</p> <p>b^*, 0 kGy = 15.10</p> <p>b^*, 10.5 kGy = 18.66</p> <p>Beef</p> <p>L^*, 0 kGy = 41.67</p> <p>L^*, 10.5 kGy = 39.86</p> <p>a^*, 0 kGy = 17.59</p> <p>a^*, 10.5 kGy = 16.29</p> <p>b^*, 0 kGy = 13.87</p> <p>b^*, 10.5 kGy = 15.34</p> <p>Turkey</p> <p>L^*, 0 kGy = 56.28</p> <p>L^*, 10.5 kGy = 57.11</p> <p>a^*, 0 kGy = 15.01</p> <p>a^*, 10.5 kGy = 20.88</p> <p>b^*, 0 kGy = 12.22</p> <p>b^*, 10.5 kGy = 16.19</p> | | Nanke et al., 1998 |

| | | | | | | |
|---|------------------------------|--------------------------------------|--|---|---|-----------------------|
| Soy protein isolate, whey protein isolate | Shrimp, cooked pizza | γ irradiation/0 and 3 kGy | Both shrimp and pizzas were stored at 4°C for 21 days and duplicate samples were taken periodically for total bacteria counts (APCs). | Using a 9 point hedonic scale ranging from 1 (most disliked) to 9 (most liked) Shrimp Appearance, 1 kGy = 0.851 Appearance, 3 kGy (IRR* coating) = 0.972 Odor, 1 kGy = 0.099 Odor, 3 kGy (IRR* coating) = 0.416 Taste, 1 kGy = 0.489 Taste, 3 kGy (IRR* coating) = 0.865 | 9 days Total bacteria counts (APCs), 0 kGy = ~8.1 log CFU/g APCs, 3 kGy = ~5 log CFU/g 21 days APCs, 0 kGy = ~11 log CFU/g APCs, 3 kGy = ~10 log CFU/g 9 days Base, 0 kGy = ~7.9 log CFU/g Base, 3 kGy = ~4 log CFU/g 21 days Base, 0 kGy = ~9.5 log CFU/g Base, 3 kGy = ~8 log CFU/g 9 days E009 0.9% (vol/wt), 0 kGy = ~5 log CFU/g E009 0.9% (vol/wt), 3 kGy = ~3 log CFU/g 21 days E009, 0 kGy = ~11.8 log CFU/g E009, 3 kGy = ~7.2 log CFU/g 9 days E018 1.8% (vol/wt), 0 kGy = ~6.9 log CFU/g E018 1.8% (vol/wt), 3 kGy = ~2.5 log CFU/g 21 days E018, 0 kGy = ~8 log CFU/g E018, 3 kGy = ~5 log CFU/g | Ouattara et al., 2001 |
| Metmyoglobin | Ground beef and beef patties | γ irradiation/0, 2, and 4 kGy | Irradiated and non irradiated samples of each of the prepared ground beef and raw beef patties were divided into two parts that required refrigerated storage at 4 ± 1°C and | Metmyoglobin accumulation at 4 ± 1°C Ground beef, 0 days = 10.71% Ground beef, 15 days = rejected (due to the deterioration of odor and their values were discarded after statistical analysis; 0.0% salt). Raw beef, 0 days = 7.79% Raw beef, 15 day = rejected Metmyoglobin accumulation at 18°C | 0 days Ground beef The differences in peroxide value of ground beef and beef patties were not statistically significant at 0 and 60 days before and after IRR. Ground beef 0 days TBARS, 0 kGy = ~0.1 mg malonaldehyde equivalents/kg lipid | Badr, 2007 |

(Continued)

TABLE 10.1 Effect of Irradiation on Proteins of Animal Origin—cont'd

| Protein | Origin | Type/Dose of Irradiation | Other Technologies | Quality Parameters | Effect of Irradiation | Reference |
|----------------------|--------|------------------------------------|--|--|---|---------------------|
| | | | frozen storage at 18°C; 0.5 and 1% carnosine. | Ground beef, 0 days = 10.51% Ground beef, 60 days = 43.33% Raw beef, 0 days = 7.78% Raw beef, 15 days = 39.55% Color, the degree of pinkness/redness, was scored from 5 (extensive) to 1 (none). 0 days Mean score Ground beef, 0 kGy = ~5 Ground beef, 4 kGy = ~4 15 days Ground beef, 0 kGy (9 days) = ~2.8 Ground beef, 4 kGy = ~1 0 days Raw beef patties, 0 kGy = ~5 Raw beef patties, 4 kGy = ~4 15 days Raw beef patties, 0 kGy (9 days) = ~2.8 Raw beef patties, 4 kGy = ~1 | TBARS, 0 kGy = ~0.6 mg malonaldehyde equivalents/kg lipid 60 days TBARS, 0 kGy = ~1 mg malonaldehyde equivalents/kg lipid TBARS, 4 kGy = ~4 mg malonaldehyde equivalents/kg lipid Raw beef patties 0 days TBARS, 0 kGy = ~0.2 mg malonaldehyde equivalents/kg lipid) TBARS, 4 kGy = ~0.8 mg malonaldehyde equivalents/kg lipid 60 days TBARS, 0 kGy = ~1.5 mg malonaldehyde equivalents/kg lipid TBARS, 0 kGy = ~5 mg malonaldehyde equivalents/kg lipid | |
| Ovalbumin, ovomucoid | | γ irradiation/0, 0.5, 1, 5, and 10 | Protein solutions irradiated were excited at 280 nm and the emission spectra were recorded from 300 to 450 nm. | Ovalbumin, 0 kGy = ~24 kDa Ovalbumin, 10 kGy = ~18.4 kDa Ovomucoid, 0 kGy = ~66 kDa Ovomucoid, 10 kGy = ~18.4 kDa | Ovalbumin Relative intensity 300 nm, 0 kGy = ~95 a.u. Relative intensity 300 nm, 10 kGy = ~97 a.u. Relative intensity 400 nm, 0 kGy = ~50 a.u. Relative intensity 400 nm, 0 kGy = ~60 a.u. Ovalbumin Elipticity 190 nm, 0 kGy = ~13 × 10 ³ deg cm ² dmol ⁻¹ Elipticity 190 nm, 10 kGy = ~13.5 × 10 deg cm ² dmol ⁻¹ | Moon and Song, 2001 |

Elipticity 250 nm, 0 kGy = $\sim 0.5 \text{ deg cm}^2 \text{ dmol}^{-1}$
 Elipticity 250 nm, 10 kGy = $\sim 0.5 \text{ deg cm}^2 \text{ dmol}^{-1}$
 Ovamucoid
 Elipticity 190 nm, 0 kGy = $\sim 5 \times 10^3 \text{ deg cm}^2 \text{ dmol}^{-1}$
 Elipticity 190 nm, 10 kGy = $\sim 5 \times 10 \text{ deg cm}^2 \text{ dmol}^{-1}$
 Elipticity 250 nm, 0 kGy = $\sim 0 \text{ deg cm}^2 \text{ dmol}^{-1}$
 Elipticity 250 nm, 10 kGy = $\sim 0 \text{ deg cm}^2 \text{ dmol}^{-1}$

| | | | | | | |
|--------------------------|---|---|---|---|---|-------------------------|
| Bovine serum albumin | γ irradiation/0, 0.5, 1, and 5 kGy | Relative intensity 300 nm, 0 kGy = ~ 250 a.u. Relative intensity 300 nm, 5 kGy = ~ 150 a.u. Relative intensity 450 nm, 0 kGy = ~ 15 a.u. Relative intensity 450 nm, 5 kGy = ~ 10 a.u. Optical density 200 nm, 0 kGy = ~ 0.18 nm Optical density 200 nm, 2 kGy = ~ 2 nm Optical density 300 nm, 0 kGy = ~ 0.1 nm Optical density 300 nm, 5 kGy = ~ 0.2 nm Molecular weight BSA, 0 kGy = ~ 78 kDa BSA, 5 kGy = ~ 47 kDa | Absorbance 1000 cm^{-1} , 0 kGy = $\sim 2.2 \text{ cm}^{-1}$ Absorbance 1000 cm^{-1} , 5 kGy = $\sim 1.2 \text{ cm}^{-1}$ Absorbance 3000 cm^{-1} , 0 kGy = $\sim 2.3 \text{ cm}^{-1}$ Absorbance 3000 cm^{-1} , 5 kGy = $\sim 2.3 \text{ cm}^{-1}$ Optical antisotropy, 0 kGy = ~ 0.06 Optical antisotropy, 5 kGy = ~ 0.9 | Gaber, 2005 | | |
| Protein %N \times 6.25 | Anchovies | γ irradiation/0 and 2 kGy | During irradiation, the fish were held under flake ice (at 13°C). | The differences in absorbance of 280 and 800 nm remained stable before and after IRR. | 20 days Colony forming units Nonpackaged, 0 kGy = ~ 7.9 log bacteria No./g Nonpackaged, 2 kGy = ~ 6 log bacteria No./g | Lakshmanan et al., 1999 |

(Continued)

TABLE 10.1 Effect of Irradiation on Proteins of Animal Origin—cont'd

| Protein | Origin | Type/Dose of Irradiation | Other Technologies | Quality Parameters | Effect of Irradiation | Reference |
|--|--------------------|---|--|---|---|---------------------|
| | | | | Fish that scored from 5 to 10 were considered acceptable, and those that scored below 5 were spoiled. | Packaged, 0 kGy = ~6 log bacteria No./g Packaged, 2 kGy = ~4.9 log bacteria No//g TVBN | |
| | | | | Sensory score for cooked anchovy, 20 days | Nonpackaged, 0 kGy = ~200 mg N/100 g Nonpackaged, 2 kGy = ~125 mg N/100 g | |
| | | | | Nonpackaged, 0 kGy = ~5.5 | Packaged, 0 kGy = ~240 mg/100 g | |
| | | | | Nonpackaged, 2 kGy = ~4.5 | Packaged, 2 kGy = ~170 mg/100 g | |
| | | | | Packaged, 0 kGy = ~4 | TVA | |
| | | | | Packaged, 2.5 kGy = ~6.5 | Nonpackaged, 0 kGy = ~15 mg N/100 g Nonpackaged, 2 kGy = ~15 mg N/100 g Packaged, 0 kGy = ~45 mg/100 g Packaged, 2 kGy = ~20 mg/100 g TBA | |
| | | | | | Nonpackaged, 0 kGy = ~1 mg N/100 g Nonpackaged, 2 kGy = ~1.9 mg N/100 g Packaged, 0 kGy = ~2.8 mg/100 g Packaged, 2 kGy ~5.2 mg/100 g | |
| BSA and β lactoglobulin | | γ irradiation/0, 0.5, 1, 5, and 10 kGy | Ascorbic acid was used at 0.02%. | BSA, 0 kGy = ~45 kDa BSA, 10 kGy = ~97.4 kDa BSA with 0.02% AA, 1 kGy = ~205 kDa BSA with 0.02% AA, 10 kGy = ~205 kDa β Lg, 0 kGy = ~0 kDa β Lg, 10 kGy = ~66 kDa β Lg with 0.02% AA, 1 kGy = ~66 kDa β Lg with 0.02% AA, 10 kGy = ~18.4 kDa | Absorbance at 280 nm BSA, 0 kGy, 0 fraction number = 0.0 BSA, 0 kGy, 100 fraction number = ~0.2 BSA, 10 kGy + AA, 0 fraction number = ~0.0 BSA, 10 kGy + AA 100, fraction number = ~0.0 Absorbance at 280 nm β Lg, 0 kGy 0, fraction number = ~0.0 β Lg, 0 kGy, 100 fraction number = ~0.1 β Lg, 10 kGy + AA, 0 fraction number = ~0.0 β Lg, 10 kGy + AA, 100 fraction number = ~0.0 | Cho et al., 1999 |
| Protein content (% wb) = 45.2 \pm 1.19 | Moist beef biltong | γ irradiation/0, 2, 4, 6, and 8 kGy | The vacuum packaged biltong was irradiated in the sealed polystyrene | R index (probability of distinguishing between different samples) R index, 0 kGy = ~60% R index, 8 kGy = ~70% | TBARS, 0 kGy = 0.888 \pm 0.054 mg malonaldehyde/kg biltong TBARS, 8 kGy = 1.010 \pm 0.062 mg malonaldehyde/kg biltong | Nortjé et al., 2005 |

containers under ambient conditions ($\pm 25^{\circ}\text{C}$). Packaged samples were closed in polystyrene containers similar to those used for irradiation and stored frozen (20°C) for 6 days before defrosting for 24 h under refrigerated conditions (4°C) before the relevant analyses were conducted

1 = dislike extremely, 9 = like extremely
Hedonic rating, 0 kGy = 5.66 ± 2.26
Hedonic rating, 8 kGy = 5.92 ± 1.91
46% of panelists
Hedonic rating, 0 kGy = 3.96
Hedonic rating, 8 kGy = 5.26
54% of panelists
Hedonic rating, 0 kGy = 7.11
Hedonic rating, 8 kGy = 6.48

| | | | | | |
|---------------------|------------------------------|---|--|---|------------|
| Chicken breast meat | γ irradiation/0.5 kGy | 5 Irradiated chicken breasts were labeled and refrigerated at 4°C . Both control and irradiated chicken breasts were cooked to an internal temperature of 165°F in a conventional oven set at 350°F for 20 min and cooled to room temperature (22°C) for 1 h in storage bags before measuring the weight of the cooked chicken breast | Cooking loss No IRR chicken meat, 0 days = $20.19 \pm 0.21\%$ No IRR chicken meat, 14 days = $24.44 \pm 0.61\%$ IRR chicken meat, 0 days = $21.44 \pm 1.43\%$ IRR chicken meat, 14 days = $23.70 \pm 0.79\%$ | Shear force No IRR chicken meat, 0 days = ~ 7.5 kg No IRR chicken meat, 14 days = ~ 7 kg IRR chicken meat, 0 days = ~ 12.5 kg IRR chicken meat, 14 days = ~ 13 kg | Yoon, 2003 |
|---------------------|------------------------------|---|--|---|------------|

(Continued)

TABLE 10.1 Effect of Irradiation on Proteins of Animal Origin—cont'd

| Protein | Origin | Type/Dose of Irradiation | Other Technologies | Quality Parameters | Effect of Irradiation | Reference |
|------------|-----------------------|--|---|---|--|--------------------|
| Fatty acid | Chicken meat | e beam irradiation/0.3 kGy | Cooked in a water bath at 85°C for 15 min. Vacuum packaged in oxygen permeable or oxygen impermeable bags (O ₂ permeability, 9.3 ml O ₂ /m ² per 24 h at 0°C). | Fatty acid composition Palmitic, 0% CLA = 20% of total lipids Palmitic, 5% CLA = 23.5% of total lipids Palmitoleic, 0% CLA = 20% of total lipids Palmitoleic, 5% CLA = 23.5% of total lipids Stearic, 0% CLA = 11.7% of total lipids Stearic, 5% CLA = 15.8% of total lipids Oleic, 0% CLA = 33.1% of total lipids Oleic, 5% CLA = 24.3% of total lipids Linoleic, 0% CLA = 26.3% of total lipids Linoleic, 5% CLA = 14.6% of total lipids Linolenic, 0% CLA = 1.4% of total lipids Linolenic, 5% CLA = 0.9% of total lipids 0 (very weak) to 15 (very strong) Off odor vacuum packaged 5 days non IRR, 0% CLA = 7.7 5 days non IRR, 5% CLA = 5.8 5 days IRR, 0% CLA = 6.1 5 days IRR, 5% CLA = 5.2 | TBA vacuum packaged 0 days Non IRR, 0% CLA = 1.91 mg/kg Non IRR, 5.5% CLA = 1.25 mg/kg IRR, 0% CLA = 1.58 mg/kg IRR, 5.5% CLA = 0.63 mg/kg 5 days Non IRR, 0% CLA = 2.75 mg/kg Non IRR, 5%CLA = 1.05 mg/kg IRR, 0% CLA = 2.77 mg/kg IRR, 5% CLA = 1.03 mg/kg Total volatiles 0 days Vacuum packaged Non IRR, 0% CLA, 6250 total ion counts × 10 ³ Non IRR, 5% CLA = 5192 total ion counts × 10 ⁴ IRR, 0%CLA = 5562 total ion counts × 10 ³ IRR, 5% CLA = 4062 total ion counts × 10 ⁴ 5 days Non IRR, 0% CLA = 6289 total ion counts × 10 ³ Non IRR, 5% CLA = 4214 total ion counts × 10 ⁴ IRR, 0% CLA = 7873 total ion counts × 10 ³ IRR, 5% CLA = 3954 total ion counts × 10 ⁴ | Du et al., 2001 |
| Myoglobin | Horse skeletal muscle | γ irradiation/0, 0.5, 1, 5, and 10 kGy | | α Helix, 0 kGy = 63% α Helix, 10 kGy = 12% β Sheet, 0 kGy = 0% β Sheet, 10 kGy = 19% | Elipcticity 190 nm, 0 kGy = ~44,000 deg cm ² dmol ⁻¹ Elipcticity 190 nm, 10 kGy = ~11,000 deg cm ² dmol ⁻¹ | Lee and Song, 2002 |

β Turn, 0 kGy = 14%
 β Turn, 10 kGy = 25%
 Random coil, 0 kGy = 23%
 Random coil, 10 kGy = 44%

Elipticity 250 nm,
 0 kGy = $\sim 0 \text{ deg cm}^{-2} \text{ dmol}^{-1}$
 Elipticity 250 nm,
 10 kGy = $\sim 0 \text{ deg cm}^{-2} \text{ dmol}^{-1}$
 Relative intensity 300 nm, 0 kGy = $\sim 150 \text{ a.u.}$
 Relative intensity 300 nm,
 10 kGy = $\sim 200 \text{ a.u.}$
 Relative intensity 400 nm, 0 kGy = $\sim 50 \text{ a.u.}$
 Relative intensity 400 nm,
 10 kGy = $\sim 200 \text{ a.u.}$

| | | | | | |
|-------------------------------|---|---|--|---|-----------------------------|
| Industrial casein Milk powder | γ irradiation/2.5, 5, and 10 kGy | The proximate chemical composition of caseins or milk powder under study was assayed by the determination of water content (drying at $102 \pm 2^\circ\text{C}$) to the constant weight. | Casein, 30 mesh Proteins (% of dry matter) = n.d. Nondissolved precipitate = 0.03% Acidity = 0.75 ml 0.1 M NaOH/g Casein, 60 mesh Proteins (% of dry matter) = n.d. Nondissolved precipitate = 0.06 cm^3 Acidity = 0.95 ml 0.1 M NaOH/g Milk powder Proteins of dry matter = 33.5% Nondissolved precipitate = 0.20 cm^3 Acidity = 0.14 ml 0.1 M NaOH/g Casein $D_0(\text{kGy}) = 0.76$ $\alpha = 0.65$ $V(\text{relative variance}) = 2.50$ $D_{10}(\text{kGy}) = 1.70$ Milk powder $D_0(\text{kGy}) = 0.81$ $\alpha = 0.70$ $V = 2.12$ $D_{10}(\text{kGy}) = 1.73$ | Casein, 30 mesh Total microflora, 0 kGy = $6.04 \log \text{ CFU}^{-1}$ Total microflora, 10 kGy = $1.30 \log \text{ CFU}^{-1}$ Coliforms, 0 kGy = $2.40 \log \text{ CFU}^{-1}$ Coliforms, 10 kGy = $<1 \log \text{ CFU}^{-1}$ Moulds and yeasts, 0 kGy = $3.40 \log \text{ CFU}^{-1}$ Moulds and yeasts, 10 kGy = $1.48 \log \text{ CFU}^{-1}$ Casein, 60 mesh Total microflora, 0 kGy = $6.56 \log \text{ CFU}^{-1}$ Total microflora, 10 kGy = $1.48 \log \text{ CFU}^{-1}$ Coliforms, 0 kGy = $2.48 \log \text{ CFU}^{-1}$ Coliforms, 10 kGy = $<1 \log \text{ CFU}^{-1}$ Moulds and yeasts, 0 kGy = $3.56 \log \text{ CFU}^{-1}$ Moulds and yeasts, 10 kGy = $1.60 \log \text{ CFU}^{-1}$ Milk powder Total microflora, 0 kGy = $6.49 \log \text{ CFU}^{-1}$ Total microflora, 10 kGy = $1.48 \log \text{ CFU}^{-1}$ Coliforms, 0 kGy = $1 \log \text{ CFU}^{-1}$ Coliforms, 10 kGy = $<1 \log \text{ CFU}^{-1}$ Moulds and yeasts, 0 kGy = $1.48 \log \text{ CFU}^{-1}$ Moulds and yeasts, 10 kGy = $<1 \log \text{ CFU}^{-1}$ | Zégota and Malolepszy, 2008 |
|-------------------------------|---|---|--|---|-----------------------------|

(Continued)

TABLE 10.1 Effect of Irradiation on Proteins of Animal Origin—cont'd

| Protein | Origin | Type/Dose of Irradiation | Other Technologies | Quality Parameters | Effect of Irradiation | Reference |
|---|-------------------------|---|---|--|-----------------------|--------------------------|
| Actin, tropomyosin, troponin, ovalbumin | Chicken meat, egg white | Chicken meat: γ irradiation/4 (+4°C), 5 (+20°C), and 7 kGy (20°C) Egg white: γ irradiation/2.5, 5, and 7 kGy | The meat samples and the lyophilized egg white samples were minced and homogenized at 0°C in 20 mM sodium \pm phosphate buffer pH 7.4 | Chicken drumstick meat Actin, 0 kGy = 16.4 ± 1.1 Actin, 7 kGy = 17.0 ± 1.4 Tropomyosin, 0 kGy = 8.4 ± 0.4 Tropomyosin, 7 kGy = 8.4 ± 0.3 Troponin, 0 kGy = 4.4 ± 0.2 Troponin, 0 kGy = 2.4 ± 0.1 Chicken white meat Actin, 0 kGy = 12.4 ± 0.4 Actin, 7 kGy = 12.1 ± 0.2 Tropomyosin, 0 kGy = 9.7 ± 0.1 Tropomyosin, 7 kGy = 9.4 ± 0.4 Troponin, 0 kGy = 5.2 ± 1.0 Troponin, 7 kGy = 5.1 ± 0.7 Egg white Ovalbumin diminishment, 0 kGy = 0% Ovalbumin diminishment, 7 kGy = $8.14 \pm 0.55\%$ Ovalbumin to referent point, 0 kGy = 33.4 ± 0.5 Ovalbumin to referent point, 7.5 kGy = 12.9 ± 1.0 | | Niciforovic et al., 1999 |

| Collagen | Native (NC) and heat denatured collagen (DC) | Ultraviolet irradiation/0, 5.47, 94, and 187 J/m ² | Width | Absorbance |
|----------|--|---|----------------------------------|--|
| | | | NC, 0 J/m ² = 117 nm | NC, 0 J/m ² = 1631 cm ⁻¹ , 55%* |
| | | | NC, 187 J/m ² = 84 nm | NC, 187 J/m ² = 1630 cm ⁻¹ , 11% |
| | | | DC, 0 J/m ² = 120 nm | NC, 0 J/m ² = 1646 cm ⁻¹ , 17% |
| | | | DC, 134 J/m ² = 85 nm | NC, 187 J/m ² = 1645 cm ⁻¹ , 29% |
| | | | Height | NC, 0 J/m ² = 1660 cm ⁻¹ , 20% |
| | | | NC, 0 J/m ² = 8 nm | NC, 187 J/m ² = 1660 cm ⁻¹ , 32% |
| | | | NC, 187 J/m ² = 7 nm | NC, 0 J/m ² = 1674 cm ⁻¹ , 7% |
| | | | DC, 0 J/m ² = 4 nm | NC, 187 J/m ² = 1674 cm ⁻¹ , 20% |
| | | | DC, 187 J/m ² = 14 nm | NC, 0 J/m ² = 1690 cm ⁻¹ , 1% |
| | | | | NC, 187 J/m ² = 1689 cm ⁻¹ , 8% |
| | | | | DC, 0 J/m ² = 1628 cm ⁻¹ , 38% |
| | | | | DC, 187 J/m ² = 1631 cm ⁻¹ , 25% |
| | | | | DC, 0 J/m ² = 1646 cm ⁻¹ , 27% |
| | | | | DC, 187 J/m ² = 1645 cm ⁻¹ , 27% |
| | | | | DC, 0 J/m ² = 1660 cm ⁻¹ , 33% |
| | | | | DC, 187 J/m ² = 1659 cm ⁻¹ , 13% |
| | | | | DC, 0 J/m ² = 1672 cm ⁻¹ , 15% |
| | | | | DC, 187 J/m ² = 1669 cm ⁻¹ , 27% |
| | | | | DC, 0 J/m ² = 1685 cm ⁻¹ , 3% |
| | | | | DC, 187 J/m ² = 1681 cm ⁻¹ , 9% |

*Relative mean of percentage area.

TABLE 10.2 Effect of Irradiation on Proteins of Plant Origin

| Protein | Origin | Type/Dose of Irradiation | Other Technologies | Quality Parameters | Effect of Irradiation | Reference |
|---------------------------------------|--|----------------------------------|--------------------|---|---|---------------------|
| Albumin, gluterin, globulin, prolamin | Edible seed from <i>Cicer arietinum</i> . Grains from <i>Oryza sativa</i> Cv 2233 and <i>Oryza sativa</i> Cv Shankar | γ irradiation/1 6 kGy | | Protein profile of <i>Oryza sativa</i> L. Cv 2233 Prolamin, 0 kGy = ~43 kDa Prolamin, 4 kGy = ~29 kDa Gluterin, 0 kGy = ~43 kDa Gluterin, 4 kGy = ~29 kDa Globulin, 0 kGy = ~43 kDa Globulin, 4 kGy = ~29 kDa <i>Oryza sativa</i> L. Cv Shankar Prolamin, 0 kGy = ~43 kDa Prolamin, 4 kGy = ~29 kDa Gluterin, 0 kGy = ~43 kDa Gluterin, 4 kGy = ~29 kDa Globulin, 0 kGy = ~43 kDa Globulin, 4 kGy = ~29 kDa <i>Cicer arietinum</i> Prolamin, 0 kGy = ~29 kDa Prolamin, 4 kGy = ~43 kDa Albumin, 0 kGy = ~29 kDa Albumin, 4 kGy = ~43 kDa Gluterin, 0 kGy = ~97 kDa Gluterin, 4 kGy = ~205 kDa Globulin, 0 kGy = ~43 kDa Globulin, 4 kGy = ~26 kDa | Protein content <i>Cicer arietinum</i> , 0 kGy = ~22.5 mg/g <i>Cicer arietinum</i> , 6 kGy = ~18 mg/g <i>Oryza sativa</i> Cv 2233, 0 kGy = ~21 mg/g <i>Oryza sativa</i> Cv 2233, 6 kGy = ~16 mg/g <i>Oryza sativa</i> Cv Shankar, 0 kGy = ~22.5 mg/g <i>Oryza sativa</i> Cv Shankar, 6 kGy = ~26 mg/g | Maity et al., 2009 |
| Albumin, prolamin, glutenin, globulin | Maize cultivars (<i>Zea mays</i>) Sorghum (<i>Sorghum bicolor</i>) grains | γ irradiation/0 and 2 kGy | | Maize 75 Albumin, 0 kGy = 22.6 \pm 0.9% Albumin, 2 kGy = 23.4 \pm 0.3% Globulin, 0 kGy = 15.2 \pm 0.3% Globulin, 2 kGy = 13.1 \pm 0.9% Prolamin, 0 kGy = 15.6 \pm 0.0% Prolamin, 2 kGy = 11.5 \pm 0.3% Gluterin, 0 kGy = 42.9 \pm 0.73% Gluterin, 2 kGy = 48.0 \pm 0.13% | <i>In vitro</i> protein digestibility (IVPD) Maize 75, 0 kGy = 77.00 \pm 2.00% Maize 75, 2 kGy = 81.00 \pm 0.3% Sorghum, 0 kGy = 51.5 \pm 2.5% Sorghum, 2 kGy = 46.4 \pm 1.4% | Hassan et al., 2009 |

Sorghum

Albumin, 0 kGy = 28.7 ± 0.6%
 Albumin, 2 kGy = 35.1 ± 0.9%
 Globulin, 0 kGy = 9.9 ± 0.9%
 Globulin, 2 kGy = 12.4 ± 0.7%
 Prolamin, 0 kGy = 14.8 ± 1.0%
 Prolamin, 2 kGy = 18.6 ± 0.45%
 Gluterin, 0 kGy = 24.1 ± 0.31%
 Gluterin, 2 kGy = 22.0 ± 0.99%

| Albumin, caseinate, gluten, zein | Egg, sodium, wheat, corn | Ultraviolet irradiation (UV) The UV light intensity at the cabinet center was 0.6 mW/m ² , and film specimens received a UV radiation dose of 51.8 J/m ² during 24 h of exposure. | Films castings were dried overnight at ambient conditions. | Lightness (<i>L</i> [*]) Egg albumin (EA), 0 J/m ² = 95.75 ± 0.09 EA, 51.8 J/m ² = 95.27 ± 0.12 Sodium caseinate (SC), 0 J/m ² = 94.95 ± 0.11 SC, 51.8 J/m ² = 93.58 ± 0.23 Wheat gluten (WG), 0 J/m ² = 90.73 ± 0.30 WG, 51.8 J/m ² = 89.86 ± 0.17 Corn zein (CZ), 0 J/m ² = 91.35 ± 0.04 CZ, 51.8 J/m ² = 91.94 ± 0.15 Redness (<i>a</i> [*]) EA $\frac{2}{0} J/m^2 = 0.42 \pm 0.07$ EA $\frac{2}{51.8} J/m^2 = 1.86 \pm 0.05$ SC $\frac{2}{0} J/m^2 = 0.42 \pm 0.04$ SC $\frac{2}{51.8} J/m^2 = 2.30 \pm 0.05$ WG $\frac{2}{0} J/m^2 = 0.71 \pm 0.02$ WG $\frac{2}{51.8} J/m^2 = 0.76 \pm 0.0$ CZ $\frac{2}{0} J/m^2 = 6.50 \pm 0.6$ CZ $\frac{2}{51.8} J/m^2 = 5.38 \pm 0.13$ Yellowness (<i>b</i> [*]) EA $\frac{2}{0} J/m^2 = 4.17 \pm 0.21$ EA $\frac{2}{51.8} J/m^2 = 9.68 \pm 0.22$ SC $\frac{2}{0} J/m^2 = 4.79 \pm 0.16$ SC $\frac{2}{51.8} J/m^2 = 16.87 \pm 0.50$ WG $\frac{2}{0} J/m^2 = 12.99 \pm 0.40$ WG $\frac{2}{51.8} J/m^2 = 19.16 \pm 0.1$ CZ $\frac{2}{0} J/m^2 = 49.27 \pm 0.80$ CZ $\frac{2}{51.8} J/m^2 = 39.12 \pm 1.11$ | Thickness EA, 0 J/m ² = 96 ± 10 μm EA, 51.8 J/m ² = 100 ± 1 μm SC, 0 J/m ² = 117 ± 4 μm SC, 51.8 J/m ² = 108 ± 4 μm WG, 0 J/m ² = 110 ± 3 μm WG, 51.8 J/m ² = 113 ± 4 μm CZ, 0 J/m ² = 169 ± 1 μm CZ, 51.8 J/m ² = 170 ± 1 μm Tensile strength (TS) EA, 0 J/m ² = 1.7 ± 0.2 MPa EA, 51.8 J/m ² = 2.9 ± 0.1 MPa SC, 0 J/m ² = 8 ± 0.3 MPa SC, 51.8 J/m ² = 8.2 ± 0.4 MPa WG, 0 J/m ² = 1.2 ± 0.2 MPa WG, 51.8 J/m ² = 2 ± 0.1 MPa CZ, 0 J/m ² = 3.0 ± 0.1 MPa CZ, 0 J/m ² = 3.6 ± 0.2 MPa Water vapor permeability (WVP) EA, 0 J/m ² = 28.2 ± 0.7 g · mm/m ² · h · kPa EA, 51.8 J/m ² = 21.6 ± 0.7 g · mm/m ² · h · kPa The differences in WVP of SC, WG, and CZ were not statistically significant before and after the IRR. | Rhim et al., 1999 |
|----------------------------------|--------------------------|--|--|--|---|-------------------|
|----------------------------------|--------------------------|--|--|--|---|-------------------|

(Continued)

TABLE 10.2 Effect of Irradiation on Proteins of Plant Origin—cont'd

| Protein | Origin | Type/Dose of Irradiation | Other Technologies | Quality Parameters | Effect of Irradiation | Reference |
|---------------------------------------|----------------------|---|--|--|---|---------------------|
| Bovine γ globulins, hemoglobin | Solid native samples | γ irradiation/2.5, 3, 20, 24, 25, and 30 kGy | Irradiations were performed at ambient temperature and/or for frozen samples placed in a γ cell in solid CO ₂ (the temperature of sublimation equal to 78.5°C). Wet γ globulin samples were dried by lyophilization, whereas the hemoglobin sample was dried in a desiccator at ambient temperature. These samples were kept in distilled water and afterwards dried simultaneously with all the procedures performed on the irradiated ones. | γ Globulin concentration (DSC) Dry, 0 kGy = 169.0 g/kg Dry, 30 kGy = 153.5 g/kg Wet, 0 kGy = 170.9 g/kg Wet, 30 kGy = 168.8 g/kg N_m Dry, 0 kGy = 1 Dry, 30 kGy = 2 Wet, 0 kGy = 2 Wet, 30 kGy = 3 T_o T_f Dry, 0 kGy = 61.2 90.0°C Dry, 30 kGy = 53.2 88.0°C Wet, 0 kGy = 61.0 89.3°C Wet, 30 kGy = no effects observed Enthalpy Dry, 0 kGy = 18.1 \pm 0.3 J/g Dry, 30 kGy = 10.2 \pm 0.4 J/g Wet, 0 kGy = 18.4 \pm 0.3 J/g Wet, 30 kGy = no effects observed Peak temperature Dry, 0 kGy = 82.1 \pm 0.1°C Dry, 30 kGy = 80.5 \pm 0.1°C Wet, 0 kGy = 82.1 \pm 0.1°C Wet, 30 kGy = no effects observed $\Delta T_{1/2}$ Dry, 0 kGy = 12.0°C Dry, 30 kGy = 10.5°C Wet, 0 kGy = 10.8°C Wet, 30 kGy = No effects observed | Hemoglobin concentration (DSC) Dry, 0 kGy = 282.9 g/kg Dry, 25 kGy = 272.8 g/kg Wet, 0 kGy = 273.7 g/kg Wet, 25 kGy = 238 g/kg T_o T_f Dry, 0 kGy = 47.0 82.8°C Dry, 25 kGy = 36.6 78.4°C Wet, 0 kGy = 46.2 80.5°C Wet, 25 kGy = 47.7 81.1°C Enthalpy Dry, 0 kGy = 12.9 \pm 0.3 J/g Dry, 25 kGy = 9.9 J/g Wet, 0 kGy = 16.5 \pm 0.3 J/g Wet, 25 kGy = 15.5 \pm 0.3 J/g Peak temperature Dry, 0 kGy = 74.8 \pm 0.2°C Dry, 25 kGy = 75.6 \pm 0.4°C Wet, 0 kGy = 75.1 \pm 0.4°C Wet, 25 kGy = 72.5 \pm 0.5°C $\Delta T_{1/2}$ Dry, 0 kGy = 12.2°C Dry, 25 kGy = 15.7°C Wet, 0 kGy = 13.9°C Wet, 25 kGy = 15.0°C N_m Dry, 0 kGy = 3 Dry, 25 kGy = 1 Wet, 0 kGy = 4 Wet, 25 kGy = 4 | Ciesla et al., 2000 |

Bovine serum albumin (BSA)

Acridine orange (AO)

Ultrasonic irradiation

Absorbance of solution acidity (pH)
BSA AO without irradiation (IRR)

$\lambda = 278 \text{ nm}$

pH 5.0 = ~0.61

pH 9.0 = ~0.46

BSA AO with IRR for 3 h

pH 5.0 = ~0.725

pH 9.0 = ~0.54

Intensity of pH

$\lambda = 280 \text{ nm}$ and $\lambda = 345 \text{ nm}$

BSA AO without IRR

pH 5.0 = ~170 a.u.

pH 9.0 = ~320 a.u.

BSA AO with IRR for 3 h

pH 5.0 = ~110 a.u.

pH 9.0 = ~210 a.u.

Absorbance of NaCl concentration

$\lambda = 278 \text{ nm}$

BSA AO without IRR, 0 mmol/l = ~0.56

BSA AO without IRR, 200 mmol/l = ~0.60

BSA AO with IRR for 3 h, 0 mmol/l = ~0.64

BSA AO with irradiation for 3 h, 200 mmol/l = ~0.66

Intensity of NaCl

$\lambda = 280 \text{ nm}$ and $\lambda = 345 \text{ nm}$

BSA AO without IRR, 0 mmol/l = ~330 a.u.

BSA AO without IRR, 200 mmol/l = ~225 a.u.

BSA AO with IRR for 3 h, 0 mmol/l = ~240 a.u.

BSA AO with IRR for 3 h, 200 mmol/l = ~165 a.u.

Fluorescence spectra BSA AO

$\lambda = 280 \text{ nm}$

Intensity BSA AO without

IRR = ~260 a.u.

BSA AO with IRR for 3 h = ~175

a.u.

Intensity BSA without IRR = ~300 a.u.

BSA with IRR for 3 h = ~225 a.u.

AO concentration 10^5 mol/l

$\lambda = 278 \text{ nm}$

BSA AO without IRR,

0.00 mol/l = ~0.49 A

BSA AO without IRR,

2.50 mol/l = ~0.79 A

BSA AO with IRR for 3 h,

0 mmol/l = ~0.50 A

BSA AO with IRR for 3 h,

200 mmol/l = ~0.90 A

Intensity AO concentration 10^5 mol/l

$\lambda = 280 \text{ nm}$ and $\lambda = 345 \text{ nm}$

BSA AO without IRR,

0.00 mol/l = ~325 a.u.

BSA AO without IRR,

2.50 mol/l = ~230 a.u.

BSA AO with IRR for 3 h,

0.00 mol/l = ~280 a.u.

BSA AO with IRR for 3 h,

2.50 mol/l = ~125 a.u.

Wang et al.,
2009

(Continued)

TABLE 10.2 Effect of Irradiation on Proteins of Plant Origin—cont'd

| Protein | Origin | Type/Dose of Irradiation | Other Technologies | Quality Parameters | Effect of Irradiation | Reference |
|----------------------------------|------------------------------------|---|---|--------------------|--|---------------------|
| Calcium caseinate, whey proteins | Strawberry <i>Fragaria</i> spp. | γ irradiation/1.5 32 kGy at dose rate of 1.5 kGy/h | Strawberries were stored under refrigeration at 4 \pm 1°C after the irradiation treatment | | <p>Molds growth (MG) <i>Fragaria</i> spp., 0 kGy Day 3 = 7% MG Day 17 = 97% MG</p> <p>Control and non irradiated coating formula <i>Fragaria</i> spp., 0 kGy Day 3 = 11% MG Day 17 = 97% MG</p> <p>Control and irradiated coating formula <i>Fragaria</i> spp., 0 kGy Day 3 = 5% MG Day 17 = 89% MG</p> <p><i>Fragaria</i> spp., 1.5 kGy Day 3 = 0% MG Day 17 = 79% MG</p> <p>Irradiated strawberries and non irradiated coating formula Day 3 = 1% MG Day 17 = 81% MG</p> <p>Irradiated strawberries and irradiated coating formula Day 3 = 0% MG Day 17 = 84% MG</p> <p>Effect of CaCl₂ or pectin agar mixture addition in coating formulation based on mixed proteins on <i>Fragaria</i> spp. <i>Fragaria</i> spp., 0 kGy, without coating Day 3 = 7% MG</p> | Vachon et al., 2003 |

Day 20 = 100% MG
Fragaria spp., 0 kGy, coated with irradiated (32 kGy) formulation based on mixed proteins
 Day 3 = 0% MG
 Day 24 = 100% MG
Fragaria spp., 0 kGy, coated with irradiated (32 kGy) formulation based on mixed proteins in the presence of CaCl₂
 Day 3 = 0% MG
 Day 35 = 100% MG

Cowpea (*Vigna unguiculata* L. Walp)

γ irradiation/0, 0.005, 0.01, and 0.015 kGy

Cooking: The cooking time was taken as the time required for the needles of 20 of the 40 plungers to penetrate the seeds

Ratings were from 1 to 9, with 1 corresponding to extreme dislike and 9 to extreme likeness.
 At 0 months, the differences in color, taste, texture, flavor, and general acceptability were not statistically significant.
 6 months
 Color, 0 kGy = 2.6
 Color, 0.015 kGy = 6.7
 Taste, 0 kGy = 1.8
 Taste, 0.015 kGy = 8.2
 Texture, 0 kGy = 2.2
 Texture, 0.015 kGy = 7.8
 Flavor, 0 kGy = 2.4
 Flavor, 0.015 kGy = 7.7
 General acceptability, 0 kGy = 1.9
 General acceptability, 0.015 kGy = 7.6

Ashaye, 2008

(Continued)

TABLE 10.2 Effect of Irradiation on Proteins of Plant Origin—cont'd

| Protein | Origin | Type/Dose of Irradiation | Other Technologies | Quality Parameters | Effect of Irradiation | Reference |
|---|-------------|---|--|---|--|---------------------------|
| 210 g/kg crude protein (Cp) (crusiferin and napin) | Canola seed | γ irradiation/15, 30, and 45 kGy | After irradiation, the samples were stored frozen at 18°C. | Cp degradation Washout fraction, 0 kGy = 451 g/kg Washout fraction, 45 kGy = 293 g/kg Potentially degradable, 0 kGy = 540 g/kg Potentially degradable, 45 kGy = 669 g/kg Rate of degradation, 0 kGy = 0.112 g/kg Rate of degradation, 45 kGy = 0.062 g/kg 16 h incubation Cp degradation, 0 kGy = 901 g/kg Cp degradation, 45 kGy = 695 g/kg IVPD, 0 kGy = 579 g/kg IVPD, 45 kGy = 730 g/kg Cp, 0 kGy = 219 g/kg Cp, 45 kGy = 216 g/kg Cruciferin and napin ~14.4 kDa in all irradiated doses | Acid detergent fiber, 0 kGy = 107 g/kg Acid detergent fiber, 45 kGy = 107 g/kg Phytic acid, 0 kGy = 25.7 g/kg Phytic acid, 45 kGy = 0 g/kg Phytic acid, 0 kGy = 23.4 μ mol/g Phytic acid, 45 kGy = 13.6 μ mol/g | Ebrahimi et al., 2009 |
| 330g/kg crude protein and 78.5% soluble protein (Sp) IVPD (porcine intestinal peptidase, porcine pancreatic trypsin, bovine pancreatic trypsin) | Sunflower | γ irradiation/10 and 20 kGy | Dry heating at 121°C for 30 min | IVPD and dry heating (Dh) IVPD, 0 min = 81.5% IVPD, 30 min = 85.5% Dh and protein solubility (Ps) Dh (0 min) + Ps = 78.5% Dh (30 min) + Ps = 54.3% | Cp and irradiation (IRR) Cp + IRR (0 kGy) = 329 g/kg Cp + IRR (20 kGy) = 332 g/kg Cp + Dh + IRR (10 kGy) = 328 g/kg Cp + Dh + IRR (20 kGy) = 330 g/kg Ps + IRR (0 kGy) = 78.47% Ps + IRR (10 kGy) = 63.47% Ps + Dh + IRR (10 kGy) = 59.23% Ps + Dh + IRR (20 kGy) = 57.90% IVPD, 0 kGy = 81.53% | Diaa & El Din Faraq, 1999 |

| | | | | | | |
|-------------------------|-------------------|--|---|---|---|-------------------|
| | | | | | IVPD, 20 kGy = 87.60% | |
| | | | | | IVPD + DH + IRR (10 kGy) = 83.87% | |
| | | | | | IVPD + DH + IRR (20 kGy) = 88.43% | |
| Cry1Ab protein | Transgenic rice | γ irradiation/0 7 kGy | All materials were kept at room temperature (20 25°C) under constant atmosphere and humidity (60 RH%) before and after irradiation. | Cry1Ab, 0 kGy = 0.16% of Sp Cry1Ab, 7 kGy = 0.04% of Sp The reduced creation of Cry1Ab protein in the seedling tissues is accompanied by the inhibition of their growth, physiologically injured by γ irradiation. Cry1Ab, 0 kGy = 0.33% of Sp Cry1Ab, 4 kGy = 0.15% of Sp Cp, 0 kGy = 8.3 \pm 0.29% Cp, 7 kGy = 8.0 \pm 0.31% Sp, 0 kGy = 2.87 \pm 0.12 mg/g DW Sp, 7 kGy = 2.79 \pm 0.13 mg/g DW | Crude lipid, 0 kGy = 1.86 \pm 0.05% Crude lipid, 7 kGy = 1.80 \pm 0.08% Total ash, 0 kGy = 3.16 \pm 0.04 mg/g DW Total ash, 7 kGy = 3.13 \pm 0.05 mg/g DW Amylose, 0 kGy = 18.2 \pm 0.16% Amylose, 7 kGy = 15.1 \pm 0.09% | Wu et al., 2004 |
| Crude protein (g/100 g) | Velvet bean seeds | γ irradiation/2.5, 5.0, 7.5, 10, 15, and 30 kGy | | Crude protein, 0 kGy = 23.21 \pm 0.42 g/100 g Crude protein, 30 kGy = 31.06 \pm 2.5 g/100 g Ps, 0 kGy = ~48% Ps, 30 kGy = ~52.5% IVPD, 0 kGy = 49.74 \pm 4.14% IVPD, 30 kGy = 59.41 \pm 6.07 | Protein digestibility corrected amino acid score (%) Threonine, 0 kGy = 76.07% Threonine, 30 kGy = 63.60% Valine, 0 kGy = 108.01% Valine, 30 kGy = 81.99% Isoleucine, 0 kGy = 156.33% Isoleucine, 30 kGy = 115.43% Leucine, 0 kGy = 78.53% Leucine, 30 kGy = 65.80% Tyrosine + phenylalanine, 0 kGy = 110.69% Tyrosine + phenylalanine, 30 kGy = 93.92% Lysine, 0 kGy = 77.01% Lysine, 30 kGy = 58.08% Histidine, 0 kGy = 86.39% Histidine, 30 kGy = 71.29% | Bhat et al., 2008 |

(Continued)

TABLE 10.2 Effect of Irradiation on Proteins of Plant Origin—cont'd

| Protein | Origin | Type/Dose of Irradiation | Other Technologies | Quality Parameters | Effect of Irradiation | Reference |
|--|---|--|---|---|--|---------------------------|
| Expansins, polygalacturonases (PGs), endoglucanases (EGs), pectin methylesterases (PMEs) | Strawberry fruit | Ultraviolet (UV C) obtained doses of 4.1 kJ/m ² | Treated and control fruit were stored at 20°C for 96 h. | 0 h β 1,4 (EGs) activity, 0 kJ/m ² = ~0.016 μ mol/s/kg β 1,4 (EGs) activity, 4.1 kJ/m ² = ~0.020 μ mol/s/kg 48 h β 1,4 (EGs) activity, 0 kJ/m ² = ~0.012 μ mol/s/kg β 1,4 (EGs) activity, 4.1 kJ/m ² = ~0.008 μ mol/s/kg 0 h PMEs activity, 0 kJ/m ² = ~4.5 μ mol/s/kg PMEs activity, 4.1 kJ/m ² = ~3.8 μ mol/s/kg 48 h PMEs activity, 0 kJ/m ² = ~3.8 μ mol/s/kg PMEs activity, 4.1 kJ/m ² = ~4 μ mol/s/kg 0 h Total PG activity, 0 kJ/m ² = ~0.0037 μ mol/s/kg Total PG activity, 4.1 kJ/m ² = ~0.004 μ mol/s/kg 48 h Total PG activity, 0 kJ/m ² = ~0.003 μ mol/s/kg Total PG activity, 4.1 kJ/m ² = ~0.0018 μ mol/s/kg | Firmness of UV C 0 days Strawberry fruit, 0 kJ/m ² = ~3.4 N Strawberry fruit, 4.1 kJ/m ² = ~3.6 N 4 days Strawberry fruit, 0 kJ/m ² = ~2.8 N Strawberry fruit, 4.1 kJ/m ² = ~3.2 N | Pombo et al., 2009 |
| Fatty acid Myristic acid (MA) Palmitic acid (PA) Margaric acid (MAA) | Hazelnuts (<i>Corylus avellana</i> L.) | γ irradiation/1.0, 1.5, 3, 5, and 7 kGy | | Fatty acid MA (C14:0), 0 kGy = 0.06 \pm 0.03 MA (C14:0), 7 kGy = 1.87 \pm 0.13 PA (C16:0), 0 kGy = 5.82 \pm 0.45 PA (C16:0), 7 kGy = 10.10 \pm 0.82 | Volatile compounds Acetaldehyde, 0 kGy u.d. (under detection limit values are the mean of six determinations) Acetaldehyde, 7 kGy = 1.74 \pm 0.07 | Mexis and Kontomina, 2009 |

Stearic acid (SA)
 Arachidic acid
 (AAA)
 Behenic acid
 (BA)
 Palmitoleic acid
 (PA)
 Gondoic acid (GA)
 Linoleic acid
 (LA)

The differences in MA (C17:0), SA (C18:0), AA (C20:0), BA (C22:0), PA (C16:1v 9), and GA (C20:1n 11) were not statistically significant before and after IRR.

LA (C18:2n 9,12), 0 kGy = 13.15 ± 0.17
 LA (C18:2n 9,12), 7 kGy = 66.26 ± 0.14
 The differences in color and texture were not statistically significant before and after IRR.

Total saturated, 0 kGy = 10.08 ± 0.47
 Total saturated, 7 kGy = 23.12 ± 1.36
 Total monounsaturated, 0 kGy = 76.51 ± 70.34
 Total monounsaturated, 7 kGy = 66.49 ± 0.31
 Total polyunsaturated, 0 kGy = 13.41 ± 0.41
 Total polyunsaturated, 7 kGy = 10.39 ± 0.14

2 Propanone, 0 kGy = 1.91 ± 0.15
 2 Propanone, 7 kGy = 3.36 ± 0.28
 2 Methylpentan, 0 kGy u.d.
 2 Methylpentan, 7 kGy = 2.15 ± 0.47
 Butanal, 0 kGy u.d.
 Butanal, 7 kGy = 0.64 ± 0.09
 Hexane, 0 kGy = 0.32 ± 0.10
 Hexane, 7 kGy = 3.16 ± 0.43
 2 Pentanone, 0 kGy = 0.76 ± 0.34
 2 Pentanone, 7 kGy = 6.52 ± 0.18
 2 Pentanol, 0 kGy u.d.
 2 Pentanol, 7 kGy = 4.49 ± 0.31
 3 Pentone, 0 kGy u.d.
 3 Pentone, 7 kGy = 4.26 ± 0.58
 4 Methyl 2 pentanone, 0 kGy= 64
 4 Methyl 2 pentanone, 7 kGy= 64
 3 Hexanone, 0 kGy u.d.
 3 Hexanone, 7 kGy= 0.24 ± 0.06
 2 Hexanone, 0 kGy u.d.
 2 Hexanone, 7 kGy = 0.42 ± 0.08
 Hexanal, 0 kGy = 0.38 ± 0.27
 Hexanal, 7 kGy = 8.38 ± 0.37
 4 Heptanone, 0 kGy u.d.
 4 Heptanone, 7 kGy = 0.89 ± 0.11
 3 Heptanone, 0 kGy u.d.
 3 Heptanone, 7 kGy = 0.26 ± 0.05
 2 Heptanone, 0 kGy u.d.
 2 Heptanone, 7 kGy = 0.78 ± 0.07
 Heptanal, 0 kGy u.d
 Heptanal, 7 kGy = 3.59 ± 0.11
 1 Heptanol, 0 kGy u.d.
 1 Heptanol, 7 kGy = 3.56 ± 0.11
 Farmic acid, 0 kGy u.d.
 Farmic acid, 7 kGy = 0.42 ± 0.10
 Nonanal, 0 kGy = 0.82 ± 0.16
 Nonanal, 7 kGy = 5.66 ± 0.26
 Decanal, 0 kGy u.d.
 Decanal, 7 kGy = 0.22 ± 0.07

(Continued)

TABLE 10.2 Effect of Irradiation on Proteins of Plant Origin—cont'd

| Protein | Origin | Type/Dose of Irradiation | Other Technologies | Quality Parameters | Effect of Irradiation | Reference |
|------------------|---|--|--|--|---|----------------------|
| Globular protein | Dry red kidney beans (<i>Phaseolus vulgaris</i>) | γ irradiation/2, 4, and 8 kGy | Bean samples were stored at 30°C and 85% relative humidity in sterile plastic bags | Physicochemical properties Deamidation, 0 kGy = 0.05% Deamidation, 8 kGy = 65.89 \pm 0.05% Sulfhydryl content SH, 0 kGy = 65.89 \pm 0.06 μ M/g Sulfhydryl content SH, 8 kGy = 23.1 \pm 0.2 μ M/g Solubility, 0 kGy = 91.2 \pm 4.1% Solubility, 8 kGy = 92 \pm 0.9% Hydrophobicity, 0 kGy = 3.3 \pm 0.1% Hydrophobicity, 8 kGy = 4.8 \pm 0.2% | Filamentous fungi, 0 kGy 0 days = \sim 3 log (CFU/g) 15 days = \sim 7.5 log (CFU/g) Filamentous fungi, 1.5 kGy 0 days = \sim 1 log (CFU/g) 15 days = \sim 4.5 log (CFU/g) Filamentous fungi, 3 kGy 0 days = \sim 1.8 log (CFU/g) 15 days = \sim 0.5 log (CFU/g) | Dogbevi et al., 2000 |
| Gluten | Wheat flour | γ irradiation/0, 0.6, 1.5, 2.4, and 3 kGy | Drying with air velocity at 0.5 \pm 0.1 m/s and temperature at 50°C | Viscosity of flour (RVU) 0 min Initial 0 kGy = 0 Final 0 kGy = \sim 170 0 min Initial 3 kGy = 0 Final 3 kGy = \sim 80 Protein content, 0 kGy = 12.6 \pm 0.1% Protein content, 3 kGy = 12.5 \pm 0.2% | Wet gluten content, 0 kGy = 28.6 \pm 0.3% Wet gluten content, 3 kGy = 23.7 \pm 0.2% Dry gluten content, 0 kGy = 10.2 \pm 0.1% Dry gluten content, 2 kGy = 10.3 \pm 0.1% Moisture content of wet gluten content, 0 kGy = 180.4 \pm 0.8% Moisture content of wet gluten content, 2 kGy = 130.1 \pm 0.5% Titratable acidity (TA), 0 kGy = 15.31 \pm 0.05 mg NaOH/100 g TA, 2 kGy = 19.91 \pm 0.05 mg NaOH/100 g | Wang and Yu, 2009 |

| | | | | | | |
|------------------|-----------------------------|---|---|---|--|----------------------|
| Gluten | Wheat | γ irradiation/0, 4, 16, 32, and 50 kGy | Irradiated films were dried at 25°C for 24 h. Dried films were peeled intact from the casting surface | Average TS, 0 kGy = ~2.8 MPa Average TS, 50 kGy = ~3.8 MPa Elongation (E), 0 kGy = ~290% E, 50 kGy = ~110% | Viscosity, 0 kGy = ~45 cP Viscosity, 50 kGy = ~70 cP WVP, 0 kGy = ~7.9 n g/m ² · s · Pa WVP, 50 kGy = ~5.97 n g/m ² · s · Pa | Lee et al., 2005a |
| Leaf protein | In desi and kabuli chickpea | γ irradiation/0.1 1 kGy | Stored at 25°C for 8 days | Protein Desi chickpea, 0 kGy = ~10 mg/g fw Desi chickpea, 1 kGy = ~10 mg/g fw Kabuli chickpea, 0 kGy = ~4 mg/g fw Kabuli chickpea, 1 kGy = ~4 mg/g fw Lipid peroxidation Desi chickpea, 0 kGy = ~48 MDA contents μ M gf/wt Desi chickpea, 1 kGy = ~30 MDA contents μ M gf/wt Kabuli chickpea, 0 kGy = ~59 MDA contents μ M gf/wt Kabuli chickpea, 1 kGy = ~30 MDA contents μ M gf/wt | Peroxidase Desi chickpea, 0 kGy = ~29 units/ μ g protein Desi chickpea, 1 kGy = ~30 units/ μ g protein Kabuli chickpea, 0 kGy = ~75 units/ μ g protein Kabuli chickpea, 1 kGy = ~55 units/ μ g protein Protease Desi chickpea, 0 kGy = ~390 units/ μ g protein Desi chickpea, 1 kGy = ~390 units/ μ g protein Kabuli chickpea, 0 kGy = ~850 units/ μ g protein Kabuli chickpea, 1 kGy = ~200 units/ μ g protein | Hameed et al., 2008 |
| Membrane protein | Cauliflower | γ irradiation/2 4 kGy | | Protein In 0 days no substantial change in protein was observed (before and after irradiation). 8 days Initial 0 kGy = ~780 mg/g fwt Final 4 kGy = ~400 mg/g fwt 0 days Phosphate:protein, 0 kGy = ~0.2 μ mol/mg Phosphate:protein, 8 kGy = ~0.27 μ mol/mg 8 days Phosphate:protein, 0 kGy = ~0.19 μ mol/mg Phosphate:protein, 8 kGy = ~0.28 μ mol/mg | Phosphorus remaining In 0 days no substantial change in phosphorus remaining was observed (before and after irradiation) 8 days Phosphorus remaining, 0 kGy = 0.89 \pm 0.05% Phosphorus remaining, 4 kGy = 1.31 \pm 0.13% | Voisine et al., 1991 |

(Continued)

TABLE 10.2 Effect of Irradiation on Proteins of Plant Origin—cont'd

| Protein | Origin | Type/Dose of Irradiation | Other Technologies | Quality Parameters | Effect of Irradiation | Reference |
|--|--------------------------------|---|---|--|---|-----------------------------|
| Momilactone A and B | Moss <i>Hypnum plumaeforme</i> | UV irradiation/10 $\mu\text{mol/m/s}$ | The plants were surface sterilized in 70% (v/v) aqueous ethanol, transplanted onto two sheets of moist filter paper, placed on petri dishes, and grown at 25°C with a 12 h photoperiod for 3 days | Cantharidin Momilactone A, 0 μM = ~30 $\mu\text{g/g}$ dry weight Momilactone A, 200 μM = ~690 $\mu\text{g/g}$ dry weight Momilactone B, 0 μM = ~10 $\mu\text{g/g}$ dry weight Momilactone B, 200 μM = ~290 $\mu\text{g/g}$ dry weight Jasmonic acid Momilactone A, 0 μM = ~60 $\mu\text{g/g}$ dry weight Momilactone A, 200 μM = ~800 $\mu\text{g/g}$ dry weight Momilactone B, 0 μM = ~10 $\mu\text{g/g}$ dry weight Momilactone B, 200 μM = ~310 $\mu\text{g/g}$ dry weight | Momilactone A, 0 min = ~50 $\mu\text{g/g}$ dry weight Momilactone A, 80 min = ~800 $\mu\text{g/g}$ dry weight Momilactone B, 0 min = ~40 $\mu\text{g/g}$ dry weight Momilactone B, 80 min = ~350 $\mu\text{g/g}$ dry weight | Noguchi and Kobayashi, 2009 |
| Mushroom tyrosinase (polyphenol oxidase) | Apple derivatives | Ultraviolet (UV C) and visible light irradiation/0, 3.9, 5.4, 7.5, and 13.8 Wm^{-2} Irradiance on the samples was 21.9 Wm^{-2} . | Polyphenol oxidase was heated at 50°C. Clear apple juice was UV C treated at 4°C | 0 days L*, 0 Wm^{-2} = 79.12 \pm 0.71 L*, 13.8 Wm^{-2} = 77.81 \pm 0.52 a*, 0 Wm^{-2} = 3.85 \pm 0.33 a*, 13.8 Wm^{-2} = 3.46 \pm 0.47 b*, 0 Wm^{-2} = 24.95 \pm 1.73 b*, 13.8 Wm^{-2} = 27.66 \pm 0.85 6 days L*, 0 Wm^{-2} = 75.27 \pm 1.17 L*, 13.8 Wm^{-2} = 74.47 \pm 1.47 a*, 0 Wm^{-2} = 2.12 \pm 0.50 a*, 13.8 Wm^{-2} = 1.08 \pm 0.55 b*, 0 Wm^{-2} = 35.44 \pm 1.71 b*, 13.8 Wm^{-2} = 29.94 \pm 0.70 | At 0 min, the differences of enzymatic activity were not statistically different before and after the IRR treatment. 100 min Enzymatic activity, 0 Wm^{-2} = ~99% Enzymatic activity, 21.9 Wm^{-2} = ~30% Absorbance (380 nm) Clear apple juice 90 min, 0 Wm^{-2} = 0.591 \pm 0.001 nm Clear apple juice 90 min, 21.9 Wm^{-2} = 0.834 \pm 0.001 | Marzocco et al., 2009 |

Pepsin, trypsin,
chymotrypsin

Safflower
oilcake
(*Curthamius
tinctorius*)

γ irradiation/0.07,
0.014, 0.028, 0.042,
0.056, and 10 kGy

Trypsin digestion, 0 kGy = 2.94 units
ml/protein

Trypsin digestion, 10 kGy = not
determined

Trypsin digestion, 0 kGy = 0.968
units mg/protein

Trypsin digestion, 10 kGy = not
determined

Chymotrypsin digestion, 0 kGy =
2.68 units ml/protein

Chymotrypsin digestion, 0 kGy =
0.59 units ml/protein

Chymotrypsin digestion, 0 kGy =
0.344 units mg/protein

Chymotrypsin digestion, 10 kGy =
0.0525 units mg/protein

IVPD

0 h

Trypsin digestion, 0 kGy = 14.14
g/100 g protein

Trypsin digestion, 10 kGy = 15.54
g/100 g protein

24 h

Trypsin digestion, 0 kGy = 31.79
g/100 g protein

Trypsin digestion, 10 kGy = 53.00
g/100 g protein

0 h

Pepsin followed by trypsin digestion,
0 kGy = 11.41 g/100 g protein

Pepsin followed by trypsin di
gestion, 10 kGy = not determined

10 h

Pepsin followed by pancreatin,
0 kGy = 47.48 g/100 g protein

Pepsin followed by pancreatin, 10
kGy = not determined

Total N%

N, 0 kGy = 6.08%

N, 10 kGy = 6.08%

Joseph and
Dikshit, 1993

(Continued)

TABLE 10.2 Effect of Irradiation on Proteins of Plant Origin—cont'd

| Protein | Origin | Type/Dose of Irradiation | Other Technologies | Quality Parameters | Effect of Irradiation | Reference |
|--------------------|----------------|------------------------------------|--------------------------------------|---|---|-------------------------|
| | | | | 26 h Pepsin followed by pancreatin, 0 kGy = 48.39 g/100 g protein Pepsin followed by pancreatin, 10 kGy = 64.43 g/100 g protein | | |
| 20 kDa polypeptide | Black truffles | γ irradiation/1.5 and 2 kGy | Refrigeration at 4°C after treatment | 0 days Lactobacill, 0 kGy = ~4.5 log ₁₀ CFU/g Lactobacill, 2 kGy = ~2.5 log ₁₀ CFU/g 30 days Lactobacill, 0 kGy = ~4.2 log ₁₀ CFU/g Lactobacill, 2 kGy = ~6.8 log ₁₀ CFU/g 0 days Clostridia, 0 kGy = ~3.9 log ₁₀ CFU/g Clostridia, 2 kGy = ~3 log ₁₀ CFU/g 30 days Clostridia, 0 kGy = ~3.7 log ₁₀ CFU/g Clostridia, 2 kGy = ~1.2 log ₁₀ CFU/ml 0 days Total mesophilic bacteria, 0 kGy = ~7 log ₁₀ CFU/g Total mesophilic bacteria, 2 kGy = ~3.5 log ₁₀ CFU/g 30 days Total mesophilic bacteria, 0 kGy = ~7.1 log ₁₀ CFU/g Total mesophilic bacteria, 2 kGy = ~5.5 log ₁₀ CFU/ml | 0 days Hydroperoxide content, 1.5 kGy = ~54.4 nM/g truffle 30 days Hydroperoxide content, 1.5 kGy = ~238.8 nM/g truffle 0 days Hydroperoxide content, 2 kGy = ~61.3 nM/g truffle 30 days Hydroperoxide content, 2 kGy = ~315 nM/g truffle 0 days Polyphenol content, 1.5 kGy = ~472.3 nM quercetin equivalent 30 days Polyphenol content, 1.5 kGy ~621 nM quercetin equivalent 0 days Polyphenol content, 2 kGy ~437.4 nM quercetin equivalent 30 days Polyphenol content, 2 kGy = ~1515.1 nM quercetin equivalent | Nazzaro et al., 2007 |

The differences in fecal coliform at 0 and 30 days were not statistically significant.

0 days

Enterococci, 0 kGy = $\sim 0.8 \log_{10}$ CFU/g

30 days

Enterococci, 0 kGy = $\sim 3.8 \log_{10}$ CFU/g

The differences at 0 and 30 days on Enterococci, 2 kGy, were not statistically significant

| | | | | | | |
|---|--|--|---|--|---|---------------------------------------|
| Protein content of ragi malt g% and protein content of ragi malt green gram malt mixture g% | Ragi malt (<i>Eleusine coracana</i>) | Ragi irradiated at 1 and 5 kGy | Viscosity analysis of the ragi porridge prepared from different ragi malts was done at ambient temperature (25°C) using the Brookfield viscometer | Proteins Raw, 0 kGy = 8.36 g% Raw, 5 kGy = 7.9 g% 24 h steeped, 0 kGy = 10.85 g% 24 h steeped, 5 kGy = 9.86 g% 24 h steeped and 72 h germinated ragi malt, 0 kGy = 8.87 g% 24 h steeped and 72 h germinated ragi malt, 5 kGy = 7.69 g% Protein content of ragi malt green gram malt 50:50, 0 kGy = 18.8% Protein content of ragi malt green gram malt 50:50, 5 kGy = 18.9% | Sensory evaluation scores of ragi green gram malt 50:50 mixture. A 7 point hedonic scale was used: 7 = excellent; 1 = very poor. Appearance, 0 kGy = 5.70 ± 0.94 Appearance, 5 kGy = 4.80 ± 0.92 Color, 0 kGy = 5.30 ± 1.25 Color, 5 kGy = 5.00 ± 1.49 Odor, 0 kGy = 5.45 ± 0.76 Odor, 5 kGy = 4.50 ± 1.53 Taste, 0 kGy = 5.80 ± 0.6 Taste, 5 kGy = 4.60 ± 0.88 Viscosity, 0 kGy = 5.70 ± 0.48 Viscosity, 5 kGy = 3.00 ± 1.15 Overall acceptability, 0 kGy = 5.65 ± 0.58 Overall acceptability, 5 kGy = 4.45 ± 0.98 | Pednekar et al., 2009 |
| Silk | <i>Bombyx mori</i> | γ irradiation/0, 1000, 1500, 2000, and 3000 kGy | Storage at 70°C | Water solubility, 500 kGy = ~ 180 min Water solubility, 3000 kGy = ~ 5 min | Amide I, 0 kGy = 48.6 Amide I, 3 kGy = 53.8 Amide II, 0 kGy = 22.7 Amide II, 3 kGy = 65.6 Amide III, 0 kGy = 6.3 Amide III, 3 kGy = 23.6 | Kojthung et al., 2008 |

(Continued)

TABLE 10.2 Effect of Irradiation on Proteins of Plant Origin—cont'd

| Protein | Origin | Type/Dose of Irradiation | Other Technologies | Quality Parameters | Effect of Irradiation | Reference |
|---------------------------|------------------------------|--|--|--|---|------------------------|
| Soluble protein (Sp) | <i>Pleurotus nebrodensis</i> | γ irradiation/0.8, 1.2, 1.6, and 2 kGy | Stored at 4°C | 1 Day proteinase activity, 0 kGy = ~0.6 U/g fw 1 Day proteinase activity, 2 kGy = ~0.6 U/g fw 22 Day proteinase activity, 0 kGy = ~1.2 U/g fw 22 Day proteinase activity, 2 kGy = ~1.0 U/g fw 1 Day Sp, 0 kGy = ~3.4 U/g fw 1 Day Sp, 2 kGy = ~3.3 U/g fw 22 Day Sp, 0 kGy = ~2 U/g fw 22 Day Sp, 2 kGy = ~1.6 U/g fw | Decrease in fruit body firmness, 0 kGy = 58% Decrease in fruit body firmness, 2 kGy = 62% Appearance of fruit body deterioration, 0 kGy = 16% Appearance of fruit body deterioration, 2 kGy = 13% | Xiong et al., 2009 |
| Soy protein | Films | UV irradiation/0, 13, 25.9, 38.9, 51.8, 77.8, and 103.7 J/m ² | Castings were dried overnight at ambient conditions. Films (70 ± 3 μm thick) were peeled from plates, and specimens of appropriate sizes were cut for subsequent UV irradiation. | L^* , 0 J/m ² = 94.20 ± 0.35 L^* , 103.7 J/m ² = 93.07 ± 0.34 a^* , 0 J/m ² = 2.33 ± 0.10 a^* , 103.7 J/m ² = 3.12 ± 0.03 b^* , 0 J/m ² = 11.50 ± 0.50 b^* , 103.7 J/m ² = 18.20 ± 0.22 | Thickness, 0 J/m ² = 70 ± 4 μm Thickness, 103.7 J/m ² = 68 ± 2 μm WVP, 0 J/m ² = 7.2 ± 0.8 g · mm/m ² · h · kPa WVP, 103.7 J/m ² = 9.0 ± 2.1 g · mm/m ² · h · kPa Average TS, 0 J/m ² = ~4.6 MPa Average TS, 103.7 J/m ² = ~5.9 MPa E, 0 J/m ² = ~125% E, 103.7 J/m ² = ~83% | Gennadios et al., 1998 |
| Soy protein isolate (SPI) | Films | γ irradiation/0, 4, 16, 32, and 50 kGy | Irradiated films dried at 25°C for 24 h. Dried films were peeled intact from the casting surface. | Average TS, 0 kGy = ~1.6 MPa Average TS, 50 kGy = ~3.2 MPa E, 0 kGy = 248.66 ± 3.40% E, 0 kGy = 164.18 ± 18.02% L^* , 0 kGy = 87.918 ± 0.44 L^* , 50 kGy = 87.378 ± 0.86 a^* , 0 kGy = 0.292 ± 0.12 a^* , 50 kGy = 2.354 ± 0.04 b^* , 0 kGy = 4.004 ± 0.66 b^* , 50 kGy = 10.614 ± 0.26 | Viscosity, 0 kGy = ~9.8 cP Viscosity, 50 kGy = ~4 cP WVP, 0 kGy = ~7 × 10 ⁻² g · m/m ² · h · Pa WVP, 50 kGy = ~5.9 × 10 ⁻² g · m/m ² · h · Pa | Lee et al., 2005b |

| | | | | | | |
|--|--------------|---|--|--|---|----------------------|
| Soy protein isolate (SPI) Whey protein isolate (WPI) Calcium caseinate, glycerol (Gly) | Edible films | γ irradiation/0 and 32 kGy | Films allowed to dry overnight at $20 \pm 1^\circ\text{C}$ | FT IR spectra of WP films 1600 cm^{-1} WP, 0 kGy = $\sim 0.0 \text{ cm}^{-1}$ WP, IRR = $\sim 0.01 \text{ cm}^{-1}$ 1700 cm^{-1} WP, 0 kGy = $\sim 0.001 \text{ cm}^{-1}$ WP, IRR = $\sim 0.0 \text{ cm}^{-1}$ | Punctuate strength of unirradiated and irradiated (50:50) WPI:calcium caseinate ratio, 0 kGy = $\sim 0.08 \text{ N}/\mu\text{m}$ WPI:calcium caseinate ratio, 32 kGy = $\sim 0.1 \text{ N}/\mu\text{m}$ SPI:Gly (2:1), 0 kGy = $31.53 \pm 2.34 \text{ N}/\text{mm}$ SPI:Gly (2:1), 32 kGy = $43.30 \pm 2.75 \text{ N}/\text{mm}$ SPI:WPI:Gly (1:1:1), 0 kGy = $28.60 \pm 2.40 \text{ N}/\text{mm}$ SPI:WPI:Gly (1:1:1), 32 kGy = $40.32 \pm 2.87 \text{ N}/\text{mm}$ | Lacroix et al., 2002 |
| Starch granule structure | Rice | γ irradiation/0, 2, 5, 8, and 10 kGy | Air drying irradiated samples were evenly placed in a sifter drying at a constant temperature oven with air velocity at $0.5 \pm 0.1 \text{ m}/\text{s}$ and temperature at 40°C . The samples were dried until they reached a final moisture content of $14.5 \pm 0.02\%$ | 0 min Viscosity, 0 kGy = 0 RVU Viscosity, 10 kGy = 0 RVU 15 min Viscosity, 0 kGy = $\sim 250 \text{ RVU}$ Viscosity, 10 kGy = $\sim 70 \text{ RVU}$ | Apparent amylase content (AAC, %), 0 kGy = $18.55 \pm 0.05\%$ AAC, 10 kGy = $16.28 \pm 0.06\%$ Gel consistency (GC), 0 kGy = $70.1 \pm 0.3 \text{ mm}$ GC, 10 kGy = $99.9 \pm 0.1 \text{ mm}$ | Yu and Wang, 2007 |

(Continued)

TABLE 10.2 Effect of Irradiation on Proteins of Plant Origin—cont'd

| Protein | Origin | Type/Dose of Irradiation | Other Technologies | Quality Parameters | Effect of Irradiation | Reference |
|---|---|---|---|--|---|-------------------|
| Stilbene synthase (STS) | Grape berries | UV irradiation | The samples were incubated in the dark at 25°C with relative humidity of 80% for 96 h | <p>0 h after UV irradiation</p> <p>Initial 30 days after full bloom = ~70 relative intensity of signal</p> <p>Final 120 days after full bloom = ~95 relative intensity of signal</p> <p>6 h after UV irradiation</p> <p>Initial 30 days after full bloom = ~100 relative intensity of signal</p> <p>Final 120 days after full bloom = ~18 relative intensity of signal</p> <p>18 h after UV irradiation</p> <p>Initial 30 days after full bloom = ~50 relative intensity of signal</p> <p>Final 120 days after full bloom = ~20 relative intensity of signal</p> <p>72 h after UV irradiation</p> <p>Initial 30 days after full bloom = ~18 relative intensity of signal</p> <p>Final 120 days after full bloom = ~78 relative intensity of signal</p> | <p>UV irradiation</p> <p>30 days after full bloom</p> <p>Initial 0 h after UV irradiation = ~5 relative intensity of signal 90 days after full bloom</p> <p>Final 96 h after UV irradiation = ~6 relative intensity of signal</p> <p>70 days after full bloom</p> <p>Initial 0 h after UV irradiation = ~7 relative intensity of signal</p> <p>Final 96 h after UV irradiation = ~50 relative intensity of signal</p> <p>90 days after full bloom</p> <p>Initial 0 h after UV irradiation = ~5 relative intensity of signal</p> <p>Final 96 h after UV irradiation = ~6 relative intensity of signal</p> <p>120 day after full bloom</p> <p>Initial 0 h after UV irradiation = ~5 relative intensity of signal</p> <p>Final 96 h after UV irradiation = ~100 relative intensity of signal</p> | Pan et al., 2009 |
| The protein content of defatted dried seed tissue (~0.1 g) determined using the bicinchoninic acid assay following solubilization of proteins in 2% sodium dodecyl sulfate solution | <i>Cannabis sativa</i> and <i>Helianthus annuus</i> | γ irradiation/0, 5, 10, 15, and 20 kGy | | <p>Viability (germination)</p> <p><i>Cannabis sativa</i>, 0 kGy = ~40%</p> <p><i>Cannabis sativa</i>, 20 kGy = ~0%</p> <p>Total tocopherol concentration</p> <p><i>Cannabis sativa</i>, 0 kGy = ~500 mg/kg lipid</p> <p><i>Cannabis sativa</i>, 20 kGy = ~300 mg/kg lipid</p> <p><i>Helianthus annuus</i>, 0 kGy = ~400 mg/kg lipid</p> <p><i>Helianthus annuus</i>, 20 kGy = ~100 mg/kg lipid</p> <p>Lipid hydroperoxides</p> | <p>Total aerobic mesophilic bacteria, 5 kGy = 3.70 log CFU/g</p> <p>Total aerobic mesophilic bacteria, 20 kGy = 4.77 log CFU/g</p> <p>Total anaerobic mesophilic bacteria, 5 kGy = 3.38 log CFU/g</p> <p>Total anaerobic mesophilic bacteria, 20 kGy = 4.17 log CFU/g</p> <p><i>Pseudomonas</i> spp., 5 kGy = 2.29 log CFU/g</p> <p><i>Pseudomonas</i> spp., 20 kGy = 3.37 log CFU/g</p> <p>Fungi, 5 kGy = 3.40 log CFU/g</p> <p>Fungi, 20 kGy = 4.38 log CFU/g</p> | Fisk et al., 2009 |

| | |
|--|--|
| <i>Cannabis sativa</i> , 0 kGy = ~40 mmol/kg lipid | Enterobacteriaceae, 5 kGy = <1 log CFU/g |
| <i>Cannabis sativa</i> , 20 kGy = ~60 mmol/kg lipid | Enterobacteriaceae, 20 kGy = 2.46 log CFU/g |
| <i>Helianthus annus</i> , 0 kGy = ~5 mmol/kg lipid | <i>Helianthus annus</i> seed microflora expressed as total aerobic mesophilic bacteria |
| <i>Helianthus annus</i> , 20 kGy = ~39 mmol/kg lipid | Initial = 0.17 log CFU/g Final = 2.19 log CFU/g |
| Acid <i>Cannabis sativa</i> | Total anaerobic mesophilic bacteria |
| Pentanoic acid, 0 kGy = 251 | Initial = 0.09 log CFU/g |
| Pentanoic acid, 0 kGy = 18,990 | Final = 2.70 log CFU/g |
| Hexanoic acid, 0 kGy = 27,536 | <i>Pseudomonas</i> spp. not determined |
| Hexanoic acid, 20 kGy = 291,914 | Fungi |
| Methyl heptanoate, 0 kGy = 2824 | Initial = 0.03 log CFU/g Final = 2.67 log CFU/g |
| Methyl heptanoate, 20 kGy = 16,426 | Enterobacteriaceae not determined |
| Methyl octanoate, 0 kGy = 3270 | |
| Methyl octanoate, 20 kGy = 17,966 | |
| Methyl nonanoate, 0 kGy = 6842 | |
| Methyl nonanoate, 20 kGy = 38,722 | |
| Acid <i>Helianthus annus</i> | |
| Pentanoic acid, 0 kGy = 193 | |
| Pentanoic acid, 20 kGy = 546 | |
| Hexanoic acid, 0 kGy = 10,413 | |
| Hexanoic acid, 20 kGy = 47,360 | |
| Methyl heptanoate, 0 kGy = 54 | |
| Methyl heptanoate, 20 kGy = 187 | |
| Methyl octanoate, 0 kGy = 502 | |
| Methyl octanoate, 20 kGy = 2012 | |
| Methyl nonanoate, 0 kGy = 1247 | |
| Methyl nonanoate, 20 kGy = 1973 | |

TABLE 10.2 Effect of Irradiation on Proteins of Plant Origin—cont'd

| Protein | Origin | Type/Dose of Irradiation | Other Technologies | Quality Parameters | Effect of Irradiation | Reference |
|---|--------------------|-----------------------------|---|--------------------|---|-------------------------|
| Whey protein isolate, calcium caseinate | Fresh strawberries | γ irradiation/32 kGy | (i) A base coating solution made from a mixture of calcium caseinate and whey protein isolate (1:1) with glycerol and (ii) base solution plus a mixture of polysaccharides (PLS) (0.2%, w/w). Samples were randomly assigned to three groups: (i) uncoated control, (ii) coated with the base solution, and (iii) coated with protein solution containing PLS. Samples were stored in a large refrigerator at $4 \pm 1^\circ\text{C}$ | | Mold contamination, 0 days = ~0% Mold contamination, 17 days = ~100% Base, 0 days = ~0% Base, 25 days = ~100% Base + PLS, 0 days = ~0% Base + PLS, 38 days = ~100% | Ouattara, et al., 2002b |

| | | | | | | |
|--------------|--------------------|---|--|---|--|--------------------------|
| Whey protein | Maillard reactions | γ irradiation/0, 20, 40, 60, 80, and 100 kGy | Whey protein L^* , 0 kGy = 86.7 L^* , 100 kGy = 80.9 a^* , 0 kGy = 1.25 a^* , 100 kGy = 0.98 b^* , 0 kGy = 9.11 b^* , 100 kGy = 37.6 β Carotene, 0 kGy = ~20% β Carotene, 100 kGy = ~80% | Relative amino group content, 0 kGy = ~100% Relative amino group content, 100 kGy = ~60% Relative sugar content, 0 kGy = ~100% Relative sugar content, 100 kGy = ~53% | Chawla et al., 2009 | |
| Zein | Corn | γ irradiation/10, 20, 30, and 40 kGy | Zein powder was heated with water at 70°C for 10 min and poured into Petri dishes. The latter were placed in ventilated oven at 50°C for 48h. Then films were conditioned for 48h at 22°C and 50 ± 5% RH. | L^* , 0 kGy = 90.43 ± 0.16 L^* , 40 kGy = 92.68 ± 0.32 a^* , 0 kGy = 6.36 ± 0.04 a^* , 40 kGy = 5.45 ± 0.03 b^* , 0 kGy = 50.56 ± 0.67 b^* , 40 kGy = 36.98 ± 0.78 Surface density, 0 kGy = 32.54 ± 0.65 mg/cm ² Surface density, 40 kGy = 42.43 ± 0.49 mg/cm ² TS, 0 kGy = 11.62 ± 0.64 MPa TS, 40 kGy = 5.60 ± 0.37 MPa E, 0 kGy = 3.1 ± 0.09% E, 40 kGy = 3.1 ± 0.16% | WVP, 0 kGy = 1.63 g · mm/m ² · h · kPa WVP, 40 kGy = 1.15 g · mm/m ² · h · kPa Viscosity, 0 kGy = ~45 cP Viscosity, 40 kGy = ~36 cP | Soliman and Furuta, 2009 |

decreased to 83.7 ± 12 nm. Heat-denatured collagen showed similar scratching patterns as those for the native collagen films. Before irradiation, the average line width was 119 ± 4.2 nm and average height was 4 ± 2 nm (Rabotyagova et al., 2008).

Globin

The shift in color in cooked beef was caused by an oxidation/reduction reaction, where irradiation caused the reduction of oxidized globin myohemichromagen to reduced globin myohemochromogen. Irradiation doses greater than 150 kRad (1.5 kGy) caused a brown discoloration of meat exposed to air. However, in the absence of oxygen and at greater irradiation, a bright red color similar to oxymyoglobin was observed. Therefore, irradiation induced an oxymyoglobin-like pigment in pork, whereas both oxymyoglobin and metmyoglobin developed in beef as a result of irradiation (Nanke et al., 1998).

10.2.3.3 Dairy products

Sodium caseinate films

UV curing did not affect the TS of sodium caseinate (SC) films but substantially reduced their total soluble matter. UV irradiation did not affect WVP of the SC films. Increased b^* was recorded for SC films as a result of UV treatment (Rhim et al., 1999).

10.2.3.4 Plant proteins

Bovine serum albumin and acridine orange

The degree of damage to BSA molecules increases with an increase of ultrasonic irradiation time and acridine orange (AO) dye concentration. Nevertheless, it slightly decreases with pH values and increases with ionic strength. It can be inferred that the synergetic effect of ultrasonic irradiation and AO dye can easily damage the BSA molecules (Wang et al., 2009).

Corn zein films

UV treatment increased the TS of zein films. Small but significant decreases in total soluble matter also were reported for UV-treated zein. UV irradiation did not affect the WVP of zein films. UV treatment decreased the b^* of zein films, possibly due to decomposition of zein pigments by UV radiation (Rhim et al., 1999).

Stilbene synthase grape berries

At the protein level, stilbene synthase enzyme production in ripening berries (from 90 to 120 DAF) exposed to UV irradiation was delayed compared to that in the unripened berries (30–70 DAF) (Pan et al., 2009).

Momilactone A and B

The concentrations of momilactone A and B respectively became 14- and 15-fold greater than those of non-UV-irradiated controls. In addition, the protein phosphatase inhibitor, cantharidin,

and jasmonic acid increased momilactone A and B concentrations in *Hypnum plumaeforme*. Momilactone A and B respectively increased 12- and 11-fold by 200 mmol/l cantharidin and 14- and 15-fold by 100 mmol/l jasmonic acid compared with nontreated controls (Noguchi and Kobayashi, 2009).

Soy protein films

The yellowness (b^*) values of UV-irradiated soy protein films increased with UV irradiation dosage. Moreover, UV irradiation resulted in significantly lower lightness L (darker) and higher redness a (greener) values. In contrast to an increase in TS, elongation decreased with increasing UV irradiation. WVP was not affected by UV irradiation (Gennadios et al., 1998).

Strawberry proteins

Expansins, polygalacturonases (PGs), endoglucanases (EGs), and pectin methylesterases are cell wall proteins or enzymes involved in fruit softening. The endo-1,4- β -D EG activity was significantly reduced in the irradiated fruit after 24 h of storage at 20°C. After that, the enzyme activity decreased in both control and treated fruit, but no difference was found between them. In the case of PG, the treatment did not significantly affect the enzyme activity during the first 24 h after irradiation. However, after 48 h of storage at 20°C, the PG activity in UV-C irradiated fruit was reduced to half of the enzyme activity found in the control. The expression of expansin genes was affected by UV-C treatment and some differences between control and irradiated fruit (Pombo et al., 2009).

Wheat gluten

Application of UV treatment induced an increase in TS of gluten and b^* value but decreased %E. However, the WVP of gluten films was not affected by UV irradiation (Micard et al., 2000; Rhim et al., 1999).

10.2.4 Effect of Microwave Irradiation on Proteins

10.2.4.1 Meat proteins

Myoglobin

The digestion of cytochrome c was near completion under microwave (MW) irradiation and the efficiency was comparable to that without MW irradiation. Lysozyme has disulfide bonds and is resistant to digestion; thus, low digestion efficiency (19%) is expected. Nevertheless, MW irradiation still enhanced the digestion efficiency (36%). MW-assisted digestion of ubiquitin for 10 min yielded a somewhat better efficiency than the classic digestion method. The percentage of the protein digested under MW irradiation increased with the relative acetonitrile content but decreased as the methanol content increased. The digestion of myoglobin was complete without MW irradiation and nearly complete with MW irradiation (Lin et al., 2005).

10.2.4.2 Dairy proteins

β -Lactoglobulin

The proteolysis of β -Lg AB by pronase was higher than that by α -chymotrypsin, independent of physical treatment applied during the enzymatic digestion. The advantage of MW irradiation compared to conventional heating (CH) is less evident for chymotrypsin as described previously for pronase because significant higher releasing of [-NH₂] groups under MW irradiation than in CH digestion was only observed during the first minute of reaction, whereas the CH digestion was most effective after 10 min (Izquierdo et al., 2005).

Whey protein

No qualitative changes were found in the peptide profile when the WPC was digested by papain and alcalase during MW irradiation compared with the hydrolysates performed under CH. The MW irradiation also increased the fractions T and D eluting between 26–28 and 34–40 min, respectively, in the alcalase hydrolysates (Izquierdo et al., 2008).

Spores exposed to 0.5 or 2 kW MW irradiation for 1 min released 5.5, 22.6, or 3.4 μ g/ml of protein, respectively. The protein released from 0.5 kW MW-irradiated spores was 2-fold that released from untreated spores; the protein released from 2 kW MW-irradiated spores was 10-fold that released from untreated spores. The amount of protein released was significantly different between 0.5 and 2 kW MW-irradiated spores (Kim et al., 2009).

Barley grain

The B-hordein subunits were easily identified by means of SDS-PAGE and consisted of two major subunits of 98.2 and 76.0 kDa. The C-hordein was composed mainly of subunits with a molecular mass ranging from 30 to 70 kDa. The molecular weight of D-hordein subunits was less than 25 kDa. Most of the hordein fractions of 7-min microwave-irradiated barley grain, particularly the C- and D-hordein subunits, were not degraded completely until 12 h of incubation in the rumen (Sadeghi and Shawrang, 2008).

Candida albicans

The protein-released contents from the experimental suspension of the *Candida albicans* were significantly higher than the control, as analyzed by the Microprote (0.09 and 0.02 mg/dl for the experimental and the control, respectively) and by the Sensiprote system (0.4 mg/dl for the experimental and 0.15 mg/dl for the control) (Campanha et al., 2007).

Canola meal

MW irradiation for 6 min decreased the *a* fraction and increased the *b* fraction of crude protein in comparison with the untreated. The cruciferin subunits of MW-irradiated canola meal were not degraded completely until 48 h incubation. MW irradiation for 6 min increased the *in vitro* digestibility of crude protein compared to untreated (Sadeghi and Shawrang, 2006a).

TABLE 10.3 Effect of Microwave Irradiation (MWI) on Proteins of Animal and Plant Origin

| Proteins | Origin | Other Technologies | Quality | Effect of Irradiation | Reference |
|--|--------|--------------------|--|--|--------------------|
| Myoglobin, cytochrome <i>c</i> , lysozyme, ubiquitin | | | Digestion efficiencies (pH = 8) H ₂ O Myoglobin = 100 (96)% Cytochrome <i>c</i> = 96 (100)% Lysozyme = 36 (19)% Ubiquitin = 42 (37)% 50% CH ₃ OH Myoglobin = 94 (100)% Cytochrome <i>c</i> = 95 (15)% Lysozyme = 21 (6)% Ubiquitin = 80 (15)% 30% CH ₃ CN Myoglobin = 94 (100)% Cytochrome <i>c</i> = 70 (14)% Lysozyme = 30 (7)% Ubiquitin = 53 (29)% CH ₃ OHCHCl ₃ H ₂ O Myoglobin = 29 (0)% Cytochrome <i>c</i> = 39 (0)% Lysozyme = 20 (4)% Ubiquitin = 20 (20)% | Sequence coverage (pH = 8) H ₂ O Myoglobin = 73 (76)% Cytochrome <i>c</i> = 89 (73)% Lysozyme = 53 (33)% Ubiquitin = 100 (62)% 50% CH ₃ OH Myoglobin = 100 (76)% Cytochrome <i>c</i> = 79 (79)% Lysozyme = 55 (51)% Ubiquitin = 100 (100)% 30 %CH ₃ CN Myoglobin = 100 (66)% Cytochrome <i>c</i> = 89(75)% Lysozyme = 71 (30)% Ubiquitin = 86 (64)% CH ₃ OHCHCl ₃ H ₂ O Myoglobin = 48 (0)% Cytochrome <i>c</i> = 56 (0)% Lysozyme = 56 (37)% Ubiquitin = 67 (45)% | Lin et al., 2005 |
| Green fluorescent protein | | | | Thermally heating a GFP solution from 7 to 40°C results in an ~1% decrease in fluorescence for every 1°C. Under 250 mW of localized microwave irradiation, the fluorescence can decrease by up to 3 10% with an accompanying temperature rise of only 1°C | Coptý et al., 2005 |

(Continued)

TABLE 10.3 Effect of Microwave Irradiation (MWI) on Proteins of Animal and Plant Origin—cont'd

| Proteins | Origin | Other Technologies | Quality | Effect of Irradiation | Reference |
|---------------------------------------|--------------------------------|--------------------|---|---|-----------------------------|
| Bovine, whey protein | Commercial bovine whey protein | | Micromoles amino groups Pronase, control = ~3.3 mg ¹ protein Pronase, MWI = ~4 mg ¹ protein Chymotrypsin, control = ~0.2 mg ¹ protein Chymotrypsin, MWI = ~1 mg ¹ protein Papain, control = ~2 mg ¹ protein Papain, MWI = ~2.75 mg ¹ protein Corolase 7089, control = ~0.7 mg ¹ protein Corolase 7089, MWI = ~2 mg ¹ protein Corolase PNL, control = ~1 mg ¹ protein Corolase PNL, MWI = ~1.5 mg ¹ protein Alcalase, control = ~1.3 mg ¹ protein Alcalase, MWI = ~2.3 mg ¹ protein Neutrase, control = ~1 mg ¹ protein Neutrase, MWI = ~1.25 mg ¹ protein | Absorbance at 495 nm Pronase, control = ~0.2 Pronase, MWI = ~0.1 Chymotrypsin, control = ~0.52 Chymotrypsin, MWI = ~0.75 Papain, control = ~0.59 Papain, MWI = ~0.05 Corolase 7089, control = ~0.3 Corolase 7089, MWI = ~0.2 Corolase PNL, control = ~0.4 Corolase PNL, MWI = ~0.5 Alcalase, control = ~0.4 Alcalase, MWI = ~0.01 Neutrase, control = ~0.3 Neutrase, MWI = ~0.4 Untreated WPC = ~1 | Izquierdo et al., 2008 |
| | <i>Candida albicans</i> | | Microprote, control = 0.02 mg/dl Microprote, experimental = 0.09 mg/dl Seniprote, control = 0.15 mg/dl Seniprote, experimental = 0.4 mg/dl K ⁺ , control = 1 K ⁺ , experimental = 26.2 Ca ²⁺ , control = 0.7 Ca ²⁺ , experimental = 3.1 DNA, control = 0.026 DNA, experimental = 0.071 | Nondamaged and damaged <i>Candida albicans</i> Yeast cells, control Nondamaged = 8.45 ml ¹ Damaged = 0.00 ml ¹ Yeast cells, experimental Nondamaged = 0.00 ml ¹ Damaged = 8.52 ml ¹ Survival counts, control = 8.43 CFU/g Survival counts, experimental = 0 CFU/g | Campanha et al., 2007 |
| Globulins, glutelins, zeins, albumins | Corn grain | | Globulins, untreated = 21.5 kDa Globulins, 7 min MWI = 45 kDa Glutelins, untreated = 45 kDa Glutelins, 7 min MWI = 35 kDa Zein, untreated = 35 kDa Zein, 7 min MWI = 18.4 kDa Albumins, 7 min MWI = 45 kDa Crude protein a, untreated = 115 g/kg | Degradation traits* Dry matter a, untreated = 164 g/kg Dry matter a, 7 min MWI = 157 g/kg Dry matter b, untreated = 812 g/kg Dry matter b, 7 min MWI = 769 g/kg Dry matter c, untreated = 0.051 g/kg Dry matter c, 7 min MWI = 0.043 g/kg Starch a, untreated = 201 g/kg | Sadeghi and Shawrang, 2006b |

Crude protein a, 7 min MWI = 59 g/kg
 Crude protein b, untreated = 857 g/kg
 Crude protein b, 7 min MWI = 787 g/kg
 02 h⁻¹ (c)
 Crude protein, untreated = 700 g/kg
 Crude protein, 7 min MWI = 568 g/kg
 05 h⁻¹ (c)
 Crude protein, untreated = 512 g/kg
 Crude protein, 7 min MWI = 391 g/kg
 08 h⁻¹ (c)
 Crude protein, untreated = 415 g/kg
 Crude protein, 7 min MWI = 305 g/kg

Starch a, 7 min MWI = 194 g/kg
 Starch b, untreated = 787 g/kg
 Starch b, 7 min MWI = 737 g/kg
 ERD at outflow rate 0.02 h⁻¹
 Dry matter, untreated = 746 g/kg
 Dry matter, 7 min MWI = 683 g/kg
 0.05 h⁻¹
 Dry matter, untreated = 572 g/kg
 Dry matter, 7 min MWI = 514 g/kg
 0.08 h⁻¹
 Dry matter, untreated = 478 g/kg
 Dry matter, 7 min MWI = 427 g/kg
 0.02 h⁻¹
 Starch, untreated = 803 g/kg
 Starch, 7 min MWI = 753 g/kg
 0.05 h⁻¹
 Starch, untreated = 646 g/kg
 Starch, 7 min MWI = 604 g/kg
 0.08 h⁻¹
 Starch, untreated = 554 g/kg
 Starch, 7 min MWI = 518 g/kg

| | | | | |
|---|------------------------------|--|---|------------------------------|
| Protein content determined with the Bio Rad assay by using bovine serum albumin as a standard | Glycoenzyme loaded liposomes | Temperature T (°C) | Enzymatic activity, 1.4 W/kg sham (12) | Ramundo Orlando et al., 2004 |
| | | T, 1.4 W/kg sham (12) = 24.77 ± 0.22°C | = 0.0098 ± 0.0011 ΔA/min | |
| | | T, 5.6 W/kg sham (10) = 25.10 ± 0.28°C | Enzymatic activity, 5.6 W/kg sham (10) = 0.0109 ± 0.0020 ΔA/min | |
| | | T, 1.4 W/kg exposed (9) = 24.97 ± 0.32°C | Enzymatic activity, 1.4 W/kg exposed (9) = 0.0097 ± 0.0010 ΔA/min | |
| | | T, 5.6 W/kg exposed (8) = 25.41 ± 0.17°C | Enzymatic activity, 5.6 W/kg exposed (8) = 0.0083 ± 0.0006 ΔA/min | |
| | | Temperature (°C), 180" | Ascorbate oxidation (AO) native rate | |
| | | T, 1.4 W/kg sham (12) = 24.63 ± 0.21°C | AO, sham 10 × 10 ⁻⁴ = ~0.012 ΔA/min | |
| | | T, 5.6 W/kg sham (10) = 25.01 ± 0.20°C | AO, MW 10 × 10 ⁻⁴ = ~0.008 ΔA/min | |
| | | T, 1.4 W/kg exposed (9) = 24.87 ± 0.28°C | | |
| | | T, 5.6 W/kg exposed (8) = 25.38 ± 0.15°C | | |

(Continued)

TABLE 10.3 Effect of Microwave Irradiation (MWI) on Proteins of Animal and Plant Origin—cont'd

| Proteins | Origin | Other Technologies | Quality | Effect of Irradiation | Reference |
|-----------------------------------|--------|--------------------|---|--|------------------------|
| D Hydantoinase | | | 2 mg/ml = ~42% relative activity 8 mg/ml = ~92% relative activity Free d hydantoinase r, classic 30°C = 0.65 mMin/min r, classic 42°C = r, microwave 30°C = 5.77 mMin/min r, microwave 42°C = Immobilized d hydantoinase r, classic 30°C = 0.09 mMin/min r, classic 42°C = 0.22 mMin/min r, microwave 30°C = 2.21 mMin/min r, microwave 42°C = 5.65 mMin/min | Free D hydantoinase Yield, classic 30°C = 60.3% Yield, classic 42°C = 77% Yield, microwave 30°C = 56.7% Yield, microwave 42°C = 50% Immobilized D hydantoinase Yield, classic 30°C = 39.9% Yield, classic 42°C = 48% Yield, microwave 30°C = 48% Yield, microwave 42°C = 39% Relative activity, 1 round = ~100% Relative activity, 8 rounds = ~50% | Jia et al., 2006 |
| β Lg, α chymotrypsin | | | NH ₂ groups 0 min pronase, conventional heating (CH) 40°C = 0 mmol/mg β Lg 30 min pronase, CH 40°C = ~9 mmol/mg β Lg 0 min pronase, MW 30 W = ~0 mmol/mg β Lg 30 min pronase, MW 30 W = ~8.9 mmol/mg β Lg 0 min chymotrypsin, CH 40°C = ~0 mmol/mg β Lg 30 min chymotrypsin, CH 40°C = ~5 mmol/mg β Lg 0 min chymotrypsin, 15 W = ~0 mmol/ mg β Lg 30 min chymotrypsin, 15 W = ~3.5 mmol/mg β Lg | Release of NH ₂ groups 10 min pronase, CH 40°C = ~5 mmol/mg β Lg 10 min pronase, MW 30 W = ~8.5 mmol/mg β Lg 20 min pronase, CH 40°C = ~9.1 mmol/mg β Lg 20 min pronase, MW 30 W = ~8.9 mmol/mg β Lg 10 min chymotrypsin, CH 40°C = ~4.5 mmol/mg β Lg 10 min chymotrypsin, 15 W = ~3.5 mmol/mg β Lg 20 min chymotrypsin, CH 40°C = ~5.9 mmol/mg β Lg 20 min chymotrypsin, 15 W = ~5 mmol/ mg β Lg | Izquierdo et al., 2005 |

Crude protein D , Barley grain
B , and C hordein

Crude protein a, untreated = 0.198
Crude protein a, 7 min MWI = 0.113
Crude protein b, untreated = 0.665
Crude protein b, 7 min MWI = 0.714
Crude protein c, untreated = 0.156
Crude protein c, 7 min MWI = 0.115
0.05 h⁻¹
Effective degradability, untreated =
0.701
Effective degradability,
7 min MWI = 0.610
0.08 h⁻¹
Effective degradability, untreated =
0.637
Effective degradability,
7 min MWI = 0.532
B hordein, untreated = ~66 and 116
kDa
B hordein, 7 min MW = 116 kDa
C hordein, untreated = ~35 and 66
kDa
C hordein, 7 min MW = 116 kDa
D hordein, untreated = ~14.4 and
18.4 kDa
D hordein, 7 min MW = 116 kDa

Dry matter a, untreated = 0.558
Dry matter a, 7 min MWI = 0.573
Dry matter b, untreated = 0.324
Dry matter b, 7 min MWI = 0.280
Dry matter c, untreated = 0.340
Dry matter c, 7 min
MWI = 0.251
0.05 h⁻¹
Effective degradability,
untreated = 0.840
Effective degradability,
7 min MWI = 0.806
0.08 h⁻¹
Effective degradability,
untreated = 0.821
Effective degradability,
7 min MWI = 0.785
Starch a, untreated = 0.434
Starch a, 7 min MWI = 0.472
Starch b, untreated = 0.526
Starch b, 7 min MWI = 0.484
Starch c, untreated = 0.261
Starch c, 7 min MWI = 0.202
0.05 h⁻¹
Effective degradability,
untreated = 0.875
Effective degradability,
7 min MWI = 0.859
0.08 h⁻¹
Effective degradability,
untreated = 0.836
Effective degradability,
7 min MWI = 0.818

Sadeghi and
Shawrang, 2008

(Continued)

TABLE 10.3 Effect of Microwave Irradiation (MWI) on Proteins of Animal and Plant Origin—cont'd

| Proteins | Origin | Other Technologies | Quality | Effect of Irradiation | Reference |
|-----------------------------|-------------------------------|--------------------|--|---|--------------------------|
| | <i>Bacillus licheniformis</i> | Boiling | 0 min protein leaked, 0.5 kW = ~2.5 µg/ml 60 min protein leaked, 0.5 kW = ~4.8 µg/ml 0 min protein leaked, 2 kW = ~2.5 µg/ml 60 min protein leaked, 2 kW = ~22.5 µg/ml 0 min nucleic acid leaked, 0.5 kW = ~2 µg/ml 60 min nucleic acid leaked, 0.5 kW = ~8 µg/ml 0 min nucleic acid leaked, 2 kW = ~2 µg/ml 60 min nucleic acid leaked, 2 kW = ~85 µg/ml Laccase activity 0 min laccase activity, 0.5 kW = ~0.6 OD45 60 min laccase activity, 0.5 kW = ~0.25 OD45 0 min laccase activity, 2 kW = ~0.6 OD45 60 min Laccase activity, 2 kW = ~2 OD45 | The logarithmic reduction and survival of <i>Bacillus licheniformis</i> spores suspended in phosphate buffer treated with microwaves 0.5 kW, 0 s = 7.81 log CFU/ml 0.5 kW, 150 s = not applicable Viability, 0 s = 100% Viability, 150 s = not applicable 2.0 kW, 0 s = 8.38 log CFU/ml 2.0 kW, 150 s = not applicable Viability, 0 s = 100% Viability, 150 s = not applicable The logarithmic reduction and survival of <i>Bacillus licheniformis</i> spores on membrane filter treated with microwaves 0.5 kW, 0 s = 7.40 log CFU/ml 0.5 kW, 90 s = not detectable Viability, 0 s = 100% Viability, 90 s = 0% 2.0 kW, 0 s = 7.40 log CFU/ml 2.0 kW, 90 s = not detectable Viability, 0 s = 100% Viability, 90 s = 0% | Kim et al., 2009 |
| Crude protein (% N*6.25) | Lentil starch | | pH, native starch = 6.3 pH, irradiated (IRR) starch = 6.2 Acidity, native starch = 0.013 mEq NaOH/g Acidity, IRR starch = 0.012 mEq NaOH/g Absolute density, native starch = 1.501 g/ml Absolute density, IRR starch = 1.812 g/ml Crude protein, native starch = 0.24% | Water absorption (WA) WA 65°C, native starch = 4.49 g water/g starch WA 65°C, IRR starch = 1.53 g water/g starch WA 90°C, native starch = 10.38 g water/g starch WA 90°C, IRR starch = not detected Solubility 65°C, native starch = 1.84% Solubility 65°C, IRR starch = 2.17% | González and Pérez, 2002 |

Crude protein, IRR starch = 0.12% Solubility 90°C, native starch = 13.35%
 Crude fat, native starch = 0.07% Solubility 90°C, IRR starch = 11.97%
 Crude fat, IRR starch = 0.09% Swelling power (SP)
 Amylographic parameters of lentil starch SP 65°C, native starch = 5.49
 50°C, native starch = 780 SP 65°C, IRR starch = 2.53
 50°C, IRR starch = 580 SP 90°C, native starch = 11.38
 90°C, native starch = 400 SP 90°C, IRR starch = not detected
 90°C, IRR starch = 240
 After 30 min at 90°C, native starch = 480
 After 30 min at 90°C, IRR starch = 400
 Setback, native starch = 300
 Setback, IRR starch = 180

| | | | | |
|---------------------|-------------|--|--|-----------------------------|
| Cruciferin, albumin | Canola meal | <p>0 h cruciferin, untreated = ~35 and 45 kDa 48 h cruciferin, untreated = ~116 kDa 0 h cruciferin, 6 min MWI = ~25 45 kDa 48 h cruciferin, 6 min MWI = ~116 kDa Albumin, untreated = ~45 116 kDa 0 h albumin, untreated = ~45 116 kDa 48 h albumin, 6 min MWI = ~116 kDa Crude protein a, untreated = 255 g/kg Crude protein a, 6 min MWI = 96 g/kg Crude protein b, untreated = 706 g/kg Crude protein b, 6 min MWI = 844 g/kg Crude protein c, untreated = 0.064 g/kg Crude protein c, 6 min MWI = 0.038 g/kg In vitro crude protein digestibility (IVPD) at different incubation times (h) 0 h IVPD, untreated = 653 g/kg IVPD, 6 min MWI = 771 g/kg 24 h IVPD, untreated = 753 g/kg IVPD, 6 min MWI = 789 g/kg</p> | <p>Dry matter a, untreated = 316 g/kg Dry matter a, 6 min MWI = 184 g/kg Dry matter b, untreated = 599 g/kg Dry matter b, 6 min MWI = 725 g/kg Dry matter c, untreated = 0.070 g/kg Dry matter c, 6 min MWI = 0.049 g/kg Crude protein a, untreated = 255 g/kg Crude protein a, 6 min MWI = 96 g/kg Crude protein b, untreated = 706 g/kg Crude protein b, 6 min MWI = 844 g/kg Crude protein c, untreated = 0.064 g/kg Crude protein c, 6 min MWI = 0.038 g/kg</p> | Sadeghi and Shawrang, 2006a |
|---------------------|-------------|--|--|-----------------------------|

(Continued)

TABLE 10.3 Effect of Microwave Irradiation (MWI) on Proteins of Animal and Plant Origin—cont'd

| Proteins | Origin | Other Technologies | Quality | Effect of Irradiation | Reference |
|----------|--------|--------------------|---|--|------------------|
| | | | <i>Escherichia coli</i> protein leaked, 20°C = 0 µg/ml | <i>Escherichia coli</i> , no MWI = ~10 log CFU/g | Woo et al., 2000 |
| | | | <i>Escherichia coli</i> protein leaked, 80°C = 24.8 µg/ml | <i>Escherichia coli</i> , MWI = ~5 log CFU/g | |
| | | | <i>Bacillus subtilis</i> protein leaked, 20°C = 0 µg/ml | <i>Bacillus subtilis</i> , no MWI = ~9.1 log CFU/g | |
| | | | <i>Bacillus subtilis</i> protein leaked, 80°C = 5 µg/ml | <i>Bacillus subtilis</i> , MWI = ~3.9 log CFU/g | |
| | | | <i>Escherichia coli</i> nucleic acid leaked, 20°C = 0 OD ₂₆₀ | | |
| | | | <i>Escherichia coli</i> nucleic acid leaked, 80°C = 0.11 OD ₂₆₀ | | |
| | | | <i>Bacillus subtilis</i> nucleic acid leaked, 20°C = 0 OD ₂₆₀ | | |
| | | | <i>Bacillus subtilis</i> nucleic acid leaked, 80°C = 0.158 OD ₂₆₀ | | |

*a, washout fraction as measured by washing loss from nylon bags; b, potentially degradable fraction; c, rate of degradation of fraction b (h^{-1}).

Green fluorescent protein

Thermal heating of a green fluorescent solution from 7 to 40°C resulted in an approximately 1% decrease in fluorescence for every 1°C. On the other hand, under 250 mW of localized MW irradiation, the fluorescence can decrease by up to 3–10% with an accompanying temperature rise of only 1°C. For MW irradiation at 8.5 GHz, the fluorescence decreased by at least 14% (Coptý et al., 2005).

Lentil starches

The crude protein of the native starch was reduced to half that of the irradiated starch (from 0.24 to 0.12%) (González and Pérez, 2002).

Liposomes Entrapping Glycoenzyme Ascorbate Oxidase

The MW treatment-induced effect was observed only at the higher 5.6 W/kg, where the ascorbate oxidation rate ($\Delta A/\text{min}$) was reduced from 0.0109 ± 0.002 to 0.0083 ± 0.0006 . A similar decrease (from 0.0090 ± 0.003 to 0.0082 ± 0.002) of the ascorbate oxidation rate was recorded. A difference in the slope of the plot of oxidation rate ($\Delta A/\text{min}$) of ascorbate as a function of its concentration $[S]$ was found between sham and irradiated samples (Ramundo-Orlando et al., 2004).

Differential Damage in Bacterial Cells with MW Radiation

MW heating up to 40°C resulted in no significant differences in the amount of protein leaked from the cells (*Escherichia coli* and *Bacillus subtilis*). However, when the treatment temperature exceeded 40°C, substantial differences in the amount of leaked protein were reported (Woo et al., 2000).

D-Hydantoinase

The concentration of D-hydantoinase up to 6 mg/ml revealed an enhancement in activity with an increase in the amount of enzyme. However, a further increase in the amount of D-hydantoinase had no significant effect on the activity displayed (Jia et al., 2006).

The effect of MW irradiation on proteins of animal and plant is given in Table 10.3.

10.3 Conclusions

The radiation-chemical changes in proteins depend strongly on irradiation conditions. Therefore, irradiation treatment can considerably increase the cohesive strength of proteins by the formation of cross-links (Lacroix et al., 1998). However, above a certain dose, the irradiation stops inducing cross-links and has the opposite effect on the protein structure (softer and considerable loss of cohesiveness). Therefore, it is very important to optimize the use of indicators such as TMA-N and TVB-N, TMA, and TBARs, in conjunction with sensory assessment, to ensure that irradiation treatment induces the desired results per case.

Most of the research to date has been carried out mainly on proteins of animal origin, such as meat (collagen, gelatin, and globulin), chicken, egg and dairy proteins (casein caseinate salts), and, to a lesser extent, on proteins of plant origin irradiated for disinfestation purposes and improvement of physical properties by means of cross-linking.

Both TVB-N and TMA-N of γ -irradiated fish increased substantially with long storage time. The latter is a very important factor that will have to be taken into account because in most cases, the previously mentioned indicators could be used to provide an indication of how long after the irradiation treatment the detection of the irradiated proteins is feasible.

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Irradiation of Cereals

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11.1 Introduction

Cereal grains have attracted widespread attention as a means of achieving better nutrition and health protection (Hetzel, 1983). Cereal meals are recommended as a good source of fiber, and production and consumption of various meals based on whole cereals is increasing (Hanis et al., 1988). During harvesting, processing, and even distribution, these products may become rather highly contaminated with various microorganisms (Aziz and El-Halfawy, 1991; Gharib and Aziz, 1995). In many countries, both fumigation with ethylene oxide and heat sterilization have been applied with varying degrees of success. However, these methods have several disadvantages with regard to their application to the sterilization of grains, such as the fact that toxic residues remain and organoleptic properties are altered (Campbell et al., 1986). Irradiation can be an effective alternative technology (Aldryhim and Adam, 1999; Loaharanu et al., 1971). Commercial-scale use of radiation processing for food and feed commodities has been successful in several countries (El-Zawahry et al., 1991; Gharib and Aziz, 1995; Grecz et al., 1986; Ley, 1983).

11.2 Effect of Irradiation on the Quality of Rice

In a study by Sirisoontaralak and Noomhorm, (2007), milled aromatic rice was γ -irradiated at doses of 0, 0.2, 0.5, and 1.0 kGy and stored in polyethylene bags at ambient temperature for 1 year. Insignificant changes in yellowness, total solids in cooking water, cooked rice hardness, and the setback value of irradiated rice were observed during storage for 1 year. More oxidative rancidity in irradiated rice samples, however, was reported after irradiation at 1.0 kGy. All changes in the physicochemical properties during storage were dependent on irradiation dose.

Milled rice (*Oryza sativa*) samples with low, intermediate, and high apparent amylose content (AAC) were treated with γ -rays (2, 4, 8, and 12 kGy). AAC was affected only by high doses of γ -rays, whereas gel consistency was significantly enhanced. Increasing levels of γ -irradiation reduced rice pour viscosity and increased the temperature of gelatinization onset (Bao et al., 2001).

Chung et al. (2007) assessed the effect of γ -irradiation for inactivating *Salmonella Typhimurium*, *Escherichia coli*, *Staphylococcus aureus*, and *Listeria ivanovii* inoculated into the ready-to-eat kimbab—steamed rice rolled by dried laver. The growth of four test organisms inoculated ($\sim 10^6$ – 10^7 CFU/g) into the kimbab was sustained by an irradiation treatment during 24 h of storage regardless of the temperature at 10, 20, and 30°C. The four pathogens inoculated into kimbab decreased 2 or 3 log CFU/g by 1-kGy treatment, and they were not detected above 3 kGy. The D_{10} values of pathogens inoculated into the kimbab varied in the range 0.31–0.44 kGy for the four organisms.

Shin and Godber (1996) investigated the effects of γ -irradiation (5, 10, and 15 kGy) on antioxidants and lipid composition of rice bran. The free fatty acid (FFA) level in rice bran irradiated at 5 kGy was not significantly different from that of raw rice bran. However, increases in irradiation doses to 10 and 15 kGy resulted in an increase in FFA levels. Gamma irradiation at 15 kGy resulted in greater loss of phospholipids in rice bran during storage. Moreover γ -irradiation had deleterious effects on lipid stability, E vitamers, and oryzanol in rice bran during irradiation and subsequent storage. The decomposition of individual E vitamers increased with an increase in irradiation level. The loss of total E vitamers and oryzanol occurred in two stages: 50–82% and 12–33% immediately following irradiation and a further 10–35% and 39–42% during storage at ambient temperature (22–26°C).

Sirisoontarak and Noomhorm (2006) found that for irradiated aromatic milled rice, thiobarbituric acid (TBA) increased slightly after irradiation. Significant increases were found at doses of 0.7 kGy, with a peak value at 1 kGy, above which it slightly decreased. The values ranged from 2.84 nmol/g rice for non-irradiated rice to 4.42 nmol/g rice for irradiated rice at 2 kGy. Increased TBA indicated pronounced lipid oxidation.

Yu and Wang (2007a) reported that an irradiation dosage (0–10 kGy) of dried rice had negative effects on drying time and apparent amylose content, and positive effects on average dehydration rate, gel consistency, and gelatinization temperature. Yu and Wang (2007b) studied the effect of irradiation (2, 5, 8, and 10 kGy) on the structural and physicochemical properties of rice starch. Apparent amylose content, gel consistency, and gelatinization temperature were all affected by irradiation pretreatment. Apparent amylose content decreased, and gel consistency and gelatinization temperature increased with increasing dose. These changes generally related to the changes of starch structure.

Females of the Indian meal moth, *Plodia interpunctella* (Hübner), irradiated as 4- or 5-day-old pupae with an absorbed dose of 0.35 kGy of γ -radiation and confined with non-irradiated males were sterile. Male moths treated similarly and confined with non-irradiated females were only partially sterile. Irradiated males confined with non-irradiated males and females at a ratio of 1:1:1 caused 18.2% of the eggs produced to be infertile; increasing the ratio to 5:1:1, 10:1:1, 15:1:1, and 25:1:1 resulted in 48.7, 46.6, 47.7, and 58.9%, respectively, infertile eggs. When

irradiated females were confined with non-irradiated males and females in the same five ratios, 15.6, 66.2, 74.3, 100, and 100%, respectively, of the eggs were infertile (Ahmed et al., 1978).

Tilton et al. (1974) studied commercially produced, bleached, and enriched wheat flour artificially infested with insects, packed in metal cans or multiwall paper bags, and irradiated with approximately 0.4 kGy in a γ -irradiator and found that insects of all species were present 1 month later but in much smaller numbers than in the controls. After 3–14 months, no living insects were detected in the irradiated flour, and healthy populations were present in the untreated flour.

Table 11.1 summarizes the effects of irradiation on the quality of rice.

11.3 Effect of Irradiation on the Organoleptic Properties of Rice

Sirisoontaralak and Noomhorm (2007) evaluated the sensory attributes of milled aromatic rice γ -irradiated at doses of 0, 0.2, 0.5, and 1.0 kGy. They found that sensory attributes were reduced with storage time. Moreover, lower sensory scores were obtained during storage of irradiated rice compared with those of non-irradiated rice. Changes in taste, texture, and odor contributed mainly to the declining overall acceptability of cooked, irradiated rice samples. The estimated shelf life of non-irradiated rice was more than 1 year, whereas rejection was reported when rice irradiated at 0.2, 0.5, and 1.0 kGy was stored for 9, 7, and 2 months, respectively.

Bao et al. (2001) assessed cooked rice (*O. sativa*) samples for color and aroma. The samples were treated with γ -rays (2, 4, 8, and 12 kGy). When the treatment dosage was greater than 2 kGy, the samples took on a noticeable yellowish hue and developed an off-odor that partially remained after cooking.

Rice flour and starch obtained from γ -irradiated white rice were studied. The white rice was treated with 0.5, 1.0, 3.0, 5.0, 7.0, and 9.0 kGy γ -radiation at room temperature. Pasting viscosities of the rice flour and starch decreased continuously with the increase in irradiation dosage. Moreover, the crystallinity increased in irradiated starch but decreased in the irradiated flour compared with the native samples (Bao et al., 2005).

The changes in color upon irradiation of cooked or uncooked rice of Lal Qilla and Pusa Basmati-1 were reflected in the decrease of color scores according to hedonic scale by 7–10 panelists. The decreases in aroma scores also suggested some loss of aroma in these two rice qualities. Irradiation had very little effect on texture and after-cooking hardening upon cooling of cooked rice. All the scores above 5.0 suggested that the rice irradiated with doses of 0.25–1.25 kGy was of acceptable quality despite the stated effects (Roy, 1997).

TABLE 11.1 Effect of Irradiation on the Quality of Rice

| Species | Irradiation Type/Dose | Other Technology | Temperature | Shelf Life | Quality | Reference |
|---|--|------------------|--------------------------------|------------|---|----------------------------------|
| Milled aromatic rice | 0.2 kGy | PE | Ambient temperature (25 ± 1°C) | 9 months | Insignificant changes in yellowness, total solids in cooking water, cooked rice hardness, and the setback value of irradiated rice were observed during storage for 1 year. However, there was more oxidative rancidity in irradiated rice samples after irradiation at 1.0 kGy | Sirisoontarak and Noomhorm, 2007 |
| | 0.5 kGy | | | 7 months | | |
| | 1.0 kGy | | | 2 months | | |
| Milled rice (<i>Oryza sativa</i>) | γ irradiation/2, 4, 8, and 12 kGy | — | — | — | Apparent amylose content was affected only by high doses of γ rays, whereas gel consistency was significantly increased. Increasing levels of γ irradiation reduced rice pour viscosity and increased the temperature of gelatinization onset | Bao et al., 2007 |
| Rice flour and starch obtained from γ irradiated white rice | γ irradiation/0.5, 1.0, 3.0, 5.0, 7.0, and 9.0 kGy | — | — | — | Pasting viscosities of the rice flour and starch decreased continuously with the increase in irradiation dosage. Moreover, the crystallinity increased in irradiated starch but decreased in the irradiated flour compared with the native samples | Bao et al., 2005 |
| Kimbab, steamed rice rolled by dried laver | γ irradiation/1 kGy | — | — | — | 2–3 log CFU/g reduction of <i>Salmonella Typhimurium</i> , <i>Escherichia coli</i> , <i>Staphylococcus aureus</i> , and <i>Listeria ivanovii</i> (from ~10 ⁶ –10 ⁷ CFU/g). | Chung et al., 2007 |
| | γ irradiation/3 kGy | — | — | — | <i>Salmonella Typhimurium</i> , <i>Escherichia coli</i> , <i>Staphylococcus aureus</i> , and <i>Listeria ivanovii</i> not detected (from ~10 ⁶ –10 ⁷ CFU/g) | |

| | | | | | | |
|----------------------|---|---|---|---|--|---|
| Rice bran | <p>γ irradiation/5 kGy —</p> <p>γ irradiation/10 and 15 kGy —</p> | — | — | <p>Ambient temperature (22–26°C) —</p> <p>—</p> | <p>The free fatty acid level in irradiated rice bran was not significantly different from that of raw rice bran. The loss of total E vitamers and oryzanol occurred in two stages: 50–82% and 12–33% immediately following irradiation and a further 10–35% and 39–42% during storage. Irradiation increased the free fatty acid levels. The loss of total E vitamers and oryzanol occurred in two stages: 50–82% and 12–33% immediately following irradiation and a further 10–35% and 39–42% during storage.</p> | <p>Shin and Godber, 1996</p> |
| Aromatic milled rice | <p>γ irradiation/0.2, 0.5, 0.7, 1.0, 1.2, 1.5, 1.7, and 2.0 kGy —</p> | — | — | — | <p>Thiobarbituric acid (TBA) increased slightly after irradiation. Significant increases were found at doses of 0.7 kGy with a peak value at 1 kGy, above which it slightly decreased. The values ranged from 2.84 nmol/g rice for non irradiated rice to 4.42 nmol/g rice for irradiated rice at 2 kGy. Increased TBA indicated increased lipid oxidation.</p> | <p>Sirisoontarak and Noomhorm, 1997</p> |
| Dried rice | <p>γ irradiation/0–10 kGy —</p> | — | — | — | <p>Irradiation dosage (0–10 kGy) had a negative effect on drying time and apparent amylose content, and it had a positive effect on average dehydration rate, gel consistency, and gelatinization temperature.</p> | <p>Yu and Wang, 2007a</p> |
| Rice starch | <p>γ irradiation/2, 5, 8, and 10 kGy —</p> | — | — | — | <p>Apparent amylose content, gel consistency, and gelatinization temperature were all affected by irradiation pretreatment. Apparent amylose content was decreased and gel consistency and gelatinization temperature were increased with increasing dose.</p> | <p>Yu and Wang, 2007b</p> |

Sirisoontarak and Noomhorm (1997) studied the effect of irradiation (0.2, 0.5, 0.7, 1.0, 1.2, 1.5, 1.7, and 2.0 kGy) on aromatic milled rice. ACPY (an aromatic compound) content reduced after irradiation. Its content in non-irradiated and irradiated rice was distinctly different at 1.0 kGy. Values ranged from 400 ng/g for non-irradiated rice to 330 ng/g for irradiated rice at 2.0 kGy. Furthermore, they found that irradiation contributed to changes in the color of irradiated cooked rice. Gamma dosage had a significant positive correlation with the *b* value and pasting properties and a negative correlation with cooked rice hardness.

The effects of irradiation on the organoleptic properties of rice are given in [Table 11.2](#).

11.4 Effect of Irradiation on Some Additional Types of Cereals

[Yu et al. \(2005\)](#) studied wheat pretreated with γ -irradiation and dried with hot air. They found that the drying characteristics and surface temperature were affected by irradiation, and the drying rate and the surface temperature of wheat increased with increasing irradiation dose. Study of the cell structure of irradiated wheat grain by electron microscope found that the changes in drying characteristics and surface temperature of wheat were due to the destruction of the cell structure by irradiation.

Semolina, a wheat product popularly termed rawa, was packed in 500-g pouches prepared individually from high-density polyethylene, biaxially oriented polypropylene:low-density polyethylene laminate, and polyester:low-density polyethylene laminate and irradiated using a cobalt-60 source at doses of 0.15–0.50 kGy. After 6 months of storage at room temperature, there was no significant difference in the moisture content and the total bacterial as well as mold counts of the irradiated and non-irradiated rawa. Gamma irradiation significantly decreased the gelatinization viscosity of rawa ([Rae et al., 1994](#)).

[Marathe et al. \(2002\)](#) performed storage studies on irradiated (0.25–1 kGy) whole-wheat flour packaged in polyethylene pouches and found that there was no adverse effect of irradiation and storage up to 6 months for whole-wheat flour treated at doses up to 1 kGy on total proteins, fat, carbohydrates, vitamin B₁ and B₂ content, sedimentation value, dough properties, and total bacterial and mold count. Moreover, irradiation as such had no effect on moisture, free fatty acids, starch, sugars, and gelatinization viscosity. Irradiation at 0.25 kGy was sufficient to extend the shelf life of whole-wheat flour up to 6 months.

The effect of different irradiation doses on the moisture of wheat grain and wheat flour is shown in [Figure 11.1](#).

Grains of the Polish winter wheat variety Begra were subjected to γ -radiation (grain harvested in 1996) within the dose range of 0.05–10 kGy. The direct γ -irradiation of grain reduced statistically significantly the decreasing number values and gelatinization enthalpy (ΔH) of the grain treated with 5- and 10-kGy γ -rays ([Dolinska et al., 2004](#)).

TABLE 11.2 Effects of Irradiation on the Organoleptic Properties of Rice

| Species | Irradiation Type/Dose | Other Technology | Temperature | Shelf Life | Sensory Scores | Reference |
|------------------------------|---|-------------------|--|------------|---|------------------------------------|
| Milled aromatic rice | γ irradiation/0.2 kGy | Polyethylene bags | Ambient temperature ($25 \pm 1^\circ\text{C}$) | 9 months | Lower sensory scores were obtained during storage of irradiated rice compared with those of non irradiated rice. Changes in taste, texture, and odor contributed mainly to the declining overall acceptability of cooked, irradiated rice samples | Sirisoontaralak and Noomhorm, 2007 |
| | γ irradiation/0.5 kGy | | | 7 months | | |
| | γ irradiation/1 kGy | | | 2 months | | |
| Rice (<i>Oryza sativa</i>) | γ irradiation/2, 4, 8, and 12 kGy | — | — | — | With dosages >2 kGy, the samples took on a noticeable yellowish hue and developed an off odor that partially remained after cooking | Bao et al., 2007 |
| Aromatic milled rice | γ irradiation/0.2, 0.5, 0.7, 1.0, 1.2, 1.5, 1.7, and 2.0 kGy | — | — | — | ACPY (an aromatic compound) content was reduced after irradiation. Its content in non irradiated and irradiated rice was distinctly different at 1.0 kGy. Values ranged from 400 ng/g for non irradiated rice to 330 ng/g for irradiated rice at 2.0 kGy. Gamma dosage had a significant positive correlation with the b^* value, pasting properties and a negative correlation with cooked rice hardness | Sirisoontaralak and Noomhorm, 1997 |

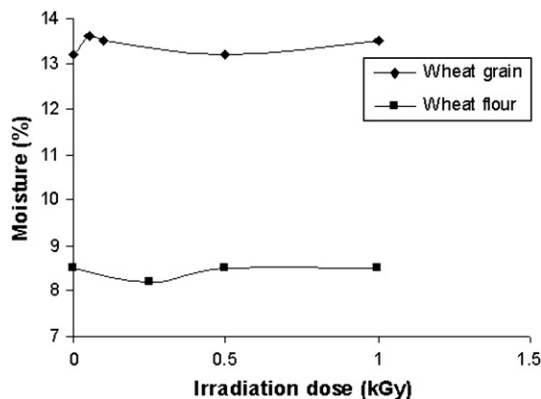


Figure 11.1: Effect of different irradiation doses on the moisture of wheat grain and wheat flour (Blaszczak et al., 2002; Marathe et al., 2002).

In a study by Gralik and Warchalewski (2006), ionizing radiation (0.05–10 kGy) of wheat grain caused an increase in the activity of endogenous amylases, statistically significant at doses of 5 and 10 kGy. Gamma irradiation of wheat grain at a dose of 0.05 kGy caused an increase of inhibition activity against *Sitophilus granarius* L. α -amylase, whereas there was a decrease at 10 kGy. Grain irradiated by 0.5- and 1-kGy doses showed a significant increase in inhibition activity against α -amylase of *Tribolium confusum* Duv., whereas at the remaining doses the inhibition activity was on the same level as the control grain. Decrease of *Ephesitia kuehniella* Zell. α -amylase was observed only at the 5-kGy radiation dose. At the remaining doses, this activity was comparable to that for non-irradiated grain. Grains of the Polish winter wheat variety Begra were subject to γ -radiation within the dose range of 0.05–10 kGy.

Irradiation was responsible for marked structural changes of wheat kernel endosperm and was pronounced with increasing dose of ionizing radiation. Endosperm microstructures of wheat kernels treated with γ -radiation ranging from 0.05 to 0.5 kGy did not differ from those of untreated ones. In irradiated grain samples at doses of 5 and 10 kGy, statistically significant decreases of falling number, sodium dodecyl sulfate (SDS) sedimentation values, dough stability and energy were observed, whereas dough weakening increased. Gamma rays at radiation doses of 1–10 kGy promoted gel-like properties of starch granules, which was responsible for an increase of starch hydration properties (the increase of flour water absorption) sufficient to compensate some decrease in gluten swelling capability (Blaszczak et al., 2002).

Figure 11.2 displays the effect of different irradiation doses on the water absorption capacity of wheat grain and wheat flour.

Koksel et al. (1998) investigated the effects of γ -irradiation treatments (2.5, 5, 10, and 20 kGy) on the gluten proteins of two bread wheats and one durum wheat cultivar. There was no

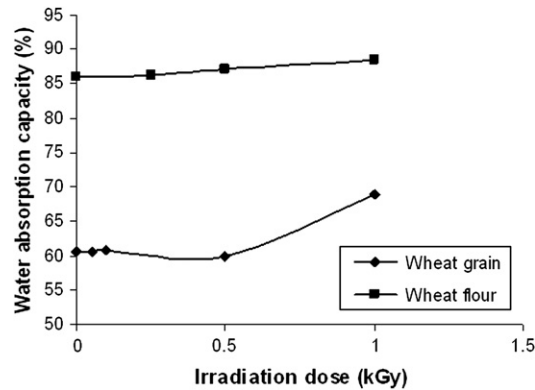


Figure 11.2: Effect of different irradiation doses on the water absorption capacity of wheat grain and wheat flour (Błaszczak et al., 2002; Marathe et al., 2002).

observable effect of irradiation on gliadin proteins. The 50% 1-propanol-insoluble (50 PI) glutenin fraction was highly affected by irradiation. Increasing levels of irradiation also progressively reduced the ratio of high-molecular-weight glutenin subunits:low-molecular-weight glutenin subunits up to 13–15% at 20 kGy, thereby indicating that irradiation had a greater effect on the largest polymers of glutenin.

According to Diehl (1979), exclusion of atmospheric oxygen by packaging under nitrogen reduced the loss of α -tocopherol in irradiated (1 kGy) rolled oats after 8 months of storage from 56 to 5%, and the loss of thiamin from 86 to 26%. Vacuum packaging was equally effective during the first 3 months and somewhat less effective during the following 5 months. Packaging under carbon dioxide showed no advantage over packaging in air. Sensory evaluation of rolled oats, raw or cooked, 1 and 3 months after irradiation with 1 kGy indicated no significant quality difference between non-irradiated and irradiated samples packaged under nitrogen.

In a study by Koxsel et al. (1998), two two-rowed barley cultivars, Tokak and Clerine, were irradiated at two different dose ranges (0.05–0.75 and 0.5–5.0 kGy). Irradiation of barley at the medium levels before malting had detrimental effects on most of the malt quality criteria. In addition, the detrimental effects of irradiation were lower at doses up to 0.25 kGy. Irradiation of malt samples caused either slight or no deterioration of quality characteristics.

Abu-Tarboush (1998) studied irradiation inactivation of tannin contents of two varieties of the sorghum grain. The Hemaira variety (red color) contained more tannin (0.68% catechin equiv) than the Shahlla variety (0.35% catechin equiv). Irradiation with 7.0 and 10.0 kGy contributed significantly to the reduction of tannin content in Shahlla (only from 0.35 to 0.26 mg of catechin equiv/100 g). The tannin content of Hemaira was not significantly affected by irradiation. However, complete destruction of tannin was not achieved by a dose of 10 kGy.

The effects of cooking followed by irradiation (10 kGy) on vitamins B₁ and C, and the anti-nutritional factors phytic acid and nitrates, in a ready-to-eat meal of sorghum porridge were investigated. Irradiation caused a dramatic decrease of vitamins B₁ and C both on a dry and on an as-is basis. Irradiation of the cooked sorghum endosperm meal decreased phytic acid significantly on both a dry and an as-is basis. Irradiation of cooked samples did not result in a significant increase in nitrate content (Duodu et al., 1999).

Changes in the fatty acid composition in lipids after γ -irradiation of whole grain rye were examined. Radiosensitivity of linoleic acid (18:2) and linolenic acid (18:3) was studied up to a dose of 63 kGy. At doses in the range 0.1–1.0 kGy, no detectable degradation of 18:2 and 18:3 was reported (Vaca and Harms-Ringdahl, 1986).

The effect of γ -irradiation (1, 3, 5, 10, and 15 kGy) on the occurrence of pathogenic microorganisms and nutritive value of wheat (*Triticum vulgare*), barley (*Hordeum vulgare*), maize (*Zea mays*), and sorghum (*Sorghum bicolor*) was studied by Aziz et al. (2006). They reported that “coliforms and ‘coagulase-positive’ staphylococci were inhibited by a dose of 1 kGy, whereas fungi were inhibited by a dose of 5 kGy. A 15-kGy dose eliminated viable microorganisms in cereal grains, and approximately 10–30 colony-forming units of *Clostridium* sp. per gram of grain survived after this dose. The total numbers of aerobic bacteria were reduced by three logarithmic decades when grains were given a dose of 10 kGy. The dose of 10 kGy did not cause any measurable destruction of total amino acids. Thiamin was reduced by 22–33% and riboflavin by 10–16% after a dose of 10 kGy. Irradiation did not increase the acid values significantly but did increase the peroxide values, which were not accompanied by the off-odors of cereals.”

The effect of irradiation on the properties of other cereals except rice is summarized in Table 11.3.

11.5 Conclusions

Irradiation at 5 and 10 kGy induced marked structural changes of wheat kernel endosperm, which were pronounced with an increasing dose of ionizing radiation. Endosperm microstructures of wheat kernels treated with γ -radiation doses ranging from 0.05 to 0.5 kGy did not differ from those of untreated ones. At high irradiation doses, the affected properties of wheat kernel displayed decreases in falling number, SDS sedimentation values, dough stability, and energy, whereas dough weakening increased.

Evaluation of the sensory attributes of milled aromatic rice samples γ -irradiated at doses of 0, 0.2, 0.5, and 1.0 kGy revealed a reduction of the attributes with storage time. Moreover, lower sensory scores were obtained during storage of irradiated rice compared with those of non-irradiated rice. Changes in taste, texture, and odor contributed mainly to the declining overall

TABLE 11.3 Effect of Irradiation on Cereals Other Than Rice

| Species | Irradiation Type/Dose | Other Technology | Temperature | Shelf Life | Irradiation Effect | Reference |
|---------------------------------|------------------------------------|--|------------------|------------|--|-------------------------------|
| Sorghum grain (Hemaira variety) | 1.0, 3.0, 5.0, 7.0, and 10 kGy | — | — | — | Irradiation with 7.0 and 10.0 kGy contributed significantly to the reduction of tannin content in Shahlla (only from 0.35 to 0.26 mg of catechin equiv./100 g). | Abu Tarboush, 1998 |
| Sorghum grain (Shahlla variety) | 1.0, 3.0, 5.0, 7.0, and 10 kGy | — | — | — | The tannin content of Hemaira was not significantly affected by irradiation. | |
| Sorghum porridge | γ irradiation/10 kGy | — | — | — | Irradiation induced a dramatic decrease of vitamins B ₁ and C both on a dry and on an as is basis. Irradiation decreased phytic acid significantly on both a dry and an as is basis. No change in nitrate content after irradiation | Duodu et al., 1999 |
| Rye | γ irradiation/0.1 1.0 kGy | — | — | — | No detectable degradation of linoleic acid (18:2) and linolenic acid (18:3) | Vaca and Harms Ringdahl, 1986 |
| Rawa (a wheat product) | γ irradiation/0.15 0.50 kGy | Packaged in different types of materials | Room temperature | — | At the end of 6 months of storage, there was no significant difference in the moisture content and the total bacterial as well as mold counts of the irradiated and unirradiated rawa. Gamma irradiation significantly decreased the gelatinization viscosity of samples | Rae et al., 1994 |

(Continued)

Table 11.3 Effect of Irradiation on Cereals Other Than Rice—cont'd

| Species | Irradiation Type/Dose | Other Technology | Temperature | Shelf Life | Irradiation Effect | Reference |
|---|------------------------------------|----------------------------------|-------------|--|--|-------------------------------|
| Wheat | γ irradiation | Dried by hot air | — | — | The drying characteristics and surface temperature were all affected by irradiation, and the drying rate and the surface temperature of wheat increased with the increase of irradiation dose | Yu et al., 2005 |
| Whole wheat flour | γ irradiation/0.25–1 kGy | Packaged in polyethylene pouches | — | Irradiation at 0.25 kGy extended the shelf life of whole wheat flour up to 6 months. | There were no adverse effects on total proteins, fat, carbohydrates, vitamin B ₁ and B ₂ content, total bacterial and mold count, free fatty acids, starch, sugars, and gelatinization viscosity | Marathe et al., 2002 |
| Grains of the Polish winter wheat variety Begra | γ irradiation/0.05–10 kGy | — | — | — | The direct γ irradiation of grain reduced the decreasing number values and gelatinization enthalpy (ΔH) of the grain treated with 5 and 10 kGy γ rays | Dolinska et al., 2004 |
| Wheat grain | γ irradiation/0.05–10 kGy | — | — | — | Irradiation at 0.05 kGy caused an increase of inhibition activity against <i>Sitophilus granarius</i> L. α amylase, whereas there was a decrease at 10 kGy | Gralik and Warchalewski, 2006 |
| | γ irradiation/0.5 and 1 kGy | — | — | — | Grain irradiated showed a significant increase in inhibition activity against α amylase of <i>Tribolium confusum</i> Duv. | |

| | | | | | | |
|---|---|---|---|---|---|------------------------|
| | γ irradiation/5 kGy | — | — | — | A decrease of <i>Ephesitia kuehniella</i> Zell. α Amylase was observed | |
| Grains of the Polish winter wheat variety Begra | γ irradiation/0.05 10 kGy | — | — | — | Irradiation caused structural changes of wheat kernel endosperm. Samples at the doses of 5 and 10 kGy showed a decrease in sodium dodecyl sulfate (SDS) sedimentation values, dough stability, and energy, whereas dough weakening increased. Gamma rays at radiation doses of 1 10 kGy promoted gel like properties of starch granules (the increase of flour water absorption) sufficient to compensate for some decrease in gluten swelling capability | Blaszczak et al., 2002 |
| Two bread wheats and one durum wheat cultivar | γ irradiation/2.5, 5, 10, and 20 kGy | — | — | — | No effect of irradiation on gliadin proteins. Increasing levels of irradiation reduced the ratio of high molecular weight glutenin subunits:low molecular weight glutenin subunits up to 13 15% at 20 kGy. The 50% I propanol insoluble (50 PI) glutenin fraction was highly affected by irradiation | Koksel et al., 1998 |

acceptability of cooked, irradiated rice samples. The estimated shelf life of non-irradiated rice was more than 1 year, whereas rejection was observed when rice irradiated at 0.2, 0.5, and 1.0 kGy was stored for more than 2 months.

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Irradiation of Fruits and Vegetables

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12.1 Introduction

Several studies have shown an association between a high consumption of vegetables and fruits and low incidences of certain chronic diseases (Lir et al., 2000; Van't Veer et al., 2000). With the increasing demand for fresh fruits and vegetables, as well as market globalization, an increase in foodborne illness due to produce is a real possibility as a result of contamination of foods with pathogenic microorganisms (Bidawid et al., 2000). Minimally processed foods such as fresh, precut vegetables and fruits, both conventional and organics, have limited shelf life and mainly rely on good manufacturing practices (GMP) for preservation and safety (Horak et al., 2006). Contaminated raw vegetables, fruits, and fruit juices have all been vehicles for transmission of pathogens (Kim et al., 2006). These foods are often consumed raw without the benefit of any pathogen-killing step (Beuchat, 1996a). In the past few decades, a number of major foodborne disease outbreaks involving up to thousands of cases and many deaths attributable to consumption of fresh, precut, and minimally processed produce have been reported in several countries (Beuchat, 1996b; Viswanathan and Kaur, 2001). The microorganisms present in this produce are the natural microflora (lactic acid bacteria, *Pseudomonas* spp., yeast and molds) or the bacteria incorporated in these products during their cultivation (irrigation and fertilization), and processing (harvest, postharvest handling, processing, and distribution) (Horak et al., 2006). Ionizing radiation is a nonthermal technology that has been reported to eliminate foodborne pathogens and extend the shelf life of fresh fruits and vegetables (Thayer and Rajkowski, 1999).

This chapter presents the microbiological, organoleptic, and physicochemical effects of ionizing irradiation, alone or in combination with various other hurdles, on fruits and vegetables.

12.2 Quality and Shelf Life Extension of Irradiated Fruits

Basson et al. (1979) found that for mango, irradiated with 1 kGy, the only compounds to undergo significant modifications are the sugars, which account for nearly 99% of the reactions. The other components that are slightly reactive are starch (0.2%), protein (0.2%), phenol

(0.4%), and ascorbic acid (0.2%). Therefore, only carbohydrate degradation needs to be considered. Furthermore, carbohydrate reactivity tends to protect the other components from degradation changes.

Fresh Tristar strawberries were irradiated with electron beam (e-beam) irradiation at 0, 1, and 2 kGy. Fruit firmness decreased as irradiation dose increased. Water-soluble pectin increased and oxalate-soluble pectin decreased at 0 and 1 day after 1- and 2-kGy irradiation. Fruit firmness was correlated with oxalate-soluble pectin content. Total pectin and nonextractable pectin were not affected by irradiation. The oxalate-soluble pectin content and firmness of irradiated strawberries increased slightly at the beginning of 2°C storage and then decreased as storage time increased. No changes occurred in water-soluble pectin, nonextractable pectin, or total pectin during storage (Yu et al., 1996).

Paull (1996) reported that papaya fruits (*Carica papaya* L.) treated with 0.25 kGy of γ -irradiation frequently softened more uniformly than did non-irradiated fruit. Fruits with less than 25% of their surface colored yellow placed immediately into storage at 10°C after irradiation developed skin scald. This was prevented by delaying storage by 12 h. Fruits that were irradiated when 30% of the skin was yellowed softened at a slower rate than non-irradiated fruits. There was no difference in softening rate between irradiated and non-irradiated fruits at the mature green stage. Fruit stored for 14 days at 10°C before returning to 25°C displayed a slightly slower rate of softening than fruit allowed to ripen at 25°C without storage. Premature flesh softening occurred occasionally in fruit that had between 8 and 18% of the skin yellow and 70–90% flesh coloring when irradiated.

In a study by Assi et al. (1997), mature green and pink tomato (*Lycopersicon esculentum* Mill.) fruit were subjected to ionizing irradiation in the range of 0.7–2.2 kGy from γ - or X-ray sources. Fruit irradiated at the mature green stage softened during post-irradiation storage (20°C) but exhibited an apparently irreversible suppression in polygalacturonase activity, with levels remaining lower than 10% of those of non-irradiated fruit. Polygalacturonase activity was less strongly affected in irradiated pink fruit than in mature green fruit, but activity remained reduced relative to the controls. Pectinmethylesterase and β -galactosidase activities were significantly enhanced in irradiated fruit of both ripening stages in the early period following irradiation, but reductions were noted after prolonged storage.

Susheela et al. (1997) found no significant loss of sugar and ascorbic acid contents in three-quarter ripe and fully ripe pineapple fruit (*Ananas comosus*) irradiated at 0.15 kGy. According to Drake and Neven (1998), irradiation can be applied to cherries, apricots, or peaches as a quarantine treatment at 0.3 kGy or less with little quality loss. Differences in stem condition and bruising were more evident for irradiated Rainier cherries than for methyl bromide (MeBr)-treated Rainier cherries, but these differences were small. Use of irradiation resulted in some firmness loss for Bing cherries compared with the use of MeBr, but irradiation treatment of cherries did not lead to a loss of fruit and stem color, whereas the use of MeBr doses resulted in

both fruit and stem color loss. Apricots (Perfection and Rival) and peaches (Regina) were tolerant to irradiation at 0.3 kGy with little quality loss. Loss of firmness, color changes, and increased internal breakdown were evident in both apricots and peaches at irradiation dose higher than 0.6 kGy.

Drake et al. (1999) found that titratable acidity (TA) of Gala apples was reduced at irradiation doses of 0.60 kGy and higher. On the other hand, no loss of TA due to the irradiation dose was evident for Fuji or Granny Smith apples.

Rubio et al. (2001) studied the effects of irradiation (0.5, 0.75, and 1 kGy) on the vitamin C content of lettuce (*Lactuca sativa*), cabbage (*Brassica oleracea*), and celery (*Apium graveolens*). There was a marked difference in the natural total ascorbic acid content of the vegetables studied, with cabbage showing the highest. Irradiation did not decrease these initial concentrations, and in the case of cabbage, it actually increased them. For lettuce, cabbage, and celery, the initial ascorbic acid content was 2.357, 3.085, and 0.549 mg/100 g, respectively, and after irradiation at 1 kGy it was 2.036, 5.018, and 0.616 mg/100 g, respectively.

D'Innocenzo and Lajolo (2001) used irradiation treatment as an imposed stress to cause changes in firmness. Physiologically mature papaya fruits were irradiated (0.5 kGy) and allowed to ripen at 22°C and 90% relative humidity (RH). Irradiation caused a 2-day delay in the onset of ripening time. The total soluble solids (°brix) of both treated and control fruits increased from 8 to 12% and were not affected by irradiation.

Single-strength orange juice was exposed to 0, 0.89, 2.24, 4.23, and 8.71 kGy γ -radiation at 5°C and then stored at 23°C for 6 days and 7°C for 21 days. Both ascorbic acid (AA) and dehydroascorbic acid (DAA) concentrations decreased with increased radiation dose. Juice irradiated at all doses had lower AA and total AA (TAA) content than non-irradiated juice. TAA loss following irradiation treatment was less than half that of AA. The conversion of AA to DHA was promoted by irradiation. Both the concentration and the percentage of DHA increased linearly with increased radiation dose. Irradiation did not alter non-AA antioxidant activity (Fan et al., 2002).

The effect of irradiation at doses of 0.125, 0.250, 0.375, and 0.5 kGy on the quality of Maroc Late oranges was investigated by Moussaid El Idrissi et al. (2002). Storage of irradiated fruits was studied at room temperature and 10°C and at 0°C in the case of control fruits. No considerable variation in the juice yield between non-irradiated fruits and those irradiated to doses of 0.125, 0.250, 0.375, and 0.5 kGy was recorded. The juice yield remained nearly the same in fruits stored at 10 and 0°C for 4 weeks, whereas in oranges stored at ambient temperature, some insignificant variations were reported for the four doses tested. There were no apparent changes in the total and volatile acid contents between control and fruits irradiated to different doses during storage for 1 month at any of the temperatures. Neither the reducing sugar nor the total sugar levels were changed by doses of irradiation used under any of the temperatures

during storage for a period of 1 month. Weight loss in oranges as a function of the storage period increased with increasing irradiation dose.

Wang and Chao (2003) investigated the irradiation effects on dehydration characteristics and quality of apples (Fuji apple). They found that vitamin C content of apples, dehydration rate, and rehydration ratio were greatly affected by irradiation dose (1.5, 4.5, 5, and 6 kGy). It was shown that the greater the dose, the higher the dehydration rate, the less the vitamin C content, and the lower the rehydration ratio.

A study was conducted on early and late season Rio Red. Fruit was treated with 0, 0.07, 0.2, 0.4 and 0.7 kGy and then stored under 10°C for 4 weeks, followed by 1 week at 20°C with 90–95% RH. It was demonstrated that irradiation doses of up to 0.7 kGy had no significant effect on vitamin C content of early season grapefruit. Late season fruit exposed to irradiation greater than or equal to 0.2 kGy caused a marked reduction in vitamin C content after 35 days of storage. Soluble solids (%) were not affected due to irradiation or storage of early season fruit. On the other hand, late season fruit had lower soluble solids (%) and acidity values than early season fruit, and the soluble solids:acid ratios after 35 days of storage were slightly higher than the initial ratios (Patil et al., 2004).

Wang et al. (2006) measured and analyzed the enzyme activity in Golden Empress cantaloupe juice after cobalt-60 irradiation. Enzyme activity determination revealed that lipoxygenase was most easily inactivated by irradiation, followed by polyphenoloxidase and peroxidase. However, all three enzymes remained active even at 5 kGy.

Vanamala et al. (2007) exposed grapefruits (*Citrus paradisi* cv. Rio Red) to γ -irradiation at 0, 0.15, and 0.3 kGy and then stored them at 10°C for 36 days, followed by an additional 20 days at 20°C. Irradiation or storage did not result in considerable changes of the content of total soluble solids in grapefruits. However, there was a considerable decline in acid content during storage. Fruits exposed to 0.3 kGy of irradiation had higher acidity compared to the control (0 Gy). Moreover, their results suggest that low-dose irradiation at 0.3 kGy enhanced or at least maintained the flavonoid content.

Alonso et al. (2007) found that X-ray irradiation doses of 0.195 and 0.395 kGy resulted in minimal differences in juice yield between X-ray irradiated and cold-treated clementine mandarin fruits (*Citrus reticulata*), with no significant difference between the control and any irradiation treatment. Both acetaldehyde and ethanol contents of the irradiated fruit were higher along with both X-ray dosage and storage period (1.5°C for 14 days).

The changes in physicochemical quality and antioxidant activity of kiwifruits by low-dose e-beam irradiation (0, 0.3, and 0.6 kGy) were investigated by Kim et al. (2007). Fruits were stored at 20°C for 28 days and evaluated after 0, 1, 2, 3, and 4 weeks of storage. Irradiation did not affect 1,1-diphenyl-2-picrylhydrazyl radical scavenging activities and pH. Vitamin C contents of irradiated fruits were higher than those of non-irradiated fruits. Irradiation caused

no significant change in total sugar contents and reducing sugar contents. Soluble solid contents in irradiated fruits were higher than those in non-irradiated fruits for the initial storage period but showed lower increment rate during the storage period. Organic acid contents of irradiated fruit revealed no significant effect for the initial storage period and during the later storage periods; the rate of decline in organic acid content of irradiated fruit was not substantially changed.

The effects of irradiation on quality improvement and shelf life extension of fruits are summarized in Table 12.1.

12.3 Sensory Properties of Irradiated Fruits

Larrigaudière et al. (1990) reported that γ -irradiation of early climacteric (breaker) cherry tomatoes (*Lycopersicon pimpinellifolium* L.) caused a sharp burst in ethylene production during the first hour. The extent of ethylene production was dose dependent, and its maximum was at approximately 3 kGy. The content of 1-aminocyclopropane-1-carboxylic acid (ACC) followed the same evolution as ethylene production, whereas malonyl ACC increased steadily with time in irradiated fruits. The burst in ethylene production was accompanied by a sharp stimulation of ACC synthase activity that began 15 min after irradiation. Gamma irradiation greatly inhibited the activity of ethylene-forming enzyme at doses higher than 1 kGy. Such sensitivity is in accordance with a highly integrated membrane-bound enzyme.

Susheela et al. (1997) described the effect of γ -radiation on the three-quarter ripe and fully ripe pineapple fruit *Ananas comosus*. After having been irradiated at 0.05, 0.1, and 0.15 kGy and stored at 25–29°C with 90–97% RH, the latter was shown to maintain its texture better than the controls. The maximum tolerable dose was approximately 0.25 kGy.

Assi et al. (1997) studied mature green and pink tomato (*Lycopersicon esculentum* Mill.) fruit that was subjected to ionizing irradiation in the range of 0.7–2.2 kGy from γ - or X-ray sources. Irradiation-induced softening was evident in mature green and pink fruit within hours following irradiation, and differences between irradiated and control fruit persisted throughout post-irradiation storage (20°C). Trends of firmness loss were more consistent and displayed much greater dose dependence on pericarp tissue than whole fruit.

Drake and his co-workers (1999) investigated the effect of irradiation on Gala, Fuji, and Granny Smith apples. They reported that “irradiation at doses between 0.30 and 0.90 kGy reduced apple firmness. Doses less than 0.30 kGy had no effect on apple firmness. Firmness lost due to irradiation was cultivar dependent. Irradiation did not influence the external color of apples, but change in the internal color of Gala and Granny Smith apples due to irradiation exposure was present. Bosc pears lost firmness due to irradiation, and the firmness loss was dose dependent. Both Anjou and Bosc ripened normally after irradiation exposure. There was an increase in scald for Anjou directly proportional to the applied dose.”

TABLE 12.1 The Effect of Irradiation on Quality Improvement and Shelf Life Extension of Fruits

| Species | Irradiation Type/ Dose | Temperature | Quality | Reference |
|---|---|--|---|-----------------------|
| Mango | γ irradiation/1 kGy | — | Only sugars undergo significant modifications, which account for nearly 99% of the reactions. The other components that are slightly reactive are starch (0.2%), protein (0.2%), phenol (0.4%), and ascorbic acid (0.2%) | Basson et al., 1979 |
| Fresh Tri Star strawberries | e beam irradiation/1 and 2 kGy | 2°C | Water soluble pectin increased and oxalate soluble pectin decreased at 0 and 1 day after 1 and 2 kGy irradiation. Total pectin and nonextractable pectin were not affected by irradiation. The oxalate soluble pectin content and firmness of irradiated strawberries increased slightly at the beginning of storage and then decreased as storage time increased. No changes occurred in water soluble pectin, nonextractable pectin, or total pectin during storage | Yu et al., 1996 |
| Mature green and pink tomato (<i>Lycopersicon esculentum</i> Mill.) fruit | γ or X ray sources/ 0.7 2.2 kGy | 10°C | Polygalacturonase activity was less affected in irradiated pink fruit than in mature green fruit, but activity remained reduced relative to the controls. Pectinmethylesterase and β galactosidase activities were significantly enhanced in irradiated fruit of both ripening stages in the early period following irradiation, but reductions were noted after prolonged storage. Irradiation enhanced electrolyte efflux in fruits of both maturity classes | Assi et al., 1997 |
| Three quarter ripe and fully ripe pineapple fruit (<i>Ananas comosus</i>) | 0.05, 0.1, and 0.15 kGy | 25 29°C with 90 97% relative humidity (RH) | Irradiated fruits maintained their texture better than the controls. The maximum tolerable dose was \sim 0.25 kGy | Susheela et al., 1997 |

| | | | | |
|---|---|--|---|----------------------------------|
| Gala apples | 0.3 and 0.9 kGy | — | Titratable acidity (TA) was reduced at irradiation doses of 0.60 kGy and higher. | Drake et al., 1999 |
| Gala, Fuji, and Granny Smith apples | 0.3 and 0.9 kGy | — | No loss of TA due to the irradiation dose was evident | |
| Lettuce (<i>Lactuca sativa</i>), cabbage (<i>Brassica oleracea</i>), celery (<i>Apium grave</i>), and pineapple (<i>Ananas comosus olens</i>) | 1 kGy | — | For lettuce, cabbage, and celery, initial ascorbic acid content was 2.357, 3.085, and 0.549 mg/100 g, respectively, and after irradiation was 2.036, 5.018, and 0.616 mg/100 g, respectively | Rubio et al., 2001 |
| Papaya | γ irradiation/0.5 kGy | 22°C and 90% RH | Irradiation caused a 2 day delay of the onset of ripening time. The total soluble solids (°brix) of both treated and control fruits increased from 8 to 12% and were not affected by irradiation | D'Innocenzo and Lajolo, 2001 |
| Orange juice | γ irradiation/0.89, 2.24, 4.23, and 8.71 kGy | 23°C for 6 days and 7°C for 21 days | Both ascorbic acid (AA) and dehydroascorbic acid (DAA) concentrations decreased with increased radiation dose. Juice irradiated at all doses had lower AA and total AA content than non irradiated juice. Irradiation did not alter non AA antioxidant activity | Fan et al., 2002 |
| Maroc Late orange | γ irradiation/0.125, 0.250, 0.375, and 0.5 kGy | Room temperature and 10°C and at 0°C in case of control fruits | No apparent change in the total and volatile acid contents between control and fruits irradiated to different doses during storage for 1 month at any of the temperatures. Neither reducing sugar nor the total sugar levels were changed by doses of irradiation used under any of the temperatures during storage for a period of 1 month. Weight loss increased with increasing irradiation dose | Moussaid El Idrissi et al., 2002 |

(Continued)

TABLE 12.1 The Effect of Irradiation on Quality Improvement and Shelf Life Extension of Fruits—cont'd

| Species | Irradiation Type/ Dose | Temperature | Quality | Reference |
|--|--|--|--|-------------------------|
| Apples (Fuji) | 1.5, 4.5, 5, and 6 kGy | — | Vitamin C content of apples, dehydration rate, and rehydration ratio were greatly affected by irradiation dose. The greater the dose, the higher the dehydration rate, the less the vitamin C content, and the lower the rehydration ratio | Wang and Chao, 2003 |
| Early season Rio Red grapefruit | γ irradiation/0.07, 0.2, 0.4, and 0.7 kGy | 10°C for 4 weeks followed by 1 week at 20°C with 90–95% RH for 35 days | Soluble solids (%) were not affected due to irradiation or storage of early season fruit. It was demonstrated that irradiation had no significant effect on vitamin C content | Patil et al., 2004 |
| Late season Rio Red grapefruit | γ irradiation/0.07, 0.2, 0.4, and 0.7 kGy | 10°C for 4 weeks followed by 1 week at 20°C with 90–95% RH for 35 days | Late season fruit exposed to irradiation ≥ 0.2 kGy caused a marked reduction in vitamin C content after 35 days of storage. There were lower soluble solids (%) and acidity values than those of early season fruit, and the soluble solids:acid ratio after 35 days of storage were slightly higher than the initial ratios | |
| Preclimacteric mango (<i>Mangifera indica</i> L. var. Alphonso) | 200 Gy | Ambient temperature (28–32°C) | Approximately 8–10 days | Janave and Sharma, 2005 |
| Preclimacteric mango (<i>Mangifera indica</i> L. var. Alphonso) | 100 Gy | Ambient temperature (28–32°C) | 5–6 days | |
| Carrot (<i>Daucus carota</i> L.) | 1 and 2 kGy | 4°C | There was no significant difference in the vitamin C content and total carotenoids in samples and control samples. Variation in the content of vitamin C and carotenoids during storage was also not statistically significant from the control samples. The qualified test panelist could not differentiate between irradiated and non irradiated samples | Bandekar et al., 2006 |

| | | | | |
|---|--|---|--|-----------------------|
| Golden Empress cantaloupe juice | γ irradiation/5 kGy | — | Enzyme activity determination indicated that lipoxygenase was the easiest to be inactivated by irradiation, followed by polyphenoloxidase and peroxidase, but the three enzymes still remained activated even at 5 kGy | Wang et al., 2006 |
| Grapefruits (<i>Citrus paradisi</i> cv. Rio Red) | 0.15 kGy | 10°C for 36 days, followed by an additional 20 days at 20°C | No considerable changes of the content of total soluble solids in grapefruits. There was a decline in acid content during storage | Vanamala et al., 2007 |
| | 0.3 kGy | 10°C for 36 days, followed by an additional 20 days at 20°C | No considerable changes of the content of total soluble solids in grapefruits, but a decline in acid content during storage. Fruits exposed to 0.3 kGy of irradiation had higher acidity compared to the control. They had enhanced flavonoid content, or they maintained their initial levels of flavonoid content | |
| Clémentine mandarin fruits (<i>Citrus reticulata</i>) | X ray irradiation/0.195 and 0.395 kGy | 1.5°C for 14 days | Minimal differences in juice yield between X ray irradiated and cold treated. Both acetaldehyde and ethanol contents of the irradiated fruit were directly proportional to both X ray dosage and storage period | Alonso et al., 2007 |
| Kiwifruits | e beam irradiation/0, 0.3, and 0.6 kGy | 20°C for 28 days | Vitamin C contents of irradiated fruits were higher than those of non irradiated fruits. Soluble solid contents in irradiated fruits were higher than those of non irradiated fruits for the initial storage period but showed lower increment rate during the storage period. No significant change in total sugar contents and reducing sugar contents | Kim et al., 2007 |

Ten citrus cultivars grown in Florida, including the 5 orange (*Citrus sinensis* L. Osbeck) cultivars—Ambersweet, Hamlin, Navel, Pineapple, and Valencia—and the 5 mandarin hybrids (*Citrus reticulata* Blanco)—Fallglo, Minneola, Murcott, Sunburst, and Temple—were exposed to irradiation at 0, 0.15, 0.3, and 0.45 kGy and stored for 14 days at 1 or 5°C plus 3 days at 20°C to determine dose tolerance based on fruit injury. Softening of Valencia, Minneola, Murcott, and Temple was dose dependent, but that of other cultivars was unaffected. The appearance of all cultivars was negatively affected by the loss of glossiness with the 0.45-kGy dose. Less than 1.0% of fruit decayed, and irradiation treatment had no effect on decay (Miller et al., 2000).

According to D’Innocenzo and Lajolo (2001), irradiated (0.5 kGy) and non-irradiated papaya fruits, stored at 22°C and 90% RH, ripened normally with respect to sugar content, color change, firmness, and general appearance of the fruit.

Rubio et al. (2001) irradiated lettuce (*Lactuca sativa*), cabbage (*Brassica oleracea*), and celery (*Apium graveolens*) at 0.50, 0.75, and 1.00 kGy. Non-irradiated samples were used as controls. The effect of irradiation was measured during 7 days of storage under refrigeration at 5–10°C. Cabbage was the most radiation resistant of the vegetables because it underwent no changes in any quality attribute upon irradiation at the doses tested. The only significant differences detected between control and irradiated samples—that is, in the appearance of lettuce and in the color of celery—were judged by produce experts to have no “commercial” significance. Moreover, all control and irradiated vegetables were given good overall acceptability scores, not significantly different from those of non-irradiated samples.

Boylston et al. (2002) irradiated papayas, rambutans, and Kau oranges at 0 (control) and 0.75 kGy and stored for 2 and 9 days to determine the effect of X-irradiation on sensory quality attributes. The effects of irradiation and storage on specific sensory attributes were shown to depend on the specific fruit. Aroma and flavor tended to be more intense in the irradiated fruit. The reported decrease in firmness, as a result of irradiation and storage, was significant only in rambutans. The color of the rambutans and oranges was considerably affected by irradiation.

Follett (2004) investigated the effect of irradiation and heat quarantine treatments on the external appearance of lychee (*Litchi chinensis*) and longan fruit (*Dimocarpus longan*). They found that “after 8 days of storage, lychee fruit treated with hot water immersion was rated as significantly less acceptable than untreated (control) fruit for pericarp appearance when held at 2 or 5°C. Pericarp appearance was more acceptable in irradiated fruit compared to hot water immersion fruit at both storage temperatures. In another experiment examining the rate of color loss, pericarp appearance ratings for lychee fruit treated by hot water immersion at 49°C were highest (the least desirable) on all days. Fruit treated by hot water immersion at 49°C was rated as unacceptable after 1 day of storage at 4°C, whereas irradiated and untreated fruit was rated as acceptable after 8 days storage at 4°C.

After 14 and 21 days of storage, the external appearance of Chompoo longan fruit treated by hot water immersion was rated less acceptable than the appearance of fruit treated by irradiation or left untreated. After 21 days of storage, the external appearance of Biew Kiew longan fruit treated with hot water immersion was rated significantly less acceptable than that of fruit treated with irradiation.”

Patil et al. (2004) studied both early and late season Rio Red grapefruit. Sensory qualities such as appearance and flavor of early season grapefruit exposed to irradiation treatments at or below 0.4 kGy were comparable to the control after 35 days of storage, with the exception of the 0.7-kGy treatment, which was found to be detrimental. Appearance rather than flavor of grapefruit was found to be more sensitive to irradiation. Irradiation had no significant effect on the sensory qualities of late season grapefruit.

Wang et al. (2006) sensorially evaluated Golden Empress cantaloupe juice and found that the juice developed a slight irradiation off-odor after treatment at 1 kGy and had strong off-odor at 2 kGy and higher. Therefore, the dosage should be less than 1 kGy in order to keep the off-odor within the acceptable range.

The data obtained by Bibi et al. (2006) on sensory evaluation of musk melons (*Cucumis melo*) revealed that doses of 2.5 kGy and higher can maintain the sensory qualities within acceptable limits during 7 days of storage (5°C). The firmness of irradiated sample for 2.5 and 3.0 kGy was 0.8 and 0.7 kgf, respectively, at 14 days of storage; thus, a dose of up to 2.5 kGy could preserve the texture to some extent. After radiation treatment (0.5–3.0 kGy), musk melons could not maintain their appearance and sensorial quality more than 7 days at refrigerated temperature and were discarded due to soft texture and high microbial load. Sensory evaluation of apples (*Pyrus malus*) showed that fresh non-irradiated samples had the highest score, whereas samples irradiated at 3.0 kGy and stored for 14 days (5°C) received the lowest scores. The hardness (kg-force) of apples decreased with increasing dose levels as well as storage time.

The effects of γ -irradiation at 0, 0.4, and 0.6 kGy on the texture, color, and disease incidence in mangoes were investigated by Uthairatanakij et al. (2006). The mangoes cv. Nam Dokmai and Chok Anan were harvested at the 70 and 90% stages of maturity and assessed after ripening at 25°C. Ripened Chok Anan mangoes harvested at 70 and 90% maturity were softer than untreated fruits. In contrast, ripened irradiated Nam Dokmai mangoes appeared firmer compared to untreated fruits. Polygalacturonase activity in Nam Dokmai mangoes of 90% maturity was not affected by γ -irradiation. Gamma irradiation had no effect on skin or flesh color and soluble solids content of mangoes of both cultivars harvested at both maturity stages. It was concluded that γ -irradiation at doses up to 0.6 kGy had no adverse effects on ripening of the test mangoes harvested at both maturity stages.

The sensory properties of irradiated fruits are given in Table 12.2.

TABLE 12.2 Sensory Properties of Irradiated Fruits

| Species | Irradiation Type/Dose | Temperature | Effect of Irradiation on Sensory Properties of Fruits | Reference |
|--|--|--|---|----------------------------|
| Early climacteric (breaker) cherry tomatoes (<i>Lycopersicon pimpinellifolium</i> L.) | γ irradiation/3 kGy | — | The content of 1 aminocyclopropane 1 carboxylic acid (ACC) followed the same evolution as ethylene production, whereas malonyl ACC increased steadily with time in irradiated fruits. The burst in ethylene production was accompanied by a sharp stimulation of ACC synthase activity that began 15 min after irradiation | Larrigaudière et al., 1990 |
| Three quarter ripe and fully ripe pineapple fruit (<i>Ananas comosus</i>) | γ irradiation/0.05, 0.1, and 0.15 kGy | 25–29°C with 90–97% relative humidity (RH) | Maintained their texture better than the controls | Susheela et al., 1997 |
| Mature green and pink tomato (<i>Lycopersicon esculentum</i> Mill.) fruit | γ or X ray sources/ 0.7–2.2 kGy | 10°C | Irradiation induced softening was evident in mature green and pink fruit within hours following irradiation, and differences between irradiated and control fruit persisted throughout post irradiation storage. Trends of firmness loss were much more consistent and showed much greater dose dependency on pericarp tissue than in whole fruit | Assi et al., 1997 |
| Gala apples | 0.30–0.90 kGy | — | Irradiation at doses between 0.30 and 0.90 kGy reduced apple firmness. Doses <0.30 kGy had no effect on apple firmness. Irradiation did not influence the external color of apples | Drake et al., 1999 |
| Gala, Fuji, and Granny Smith apples | 0.30–0.90 kGy | — | Irradiation at doses between 0.30 and 0.90 kGy reduced apple firmness. Doses of <0.30 kGy had no effect on apple firmness. Irradiation hardly affected the external color of apples | |
| Bosc pears | 0.30–0.90 kGy | — | Firmness loss due to irradiation, and the firmness loss was dose dependent | |

| | | | | |
|--|--|---|---|------------------------------|
| Lettuce (<i>Lactuca sativa</i>), cabbage (<i>Brassica oleracea</i>), and celery (<i>Apium graveolens</i>) | γ irradiation/0.50, 0.75, and 1.00 kGy | 5 10°C for 7 days | All control and irradiated vegetables received good overall acceptability scores, not significantly different from those of non irradiated samples. Cabbage was the most irradiation resistant | Rubio et al., 2001 |
| Early season Rio Red grapefruit | — | 10°C for 4 weeks followed by 1 week at 20°C with 90–95% RH | Sensory qualities such as appearance and flavor of early season grapefruit exposed to irradiation treatments at or below 0.4 kGy were comparable to those of the control after 35 days storage | Patil et al., 2004 |
| | γ irradiation/0.07, 0.2, and 0.4 kGy | 10°C for 4 weeks, followed by 1 week at 20°C with 90–95% RH | | |
| | γ irradiation/0.07, 0.2, 0.4, and 0.7 kGy | 10°C for 4 weeks, followed by 1 week at 20°C with 90–95% RH | Irradiation had no considerable effect on the sensory qualities of late season grapefruit | |
| Ten citrus cultivars, including the 5 orange (<i>Citrus sinensis</i> (Osbeck) cultivars—Ambersweet, Hamlin, Navel, Pineapple, and Valencia—and the 5 mandarin hybrids (<i>Citrus reticulata</i>)—Fallglo, Minneola, Murcott, Sunburst, and Temple | 0, 0.15, 0.3, and 0.45 kGy | Stored for 14 days at 1°C or 5°C plus 3 days at 20°C | Softening of Valencia, Minneola, Murcott, and Temple was dose dependent, but that of other cultivars was unaffected. The appearance of all cultivars was negatively affected by the loss of glossiness with the 0.45 kGy dose | Miller et al., 2000 |
| Papaya | γ irradiation/0.5 kGy | 22°C and 90% RH | Both irradiated and non irradiated fruits ripened normally with respect to sugar content, color change, firmness, and general appearance of the fruit | D’Innocenzo and Lajolo, 2001 |

(Continued)

TABLE 12.2 Sensory Properties of Irradiated Fruits—cont'd

| Species | Irradiation Type/Dose | Temperature | Effect of Irradiation on Sensory Properties of Fruits | Reference |
|-------------------------------------|----------------------------------|---|--|-----------------------------|
| Papayas, rambutans, and Kau oranges | 0.75 kGy | — | Aroma and flavor tended to be more intense in the irradiated fruit. Firmness decreased as a result of irradiation and storage, although it was significant only in rambutans | Boylston et al., 2002 |
| 100 random fruit samples | 1.5 kGy | Refrigeration temperature (<10°C) for 28 days | Initial viable population of fungi ranged from 4.8×10^4 to 6.8×10^5 CFU/g and decreased to 4.88×10^2 CFU/g after storage | Aziz and Moussa, 2002 |
| | 3.5 kGy | Refrigeration temperature (<10°C) for 28 days | Initial viable population of fungi ranged from 4.8×10^4 to 6.8×10^5 CFU/g and decreased to 1.39×10^1 CFU/g after storage | |
| Mangoes cv. Nam Dokmai | 0.4 and 0.6 kGy | 25°C (ripening) | Ripened irradiated Nam Dokmai mangoes appeared firmer compared to untreated fruits. Gamma irradiation had no effect on skin or flesh color | Uthairatanakij et al., 2006 |
| Mangoes cv. Chok Anan | 0.4 and 0.6 kGy | 25°C (ripening) | Ripened irradiated Chok Anan mangoes harvested at 70 and 90% maturity were softer than untreated fruits. Gamma irradiation had no effect on skin or flesh color | |
| Melons (<i>Cucumis melo</i>) | γ irradiation/2.5 kGy | 5°C for 14 days | Maintained the sensory qualities within acceptable limits | Bibi et al., 2006 |
| Apples (<i>Pyrus malus</i>) | γ irradiation/0.5–3.0 kGy | 5°C for 14 days | Hardness of apples decreased with increasing dose levels as well as during storage | |
| Golden Empress cantaloupe juice | γ irradiation/1 kGy | — | Slight irradiation off odor after treatment at 1 kGy | Wang et al., 2006 |
| Golden Empress cantaloupe juice | γ irradiation/2 kGy | — | Strong off odor at 2 kGy and higher | |

12.4 The Microflora of Irradiated Fruits

Susheela et al. (1997) found that the effect of γ -radiation at 0.05, 0.1, and 0.15 kGy and stored at 25–29°C with 90–97% RH on the three-quarter ripe and fully ripe pineapple fruit (*Ananas comosus*) was a reduced incidence of fungal infection, predominantly caused by *Ceratocystis paradoxa*.

Different doses of γ -irradiation (1–10 kGy) were used by Bidawid et al. (2000) to investigate the inactivation of hepatitis A virus (HAV) inoculated onto strawberries at ambient temperature. The number of surviving viruses at a given dose of radiation was determined with a plaque assay. Data analysis with a linear model indicated that a D_{10} value of 2.97 ± 0.18 kGy was required to achieve a 1-log reduction in HAV titer in strawberries.

Lettuce (*Lactuca sativa*), cabbage (*Brassica oleracea*), and celery (*Apium graveolens*) were artificially contaminated with *Vibrio cholerae* El Tor 01 Inaba and irradiated at 0.50, 0.75, and 1.00 kGy. Non-irradiated samples were used as controls. The effect of irradiation was measured during 7 days of storage under refrigeration (5–10°C). Irradiation proved to be an effective technique to eliminate *V. cholerae* in fresh vegetables. Doses of less than 0.75 kGy were sufficient to eliminate an initial contamination of 10^5 cells/g of *V. cholerae* (Rubio et al., 2001).

Aziz and Moussa (2002) collected and analyzed 100 random fruit samples for mycotoxins. The effect of γ -irradiation on the production of mycotoxins in fruits was also investigated. The analysis of fruits revealed the occurrence of penicillic acid, patulin, cyclopiazonic acid (CPA), citrinin, ochratoxin A, and aflatoxin B₁. Of the 100 samples examined, 60 were positive for one or more mycotoxins. Irradiation of fruits at doses of 1.5 and 3.5 kGy decreased significantly the total fungal counts compared with non-irradiated controls. After 28 days of storage at refrigeration temperature (<10°C), the total fungal counts of 1.5- and 3.5-kGy irradiated fruit samples had an average of 4.88×10^2 and 1.39×10^1 per gram, respectively, whereas the fungal counts for the non-irradiated fruit samples increased up to approximately 6.05×10^6 per gram.

Wang et al. (2006) investigated microorganism survival in Golden Empress cantaloupe juice after cobalt-60 irradiation. According to these researchers, “microorganism survival determination indicated that *Escherichia coli* was sensitive to irradiation and could be reduced by 7 log cycles at 1 kGy, whereas total colony and target spore bacteria in the juice demonstrated greater endurance to the irradiation, suggested by D_{10} values of 0.9908 and 1.1923 kGy, respectively. It was thereby concluded that it is more difficult to inactivate both total colony and target spore bacteria than *E. coli*. The study revealed that γ -irradiation cannot completely inactivate total colony and target spore bacteria in cantaloupe juice on the premise of acceptable off-odor.”

Mohacsi-Farkas et al. (2006) found that for precut cantaloupe samples (*Cucumis melo*), 1-kGy irradiation caused 2 log cycle reduction of *Listeria monocytogenes* and an approximately 5 log

cycle reduction of inoculated *E. coli* O157. 1 kGy irradiation had the same effect on precut watermelon (*Citrullus lanatus*) with initial pH of 5.5. After irradiation, the surviving cells of both pathogens examined were able to grow at 15°C, whereas *L. monocytogenes* grew even at 5°C.

The impact of irradiation on the survival of Enterobacteriaceae and *L. monocytogenes* on watermelon is shown in Figure 12.1.

Trigo et al. (2006b) investigated the effect of irradiation on blueberries (*Vaccinium* sp.). The fruits were packed in polymeric film bags and sealed. Blueberry packages were irradiated at several doses (0 up to 3 kGy at intervals of 0.5 kGy), and stored at 4°C. The shelf life of 0.5- and 1-kGy irradiated blueberries was shorter compared with that of non-irradiated fruit. Inactivation of blueberry microbial load after irradiation at the doses mentioned led to reduction by approximately 1.5 log for total counts and 5 log for coliforms.

According to Bibi et al. (2006), “the total viable count for control samples of musk melons (*Cucumis melo*) increased from 4.8×10^5 to 6.7×10^7 CFU/g after 7 days of storage at refrigeration temperature (5°C). Very few colonies were recorded in the samples irradiated at the dose of 3.0 kGy, which increased to 3.9×10^2 CFU/g after 7 days of storage. A radiation dose of 1.0 kGy completely controlled fungal growth and coliform bacteria during 7 days of storage. After 1 week, all the samples, irrespective of treatment, were spoiled and discarded. It was also found that irradiation treatments of minimally processed apple (*Pyrus malus*) lowered the bacterial load initially and by the end of the experiment, and after 14 days of storage, the total bacterial count (TBC) values increased to 3.7×10^4 , 2.6×10^3 , 8.5×10^2 , and 4.0×10^2 for 1.0-, 2.0-, 2.5-, and 3.0-kGy treated samples, respectively. Minimum TBCs were recorded for 2.5- and 3.0-kGy treated minimally processed apples. In the case of coliform and fungal load samples treated with 2.0 kGy or higher, they were found completely free of coliforms. These results suggested that to keep the minimally processed apples microbiologically acceptable,

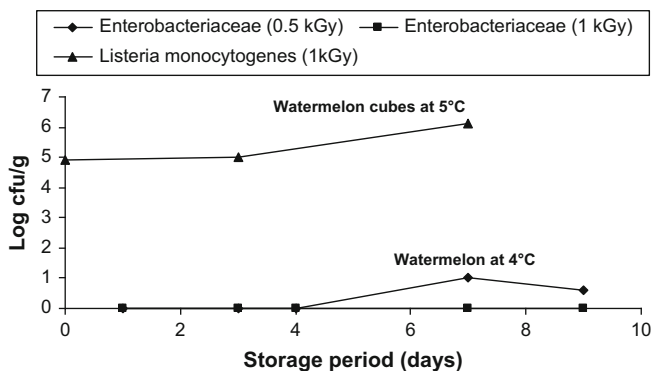


Figure 12.1: Effect of irradiation on the survival of Enterobacteriaceae and *Listeria monocytogenes* on watermelon and watermelon cubes (Mohacsi-Farkas et al., 2006; Trigo et al., 2006a).

they should be treated with a dose of 2.5 kGy. Mycotoxin production in fruits decreased with increasing irradiation dose and was not detected at 5.0 kGy.”

Pillai et al. (2006) carried out studies using poliovirus type 1 and bacteriophage MS2 to determine whether e-beam irradiation (10 MeV) could be used to inactivate these viruses on cantaloupe *Cucumis melo reticulatus* surfaces. The D_{10} values of poliovirus type 1 and MS2 bacteriophage were found to be 4.76 and 4.54 kGy, respectively.

Gamma irradiation (doses of 0.75 and 1 kGy) reduced the lesion size caused by *Colletotrichum gloeosporioides* and anthracnose incidence in papaya fruit (*Carica papaya*) when applied after fruit inoculation, but it did not protect the fruit when applied 24, 48, or 72 h before inoculation. These doses inhibited *C. gloeosporioides* conidial germination and mycelial growth but stimulated fungal sporulation. The fruits were stored at 25°C/80% RH for 7 days (Cia et al., 2007).

The effect of irradiation (type/dose) on fruit microflora is given in Table 12.3.

12.5 Irradiation and Hurdle Technology of Fruits

El-Samahy et al. (2000) reported that irradiation treatments (0.5, 0.75, 1.0, and 1.5 kGy) in conjunction with hot water dipping (55°C/5 min) initiated a significant decrease in firmness values of mango fruits (*Mangifera indica* L.), variety Zebda, either at zero time or during the storage ($12 \pm 1^\circ\text{C}$ and 80–85% RH). This decline in firmness was directly proportional to the radiation dose. The results clearly indicated that samples irradiated up to 1.0 kGy were acceptable organoleptically until 50 days of storage at 12°C. After 60 days, mangoes were overripe with a buttery texture. Phenolic compounds and total content of carotenoids in mango significantly increased when the latter was subjected to irradiation. The increase in phenolic compounds was directly proportional to the radiation dose used. Irradiation at 0.5–1.5 kGy caused a slight loss of vitamin C due to oxidation of ascorbic acid. A substantial reduction in acidity was recorded in all treatments with prolongation of storage time. However, the percentage decrease in non-irradiated samples was higher than that in irradiated samples.

Figure 12.2 displays the effect of irradiation (1 kGy) on total carotenoid content of mango fruits and coriander leaves.

Drake et al. (2003) exposed commercially packed Fuji and Granny Smith apples and Anjou and Bosc pears to γ -irradiation treatments at doses of 150, 300, 600, and 900 Gy. After irradiation, apples were stored for 30, 60, and 90 days and pears were stored for 30 and 90 days in ambient atmosphere at 1°C. Irradiation treatment did not affect the total carbohydrate or individual sucrose, glucose, fructose, or sorbitol concentrations in either apples or pears, regardless of the cultivar. Carbohydrate concentrations were altered in both apples and pears as storage time progressed, and these changes were shown to be cultivar dependent. Total carbohydrates and

TABLE 12.3 The Effect of Irradiation on Fruit Microflora

| Species | Irradiation Type/Dose | Temperature | Irradiation Effect on Microflora | Reference |
|---|-------------------------------------|---|--|-----------------------------|
| Strawberries | γ irradiation/ 1–10 kGy | Ambient temperature | D_{10} value of 2.97 ± 0.18 kGy was required to achieve a 1 log reduction in HAV titer | Bidawid et al., 2000 |
| Lettuce (<i>Lactuca sativa</i>), cabbage (<i>Brassica oleracea</i>), and celery (<i>Apium graveolens</i>) | γ irradiation/ 0.75 kGy | 5–10°C for 7 days | Elimination of an initial contamination of 10^5 cells/g of <i>V. cholerae</i> | Rubio et al., 2001 |
| Cantaloupe (<i>Cucumis melo reticulatus</i>) | e beam irradiation/ 4.76 kGy | — | D_{10} values of poliovirus type 1 | Pillai et al., 2006 |
| | e beam irradiation/ 4.54 kGy | — | D_{10} values of MS2 bacteriophage | |
| Melons (<i>Cucumis melo</i>) | 3 kGy | 5°C | Very few colonies remained Complete control of fungal growth and coliform bacteria during 7 days of storage | Bibi et al., 2006 |
| | 1 kGy | 5°C | | |
| Apple (<i>Pyrus malus</i>) | 2.0 kGy | 5°C | Complete control of fungal growth and coliform bacteria during 7 days of storage | |
| Cantaloupe | 1 kGy | 5°C | 2 log cycle reduction of <i>L. monocytogenes</i> . 5 log cycle reduction of inoculated <i>E. coli</i> O157 | Mohacsi Farkas et al., 2006 |
| Golden Empress cantaloupe juice | 1 kGy | — | <i>E. coli</i> was reduced by 7 log cycles, whereas total colony and target spore bacteria in the juice had greater endurance to the irradiation, suggested by D_{10} values of 0.9908 and 1.1923 kGy, respectively | Wang et al., 2006 |
| Papaya fruit | γ irradiation/0.75 and 1 kGy | Stored at 25°C/ 80% RH for 7 days | There was a reduced lesion size due to <i>Colletotrichum gloeosporioides</i> and anthracnose incidence in papaya fruit (<i>Carica papaya</i>) when applied after fruit inoculation. These doses inhibited <i>C. gloeosporioides</i> conidial germination and mycelial growth but stimulated fungal sporulation | Cia et al., 2007 |

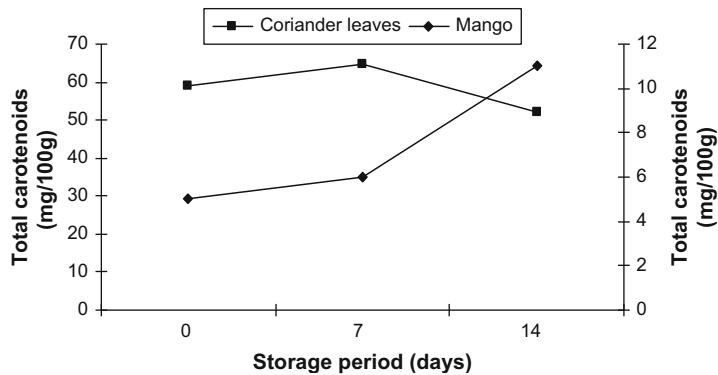


Figure 12.2: Effect of irradiation (1 kGy) on total carotenoid content of mango fruit (*Mangifera indica*) variety Zebda and coriander leaves (*Coriandrum sativum*) (El-Samahy et al., 2000; Kamat et al., 2003).

glucose, fructose, and sorbitol concentrations increased, whereas sucrose decreased, in apples as storage progressed. Total carbohydrates and fructose increased whereas sucrose, glucose, and sorbitol concentrations decreased in Anjou pears with storage time. Total and individual carbohydrate concentrations decreased in Bosc pears as storage progressed from 30 to 90 days.

Janave and Sharma (2005) reported that “low-dose γ -irradiation of preclimacteric mango (*Mangifera indica* L. var. Alphonso) fruits at 100 Gy extended the shelf life at ambient temperature (28–32°C) by 5 or 6 days. The extension of shelf life was dose dependent, with a maximum extension of approximately 8–10 days at 200 Gy. Wrapping the fruits in food-grade Klin Wrap film resulted in a greater number of fruits remaining in semi-ripe condition after 21 days of storage. The physiological weight loss was reduced by 50% in Klin film-wrapped fruits compared to that in unwrapped fruits. More than 70–80% of fruits remained as marketable fruits at the end of the experiment, whereas control fruits were slightly overripe. The shelf life of Klin film-wrapped irradiated mangoes was extended by approximately 10–15 days over irradiated unwrapped fruits, resulting in a total shelf life of approximately 25–30 days at room temperature. In mangoes of variety Dasherri, γ -irradiation extended the shelf life by 4 or 5 days, which could be extended another 7–10 days by use of Klin wrap packaging.”

The synergic effects of calcium ascorbate (CaA) and ionizing radiation on the quality of Gala apple slices under MAP were investigated by Fan et al. (2005). Gala apple slices, treated with water or 7% CaA followed by either non-irradiation (0 kGy) or irradiation at 0.5 and 1.0 kGy, were stored at 10°C for up to 3 weeks. Irradiation did not affect titratable acidity and pH of sliced apples. Fruit slices softened during irradiation and storage, but this decrease in firmness during storage was reduced by the CaA treatment. Although the ascorbic acid content of apple slices treated with CaA decreased rapidly during storage, it was always higher in CaA-treated samples than in the apple slices treated with water. Irradiation decreased both L^* and hue

values of apple slices. CaA increased L^* and hue values of apple slices, suggesting that CaA reduced browning, even in irradiated samples. The combination of CaA and irradiation enhanced the microbial food safety while maintaining the quality of fresh-cut apple slices.

The results reported by Faridah et al. (2006) showed that both *L. monocytogenes* and *E. coli* O157 have different D_{10} values in different fruits, aerobically packaged and stored at $5 \pm 2^\circ\text{C}$, when irradiated with γ -rays. *Listeria monocytogenes* is proven to be more radiation resistant than *E. coli* O157. D_{10} values of *L. monocytogenes* were 0.15 kGy in pineapple (*Ananas comosus*) and 0.4 kGy in jackfruit (*Artocarpus heterophyllus*). D_{10} values of *E. coli* O157 were considerably lower—0.08 kGy in pineapple, 0.16 kGy in jackfruit, and 0.14 kGy in mixed fruit (pineapple and guava). Moreover, irradiation with 0.5–3 kGy induced a 1–3 log cycle reduction in the aerobic plate count of these fruits. Moreover, after 3 days of storage, panelists gave the highest score to the irradiated pineapple (1.5 kGy), and on Day 8 of storage the highest score was shared by the non-irradiated and irradiated sample.

The irradiation (0.5 and 1 kGy) of watermelon (*Citrullus lanatus*) caused a microbial reduction of 1 or 2 log in the total aerobic mesophilic counts and total aerobic psychrotrophic counts. The color was slightly darker after irradiation (Day 1), but this difference lessened with storage time prolongation. Sensorial results of irradiated and non-irradiated watermelon also indicated an extended shelf life for irradiated watermelon at 0.5 kGy (up to 9 days) compared with non-irradiated watermelon (4 days). The watermelon irradiated at 1 kGy exhibited a shorter shelf life (3 days). Furthermore, for melon (*Cucumis melo*), the irradiation (0.5 and 1 kGy) caused a microbial reduction of 1 or 2 log in the total aerobic mesophilic counts and total aerobic psychrotrophic counts. Irradiated melon at 0.5 and 1 kGy displayed similar shelf life (9 days) to that of non-irradiated ones. All fruit samples were packed in a Nutrip-PS (polystyrene) tray and then in polymeric film bags and stored at 4°C (Trigo et al., 2006b).

Moreno et al. (2007) reported that no significant weight losses were induced to packaged fresh blueberries (*Vaccinium corymbosum* L.) by e-beam irradiation (1.1, 1.6, and 3.2 kGy). Moisture content and water activity of the fruits ranged between 79.6 and 81.8 g/100 g and 0.87 and 0.92, respectively. These results indicated that exposure of blueberries to irradiation up to 3.2 kGy did not affect the juiciness of the fruits. Irradiating the blueberries up to 3.2 kGy did not affect their pH, and the fruits had acceptable acidity levels that remained unchanged throughout storage time (at 5°C and 70.4% RH for 14 days). Only irradiation at doses higher than 1.6 kGy induced undesirable texture changes (i.e., softening) in the fruits.

Pimentel et al. (2007) “evaluated the quality of papaya submitted to irradiation and heat shock treatment through immersion in hot water. Green papayas were submitted to the following treatments: (a) control, (b) 0.25 kGy, (c) 0.5 kGy, (d) heat shock (60°C for 30 s), (e) 0.25 kGy and heat shock, and (f) 0.5 kGy and heat shock. The papayas were stored at $21 \pm 1^\circ\text{C}$ and 85–90% RH, and after 8 days they were evaluated by their soluble solid content, pH, titratable acidity, firmness, decay index, and internal color. The analyses of fresh matter loss and external

color were carried out at 0, 2, 4, and 7 days after irradiation. It was observed that in treatments submitted to hot water (d–f) decay was controlled, and in combined treatments (e and f) higher firmness was verified. On the second day, irradiated treatments (b, c, e, and f) were more yellow than the others.”

Palou et al. (2007) investigated the effects of the combination of sodium carbonate (SC) (dips at 20°C for 150 s in aqueous 3% SC solutions) treatments and X-ray irradiation (at doses of 0.510 and 0.875 kGy) on artificially inoculated *Clemenules clementine* mandarins for the control of postharvest green and blue molds, caused by *Penicillium digitatum* and *Penicillium italicum*, respectively. X-ray irradiation at 0.195, 0.395, 0.510, and 0.875 kGy did not affect either decay incidence or the area under the disease progress curve of lesions of green and blue molds on mandarins inoculated with the pathogens 2, 3, or 6 days after irradiation and incubated for 7 days at 20°C. X-ray irradiation at doses up to 0.875 kGy followed by either 14 days of storage at 20°C or 60 days of storage at 5°C caused very slight rind pitting, minor decreases in fruit firmness, and modest increases in juice acetaldehyde and ethanol contents, with no impact on fruit quality.

The quality of γ -irradiated (0.1–0.5 kGy) Ambri, Golden Delicious, and Royal Delicious apples stored under ambient ($15 \pm 2^\circ\text{C}$) and refrigerated ($3 \pm 1^\circ\text{C}$) conditions was investigated by Hussain et al. (2008). The irradiation doses of 0.2, 0.3, and 0.5 kGy proved beneficial to maintaining the overall quality of all three varieties of apple under both storage conditions. Gamma irradiation significantly reduced the yeast and mold counts of apples under storage.

Blueberries packed in plastic clamshell containers (trays) were irradiated at medium doses (1.0–3.2 kGy) using a 10-MeV linear accelerator. Irradiation of blueberries at 1.1 kGy had no significant effect on the fruit quality with the exception of ascorbic acid. Compared with the control, a reduction ($\sim 28.15\%$) of ascorbic acid was recorded by Day 3 in all irradiated samples. By Day 14, the samples treated with low (1.1 kGy) and medium (1.6 kGy) doses had the highest ascorbic acid concentrations, whereas the samples treated with the high dose (3.2 kGy) had the lowest ascorbic acid content. The total phenolics content in irradiated blueberries was higher than that in non-irradiated control, with concentrations significantly higher in samples irradiated at 1.6 kGy immediately after irradiation (Day 0). On Day 3, the samples exposed to low (1.1 kGy) and medium (1.6 kGy) doses had the higher concentrations (Moreno et al., 2008).

The impact of irradiation in conjunction with hurdle technology on shelf life and the sensory and physical properties of fruits are given in Table 12.4.

12.6 Quality and Shelf Life Extension of Irradiated Vegetables

Fan and Sokorai (2005) assessed radiation sensitivity of fresh-cut vegetables using electrolyte leakage measurement. Fresh-cut vegetables were γ -irradiated at doses up to 3 kGy at 0.5-kGy intervals. Electrolyte leakage increased linearly with higher radiation dose for all vegetables. Red cabbage, broccoli, and endive had the highest radiation resistance, whereas celery, carrot, and green onion were the most sensitive to radiation. The radiation sensitivity was not necessarily correlated with endogenous antioxidant capacity or phenolics content of the vegetables, which displayed large variation among the test samples.

Song et al. (2006) investigated carrot and kale juice during a 3-day storage period (10°C). They reported that the total phenolic contents of both vegetable juices were significantly higher in the irradiated (3 kGy) samples than in the non-irradiated control. The antioxidant capacity of the irradiated carrot juice was higher than that of the non-irradiated control. On the other hand, during the storage period, the antioxidant capacity decreased despite an increase in the phenolic content of the kale juice.

Wang and Du (2005) found that vitamin C content and rehydration ratio of dried potato were greatly affected by irradiation dose (2, 4, 5, 6, 8, or 10 kGy). They claimed that the greater the dose, the lower the vitamin C content and the rehydration ratio.

The effects of cooking followed by irradiation (10 kGy) on vitamins B₁ and C, and the anti-nutritional factors phytic acid and nitrates, in a ready-to-eat meal of sorghum porridge and spinach-based relish were investigated by Duodu et al. (1999). Cooking reduced vitamin B₁ and C contents of the spinach relish, and irradiation caused further losses. Cooking did not alter vitamin B₁ content (0.28 mg/g) of the sorghum porridge, but irradiation decreased it drastically (0.04 mg/g). Cooking did not decrease phytic acid in the sorghum porridge, whereas irradiation caused a significant decrease.

According to Mohacsi-Farkas et al. (2006), a radiation dose of 1 kGy had no significant effect on total carotenoid and vitamin C content of sliced tomatoes (*Lycopersicon* syn. *L. esculentum*). However, this dose caused an approximately 40% decrease in α -tocopherol.

Bandekar et al. (2006) studied the effect of radiation processing on vitamin C, total carotenoids, texture, and organoleptic properties of carrot and cucumber. No significant difference in the vitamin C content and total carotenoids in the radiation processed (1 and 2 kGy) samples and control samples was reported. Variation in the content of vitamin C and carotenoids during storage was not statistically significant from the control samples. The trained test panel could not differentiate between irradiated and non-irradiated samples.

No substantial effect of irradiation on sugar content of onions has been observed (Diehl, 1977; Guma and Rivetti, 1970; Thomas et al., 1986). Furthermore, gas chromatography of silylated extracts displayed no changes in the levels of glucose, fructose, or malic acid in four onion

TABLE 12.4 The Effect of Irradiation and Hurdle Technology on Shelf Life and Sensory and Physical Properties of Fruits

| Species | Irradiation Type/Dose | Other Technology | Temperature | Shelf Life | Sensory Properties | Irradiation Effect | Reference |
|--|---|--|--|--------------------------------|---|--|------------------------|
| Mango fruits (<i>Mangifera indica</i> L.) variety Zebda | — γ irradiation/ 0.5, 0.75, 1.0, and 1.5 kGy | Hot water dipping (55°C/5 min) Hot water dipping (55°C/5 min) | 12 ± 1°C and 80–85% relative humidity (RH) 12 ± 1°C and 80–85% RH | 25 days 50 days (1 kGy) | — The results clearly indicated that samples irradiated up to 1.0 kGy were acceptable organoleptically until 50 days of storage at 12°C. | Phenolic compounds and total content of carotenoids in mango were significantly increased by exposure to irradiation. Irradiation caused a slight loss of vitamin C. Significant reduction in acidity was recorded in all treatments as storage time lengthened. Irradiation treatments caused additional significant reductions in total bacterial counts | El Samahy et al., 2000 |
| Fuji and Granny Smith apples | 150, 300, 600, and 900 Gy | Commercially packed | 1°C | — | — | Irradiation treatment did not influence the total carbohydrate or individual sucrose, glucose, fructose, or sorbitol concentrations | Drake et al., 2003 |
| Anjou and Bosc pears | γ irradiation/ 150, 300, 600, and 900 Gy | Commercially packed | 1°C | — | — | | |

(Continued)

TABLE 12.4 The Effect of Irradiation and Hurdle Technology on Shelf Life and Sensory and Physical Properties of Fruits—cont'd

| Species | Irradiation Type/Dose | Other Technology | Temperature | Shelf Life | Sensory Properties | Irradiation Effect | Reference |
|---|-----------------------|--|------------------------|--|--|---|---------------------|
| Watermelon (<i>Citrullus lanatus</i>) | 0.5 and 1 kGy | Packed in a Nutrip PS (polystyrene) tray and then in polymeric film bags | 4°C | 9 days for 0.5 kGy (4 days for control and 3 days for 1 kGy) | The color was slightly darker after irradiation (1st day); nevertheless, this difference lessened with storage time. Texture results indicated no detectable differences after irradiation | 1 or 2 log reduction in the total aerobic mesophilic counts and total aerobic psychrotrophic counts | Trigo et al., 2006a |
| Melon (<i>Cucumis melo</i>) | 0.5 and 1 kGy | Packed in a Nutrip PS (polystyrene) tray and then in polymeric film bags | 4°C | 9 days similar to control | Color and texture results indicated no detectable differences after irradiation, along storage time | 1 or 2 log reduction in the total aerobic mesophilic counts and total aerobic psychrotrophic counts | |
| Gala apple slices | — | 7% CaA | 10°C for up to 3 weeks | — | — | The microflora population of apple slices was not affected by CaA | Fan et al., 2005 |
| | 0.5 and 1.0 kGy | 7% CaA | 10°C for up to 3 weeks | — | Irradiation decreased both L^* and hue values of apple slices. CaA increased L^* and hue values of apple slices, suggesting CaA reduced browning, even in irradiated samples | Irradiation did not affect titratable acidity and pH of sliced apples. Fruit slices softened during irradiation and storage, but this decrease in firmness during storage was reduced by the CaA treatment. The combination of CaA and irradiation enhanced microbial food safety | |

| | | | | | | | |
|---|--|--|------------------------------|-----------------|--|---|----------------------|
| Jackfruit (<i>Artocarpus hetero-phyllus</i>) | 0.4 kGy | Aerobically packaged | 5 ± 2°C | At least 8 days | — | <i>L. monocytogenes</i> ($D_{10} = 0.4$ kGy) | Faridah et al., 2006 |
| | 0.16 kGy | | 5 ± 2°C | At least 8 days | — | <i>E. coli</i> O157 ($D_{10} = 0.16$ kGy) | |
| Pineapple (<i>Ananas comosus</i>) | 0.15 kGy | | 5 ± 2°C | At least 8 days | — | <i>L. monocytogenes</i> ($D_{10} = 0.15$ kGy) | |
| | 0.08 kGy | | 5 ± 2°C | At least 8 days | — | <i>E. coli</i> O157 ($D_{10} = 0.08$ kGy) | |
| Mixed fruit (pineapple and guava [<i>Psidium guajava</i>]) | 0.14 kGy | | 5 ± 2°C | At least 8 days | — | <i>E. coli</i> O157 ($D_{10} = 0.14$ kGy) | |
| Fresh blueberries (<i>Vaccinium corymbosum</i> L.) | Gamma beam irradiation/ 1.1, 1.6, and 3.2 kGy | Packaged (trays consisted of plastic clamshell containers) | 5°C and 70.4% RH for 14 days | — | Only irradiation at doses greater than 1.6 kGy induced undesirable texture changes (i.e., softening) in the fruits. Blueberries exposed up to 1.6 kGy dose were found acceptable by the panelists in terms of overall quality, color, texture, and aroma | Exposure of blueberries to irradiation up to 3.2 kGy does not affect the juiciness of the fruits. Irradiating the blueberries up to 3.2 kGy did not affect their pH, and the fruits had acceptable acidity levels that remained unchanged throughout storage time | Moreno et al., 2007 |

(Continued)

TABLE 12.4 The Effect of Irradiation and Hurdle Technology on Shelf Life and Sensory and Physical Properties of Fruits—cont'd

| Species | Irradiation Type/Dose | Other Technology | Temperature | Shelf Life | Sensory Properties | Irradiation Effect | Reference |
|--|---|---|---|------------|---|--|----------------------|
| Clementine mandarins | γ and X ray irradiation/ 0.510 and 0.875 kGy | Sodium carbonate (SC) (dips at 20°C for 150 s in aqueous 3% SC solutions) | 14 days at 20°C or 60 days at 5°C | — | X ray irradiation at doses up to 0.875 kGy followed by either 14 days at 20°C or 60 days at 5°C caused very slight rind pitting and minor decreases in fruit firmness | X ray irradiation at 0.195, 0.395, 0.510, and 0.875 kGy did not influence either decay incidence or the area under the disease progress curve of lesions of green and blue molds on mandarins inoculated with <i>Penicillium digitatum</i> and <i>Penicillium italicum</i> . Rind color, titratable acidity, soluble solids concentration, maturity index, and juice yield were not influenced by irradiation | Palou et al., 2007 |
| Apple varieties Ambri, Golden Delicious, and Royal Delicious | γ irradiation/ 0.1 0.5 kGy | Refrigerated storage | Ambient (15 \pm 2°C) and refrigerated (3 \pm 1°C) | — | The irradiation doses of 0.2, 0.3, and 0.5 kGy proved beneficial in maintaining the overall quality of all three varieties of apple under both storage conditions | Irradiation significantly reduced the yeast and mold counts of apples under storage | Hussain et al., 2008 |
| Blueberries | e beam irradiation/ 1.0 3.2 kGy | Packed in plastic clamshell containers | 5 \pm 1°C and 70.4% RH | 14 days | — | A reduction (\sim 28.15%) of ascorbic acid was recorded by Day 3 in all irradiated samples. The total phenolic content in irradiated blueberries was higher than that in non irradiated control, with concentrations significantly higher in samples irradiated at 1.6 kGy immediately after irradiation (Day 0). At Day 3, the samples exposed to low (1.1 kGy) and medium (1.6 kGy) doses had the higher concentrations | Moreno et al., 2008 |

cultivars grown in Germany when irradiated with 10 MeV electrons at doses of 0.05 or 0.10 kGy and stored at 10 or 20°C. Sucrose level was approximately 2.2% of fresh weight at the beginning of the storage period and declined to 1.5% in irradiated as well as non-irradiated bulbs (Diehl, 1977; Grunewald, 1978). Similarly, doses of 0.05–0.5 kGy had no appreciable effect on the total free sugar content (sucrose, glucose, and fructose) in onion bulbs of 11 cultivars produced in different locations in Japan, although sucrose content seemed to slightly increase by irradiation (Nishibori and Namiki, 1982). The vitamin C content in three onion cultivars grown in Israel following irradiation to 0.07 kGy and 5 months of storage at ambient temperature was essentially the same as that in non-irradiated controls (Molco and Padova, 1969).

An increase in ascorbic acid content with increasing dose from 0.03 to 0.18 kGy was observed in a study by Nandpuri et al. (1969), whereas Salems (1974) reported an 18% reduction of ascorbic acid by 0.08-kGy irradiation. In a study on onion cultivars of Hungary, no significant differences in the vitamin C content of irradiated and non-irradiated samples were observed during a 10-month storage period, and the vitamin C content of irradiated samples seemed not to be influenced by the time of irradiation after harvest (Mahmoud et al., 1978). On the contrary, Guo et al. (1981) reported a drastic reduction in vitamin C content of onions immediately after irradiation at 0.1–0.5 kGy. However, the decrease in vitamin C during the remaining 8 months of storage was much lower in irradiated than in control onions.

Regarding potatoes, there have been many results reported in the literature on the effect of irradiation on sugar content of potatoes during storage. In Danish potato cultivars irradiated in the range 0.04 and 0.16 kGy, sucrose and glucose increased while fructose decreased. These changes were reversible and disappeared after storage for some months at 5°C (Jaarma, 1958). Pre-storage of potatoes for 4 weeks at 2–15.5°C prior to irradiation to 0.1 kGy affected the sugar content during post-irradiation storage. Pre-irradiation storage of tubers showed a marked temporary increase in sucrose, reaching a maximum after 3–7 days before decreasing to a level that was still higher than that of non-irradiated tubers. Tubers stored at 2°C exhibited an immediate decrease in sucrose after irradiation, followed within 3 days by a rise to values not significantly different from those of the controls (Burton, 1975). Moreover, in potato cultivars grown in the United Kingdom, a marked increase was observed in sucrose in tubers irradiated with 0.1 kGy and stored at 10°C. The maximum content was reached 5 days after irradiation, and afterwards decreased. It is remarkable that 26 days after irradiation, the sucrose content remained the same as that in non-irradiated tubers (Burton et al., 1959).

A comparison of sugar changes in 0.1 kGy-treated potatoes during storage at 14°C and in non-irradiated potatoes at 4 or 5°C for 6 months of storage showed a 50% lower content of reducing and total sugars as well as a 15% greater starch content in the irradiated tubers than in controls (Eisenberg et al., 1971). A similar study with several Indian potato cultivars revealed that sugar

accumulation in non-irradiated tubers stored at 2–4°C progressed at a more rapid rate than in irradiated tubers at 15°C during a 6-month storage period (Joshi et al., 1990).

Adesuyi and Mackenzie (1973) reported that in yam tubers (*Dioscorea rotundata*), starch levels were almost identical in control and 0.15-kGy treated tubers after a storage period of 5 months under normal conditions (25–37°C, 50–85% RH). A decrease in starch level was recorded in tubers irradiated to 0.1 and 0.125 kGy, but those exposed to 0.025, 0.05, and 0.075 kGy displayed higher starch content than the 0.1- and 0.125-kGy treated samples.

Several researchers have studied the stability of vitamin C in potatoes irradiated for sprout inhibition purposes. Irradiation with 0.07–1.0 kGy, 2 weeks after harvest, had no effect on vitamin C (Metlitsky et al., 1968). In another study, no immediate change in vitamin C content was observed after exposure to 0.1–1.0 kGy, whereas after 1 week the levels decreased in proportion to increasing dose (Gounelle et al., 1968). An immediate oxidation of vitamin C was observed following irradiation at 0.1 kGy, but the difference in content between irradiated and non-irradiated tubers disappeared with prolonged storage (Salkova, 1957).

In South African potato cultivars, no detrimental effect on ascorbic acid was reported after their exposure up to 0.15 kGy during 16 weeks of storage (Winchester and Visser, 1975). Potatoes treated with X-rays to doses up to 0.09 kGy exhibited no effect on ascorbic acid, but at 0.135 kGy a significant reduction occurred (Berger and Hansen, 1962).

Studies of several Indian potato cultivars showed that ascorbic acid levels decreased during the initial period of storage following irradiation with 0.1 kGy, regardless of the cultivar, when stored either at tropical ambient temperatures or at 15°C. However, on prolonged storage, ascorbic acid levels were equal to or even higher than those of control samples. Irradiated tubers stored at 15°C recorded higher levels of ascorbic acid compared to controls stored at 2–4°C for identical periods (Joshi et al., 1990; Thomas, 1984). Studies on nine Indian potato cultivars indicated that irradiation at 0.1 kGy resulted in decreased levels of carotenoids in the tuber flesh, particularly at 15°C, where 50% reduction in its content occurred after 6 months of storage. A partial recovery of the carotenoid content occurred when such tubers were reconditioned at 34 or 35°C for 6–12 days (Janave and Thomas, 1979). In the Indian potato cultivar, aspartic acid, asparagine, threonine, serine, alanine, isoleucine, leucine, lysine, and arginine displayed increases 24 h after irradiation at 0.1 kGy, whereas glutamic acid, proline, methionine, and phenylalanine decreased. Lysine content displayed a sixfold increase after 1 week of storage, and at 1 month the concentration was still three times higher than the control values (Ussuf and Nair, 1972).

Exposure of potatoes to doses of 0.07–0.1 kGy 2 weeks after harvesting or later did not appreciably affect the nitrogenous substances except during the initial storage period, when some of the nonprotein nitrogen increased at the expense of decomposition of protein nitrogen. With

prolonged storage, protein nitrogen and nonprotein nitrogen were found to be equal in irradiated and control tubers (Metlitsky et al., 1968).

Although irradiation at 0.1 kGy had no effect on the total sulfur and thiosulfonate content of garlic bulbs during storage at $3 \pm 1^\circ\text{C}$ and $80 \pm 5\%$ RH for 10 months, the contents of both components exhibited a significant reduction in control and irradiated after 6–8 months of storage compared to initial values (Kwon et al., 1989). Similarly, no appreciable changes were detected in either gas liquid chromatograms or visible and infrared spectrographs of ether extracts of garlic bulb cv. Red irradiated with 0.05 kGy and stored in a commercial warehouse ($6\text{--}32^\circ\text{C}$, $58\text{--}86\%$ RH) for 6 months (Curzio and Ceci, 1984).

A Canadian study revealed that total weight loss due to sprouting and shrinkage of onion bulbs irradiated with 0.06 and 0.076 kGy was 5.7% compared to 23.2% for the non-irradiated bulbs after 5 months of storage at 12.8°C (Anonymous, 1962). In the Valenciana Sintética 14 cultivar grown in Argentina, the weight loss at the end of a 270-day test storage in a commercial warehouse ($6\text{--}32^\circ\text{C}$, $50\text{--}90\%$ RH) was 43.3% in the control compared to only 22.8% in the 0.03-kGy treated samples (Curzio and Croci, 1983).

In a pilot-scale study conducted in India, weight loss due to dehydration after 4.5 months of storage at ambient temperature under commercial conditions ($23\text{--}32^\circ\text{C}$, $60\text{--}80\%$ RH) was 15.2% in irradiated (0.06 kGy) samples compared to 27.7% in non-irradiated bulbs (Thomas et al., 1986). In the garlic bulb cv. Red, the weight losses amounted to 55 and 24% in the control and irradiated (0.03 kGy), respectively, after 300 days of storage at $6\text{--}32^\circ\text{C}$ and $58\text{--}86\%$ RH (Croci and Curzio, 1983).

In three Japanese potato cultivars, the weight loss during storage at room temperature was reduced by 0.07 and 0.15 kGy but not during storage at 5°C (Umeda et al., 1969a,b). A commercial-scale study involving five Japanese cultivars under varying storage regimes confirmed that irradiation prevented weight loss compared to that of non-irradiated potatoes, especially at 7°C storage (Matsuyama and Umeda, 1983; Umeda, 1978).

In a semicommercial experiment with two potato cultivars, the weight loss during 6 months of storage at 20°C varied from 28 to 51% in non-irradiated compared to 17–40% in samples irradiated at 0.1 kGy (Khan et al., 1986). A progressive reduction in weight loss in yams (*Dioscorea rotundata*) was reported with increasing doses from 0.025 to 0.15 kGy after 5 months of storage in a yam barn ($25\text{--}37^\circ\text{C}$, $50\text{--}85\%$ RH), with the loss being 39.7% in controls compared to only 17.7% in 0.15-kGy irradiated (Adesuyi and Mackenzie, 1973). A dose between 0.05 and 0.20 kGy caused more than 50% reduction in weight loss in nine yam cultivars grown in Nigeria in comparison to controls (Adesuyi, 1976, 1978).

Table 12.5 summarizes the quality characteristics and shelf life extension of irradiated vegetables.

12.7 Sensory Properties of Irradiated Vegetables

Irradiation at doses of 0.06–0.5 kGy neither affected the skin color nor influenced the rate of fading of bulb color during 3 months of storage at ambient temperatures (25–30°C) in the cultivar Nashik Red Globe, as evidenced by their anthocyanin content (Bandyopadhyay et al., 1973). Similar observations were reported for cultivar Giza-6 exposed to 0.06 kGy (Salems, 1974). Studies employing gas liquid chromatography, thin-layer chromatography, infrared spectroscopy, and sensory tests of head space gases showed no changes in the flavor components of Red Globe onions irradiated with doses of 0.06, 0.1, 0.2, and 0.5 kGy and stored at ambient temperature (25–30°C) up to 3 months (Bandyopadhyay et al., 1973). Moreover, no appreciable differences were reported in the pungency and flavor strength in irradiated (0.06 kGy) onions under commercial conditions (Thomas et al., 1986).

Enzymic pyruvate, closely related to flavor development in crushed garlic, increased in both control and irradiated bulbs during storage, and the average values were higher in irradiated bulbs (Ceci et al., 1991). At 20°C, radiation doses sufficient to achieve a 5-log₁₀ kill (3.9–4.6 kGy) caused significant softening of peas and broccoli stems but not of corn or lima beans. Lower doses of comparable antimicrobial efficacy delivered at 5°C (2.5–3.1 kGy) did not lead to significant changes in texture in any of the studied vegetables. Color varied significantly among the dose–temperature combinations only for broccoli florets; this variation did not demonstrate a clear pattern of quality changes in response to irradiation (Niemira et al., 2002).

Minaar et al. (2002) studied the effect of irradiation (0, 10, 20, and 30 kGy at 5°C) on the consumer acceptability of a traditional South African ready-to-eat (RTE) meal consisting of spinach (morogo) and sorghum porridge. The two components of the meal remained acceptable up to a dose of 10 kGy. The limiting factor for using higher doses was the porridge component, especially in terms of texture (too soft) and taste (off-flavor development). Therefore, the use of irradiation at 10 kGy in combination with different levels of sodium nitrite was proposed to improve the storability of the RTE meal.

Bari et al. (2005) reported that the appearance, color, texture, taste, and overall acceptability of broccoli and mung bean sprouts, irradiated at 1.0 kGy, did not undergo significant changes after 7 days of post-irradiation storage at 4°C in comparison with control samples.

The *L** color values of dried potato were greatly affected by irradiation dose (2, 4, 5, 6, 8, or 10 kGy), according to Wang and Du (2005). The *L** values of the dried product under low-dose irradiation were greater than those for non-irradiation, and at higher than 6 kGy, the higher the dose, the lower the value.

Segsarnviriyaya et al. (2005) conducted a sensory test in which overall appearance, color, odor, taste, texture, and overall quality were scored by trained panelists on each vegetable at 1, 4, and

TABLE 12.5 Quality and Shelf Life Extension of Irradiated Vegetables

| Species | Irradiation Type/ Dose | Temperature | Quality | Reference |
|--|---------------------------|--|--|-----------------------------|
| Potatoes | 0.1 kGy | 10°C | Significant increase in sucrose. Maximum content was reached 5 days after irradiation, after which it decreased; 26 days after irradiation it was approximately the same as in non irradiated tubers | Burton et al., 1959 |
| Onion bulbs | — | 12.8°C for 5 months | Weight loss due to sprouting and shrinkage of onion bulbs was 23.2% | Anonymous, 1962 |
| | 0.06 and 0.076 kGy | 12.8°C for 5 months | Weight loss due to sprouting and shrinkage of onion bulbs was 5.7% | |
| Japanese potato cultivars | 0.07 and 0.15 kGy | Room temperature | Weight loss | Umeda et al., 1969a,b |
| | | 5°C | No weight loss | |
| Potato | 0.1 kGy | — | Aspartic acid, asparagine, threonine, serine, alanine, isoleucine, leucine, lysine, and arginine showed increases 24 h after irradiation, whereas glutamic acid, proline, methionine, and phenylalanine decreased | Ussuf and Nair, 1972 |
| Yam tubers (<i>Dioscorea rotundata</i>) | — | 25–37°C, 50–85% relative humidity (RH) | No appreciable change in starch levels | Adesuyi and Mackenzie, 1973 |
| | 0.15 kGy | 25–37°C, 50–85% RH | | |
| Potatoes | 0.1 kGy | 15°C | Decreased levels of carotenoids in the tuber flesh, particularly at 15°C, where 50% reduction in its content occurred after 6 months of storage. A partial recovery of the carotenoids content occurred when such tubers were reconditioned at 34 or 35°C for 6–12 days. | Janave and Thomas, 1979 |

(Continued)

TABLE 12.5 Quality and Shelf Life Extension of Irradiated Vegetables—cont'd

| Species | Irradiation Type/ Dose | Temperature | Quality | Reference |
|---|--|-----------------------------------|---|-----------------------------|
| Onion | 0.1 0.5 kGy | — | Significant reduction in vitamin C content immediately after irradiation | Guo et al., 1981 |
| Onion bulbs | 0.05 0.5 kGy | — | No significant effects on the total free sugar content (sucrose, glucose, and fructose) | Nishibori and Namiki, 1982 |
| Onion bulbs cv. Valenciana Sintética 14 | — | 6 32°C, 50 90% RH for 270 days | Weight loss was 43.3% | Curzio and Croci, 1983 |
| | 0.03 kGy | 6 32°C, 50 90% RH for 270 days | Weight loss was 22.8% | |
| Red garlic bulbs | 0.05 kGy | 6 32°C, 58 86% RH for 6 months | No appreciable changes were detected in ethereal extracts of Red garlic bulbs | Curzio and Ceci, 1984 |
| Potato cultivars | — | 20°C for 6 months | Weight loss was 28 51% | Khan et al., 1986 |
| | 0.1 kGy | 20°C for 6 months | Weight loss was 17 40% | |
| Onion bulbs | — | 23 32°C, 60 80% RH for 270 days | Weight loss was 27.7% | Thomas et al., 1986 |
| | 0.06 kGy | 23 32°C, 60 80% RH for 4.5 months | Weight loss was 15.2% | |
| Garlic bulbs | 0.1 kGy | 3 ± 1°C, 80 ± 5% RH for 10 months | No influence on the total sulfur and thiosulfonate content | Kwon et al., 1989 |
| Red cabbage, broccoli, and endive | γ irradiation/0.48, 0.98, 1.46, 1.94, 2.49, and 2.90 kGy | — | Highest radiation resistance. Electrolyte leakage increased linearly with higher radiation dose for all vegetables | Fan and Sokorai, 2005 |
| Sliced tomatoes (<i>Lycopersicon</i> syn. <i>L. esculentum</i>) | 1 kGy | — | No significant effect on total carotenoid and vitamin C content of sliced tomatoes (<i>Lycopersicon</i> syn. <i>L. esculentum</i>); however, it caused approximately 40% decrease in α tocopherol | Mohacsi Farkas et al., 2006 |
| Celery, carrot, and green onion | γ irradiation/0.48, 0.98, 1.46, 1.94, 2.49, and 2.90 kGy | — | Sensitive to radiation. Electrolyte leakage increased linearly with higher radiation dose for all vegetables | |

| | | | | |
|---------------------------------------|----------------------------|-----------------|--|-----------------------|
| Carrot and juice | γ irradiation/3 kGy | 10°C for 3 days | Total phenolic contents were significantly higher in the irradiated samples than in the non irradiated control. Antioxidant capacity increased | Song et al., 2006 |
| Kale juice | γ irradiation/3 kGy | 10°C for 3 days | Total phenolic contents were significantly higher in the irradiated samples than in the non irradiated control. Antioxidant capacity decreased | |
| Organic watercress | — 1 kGy | 7 7 | 14.5 Day shelf life 16 Day shelf life | Landgraf et al., 2006 |
| Carrot (<i>Daucus carota</i> L.) | 1 and 2 kGy | 4°C | There was no significant difference in the vitamin C content and total carotenoids in samples and control samples. Variation in the content of vitamin C and carotenoids during storage was also not statistically significant from the control samples The qualified test panelist could not differentiate between irradiated and unirradiated samples | Bandekar et al., 2006 |
| Cucumber (<i>Cucumis sativus</i> L.) | 1 and 2 kGy | 4°C | | |
| Carrot juice | — | 10°C | Non irradiated samples stored for 3 days had similar or slightly lower levels of total ascorbic acid than their irradiated ones. 1 Day shelf life | Song et al., 2007 |
| Kale juice | — | 10°C | Dose dependent reduction of the ascorbic acid content. The contents of the total ascorbic acid, including dehydroascorbic acid, were stable up to 3 kGy | |
| Carrot juice | 3 and 5 kGy | 10°C | | |
| Kale juice | 3 and 5 kGy | 10°C | Dose dependent reduction of the ascorbic acid content. The contents of the total ascorbic acid, including dehydroascorbic acid, were stable up to 3 kGy. 3 Day shelf life | |

7 days after irradiation. The 10 vegetables reported to be acceptable by the panelists up to 7 days of storage at $10 \pm 1^\circ\text{C}$ after irradiation were okra, baby corn, chaom, bird pepper, goat pepper, brinjal, eggplant, bitter cucumber, asparagus, and basil.

Horak et al. (2006) investigated the following minimally processed conventional and organic vegetables: conventional and organic chicory (*Chicorium endive*), organic rugola (*Eruca sativa* Mill), soy sprouts (*Glycine max*), alfalfa sprouts (*Medicago sativa*), and a mixed salad composed of cherry tomatoes (*Solanum lycopersicum*), carrots (*Daucus carota* L.), lettuce (*Lactuca sativa*), and cabbage (*Brassica oleracea*). In the case of conventional chicory and soy sprouts, the sensorial evaluation showed that these products had a higher general acceptability after irradiation with at least twice the disinfection dose (1.2 and 2 kGy, respectively). This dose seemed to improve considerably the shelf life of these products.

Landgraf et al. (2006) reported that the cubes of mango (*Mangifera indica*) cultivar Tommy Atkins were sensorially accepted until Day 4 when exposed to 1 kGy. This cultivar showed a better response to irradiation than Haden cultivar. Pineapple (*Citrullus vulgaris*) and watermelon (*Citrullus vulgaris*) in cubes exposed to 1 and 2.5 kGy irradiation were sensorially acceptable. Irradiation did not affect the watermelon sweetness or pineapple sourness.

The results of the sensory evaluation of carrot stored at room temperature for 3 and 7 days indicated that irradiation with lower than 2 kGy had no significant effect on color, lightness, flavor, sweetness, odor, and taste. During storage, the overall acceptability of control samples was not higher than that of samples irradiated with doses below 2 kGy. The results of sensory evaluation of carrot stored at refrigerator temperature ($4\text{--}7^\circ\text{C}$) for 4 and 10 days, indicated that color, lightness, odor, taste, sweetness, and flavor of samples irradiated with lower than 2.0 kGy (included 2 kGy) were not considerably different than those of non-irradiated ones. The overall acceptability of samples irradiated with doses lower than 2.0 kGy was higher than that of non-irradiated samples. Furthermore, color, taste, sweetness, and flavor of tomato stored at room temperature irradiated with doses higher than 1.0 kGy were significantly lower than control samples, particularly taste and flavor. The overall acceptability of non-irradiated samples was higher than that of irradiated samples. Samples irradiated with doses above 2 kGy were not sensorially acceptable (Shurong et al., 2006).

Bandekar et al. (2006) reported that the dose of 2 kGy did not alter the organoleptic properties of carrot (*Daucus carota* L.) and cucumber (*Cucumis sativus* L.). The radiation processing did not affect the textural properties of the previously mentioned minimally processed produce. There was significant reduction in the firmness of the peripheral region of the carrot after exposure to γ -rays. However, the acceptability of radiation-processed carrot was not affected. In fact, there was a slight increase in the sweetness after irradiation, and the taste panel preferred irradiated carrot over control. During storage, there was a significant increase in the firmness of the peripheral region of both control and irradiated samples.

Mohacsi-Farkas et al. (2006) performed a sensory testing of precut, irradiated tomatoes (*Lycopersicon* syn. *L. esculentum*), cantaloupe melon (*Cucumis melo*), and watermelon (*Citrullus lanatus*). Statistically significant differences in organoleptic properties (color, odor, taste, and texture) were reported only in the case of watermelon at doses higher than 1.5 kGy. Firmness of the samples showed statistically significant softening (tendering) only of watermelon cubes at the radiation dose of 2 kGy.

Bibi et al. (2006) reported “the appearance and flavor scores for tomatoes (*L. esculentum*) showed similar trends as those for cucumbers (*Cucumis sativus*) stored at 5°C. The appearance score was lower for non-irradiated samples than for 3.0-kGy treated samples. The flavor of tomatoes was enhanced with irradiation. The non-irradiated samples had lower mean score than 3.0-kGy treated samples. The trend of changes in firmness of tomatoes was also similar to that of cucumbers. The firmness of 0.5-kGy treated samples was similar to that of control samples, whereas the 3.0-kGy irradiated samples displayed the minimum firmness. Furthermore, it was determined that the appearance scores of minimally processed carrots (*Daucus carota*) were affected by radiation doses, and the mean scores decreased from 7.6 (control) to 6.33 (3.0-kGy treated). This suggested that minimally processed carrots should not be irradiated at higher than 2.0 kGy dose for storage at low temperature (5°C). It is evident from these data that the appearance of irradiated minimally processed cabbage (*Lactuca sativa* var. *capitata*) was not affected significantly by the applied γ -radiation for doses from 0.5 up to 3.0 kGy.”

The effect of different irradiation doses on *E. coli* population in polypropylene-packed jackfruit (*Artocarpus heterophyllus*) and PE-packed cabbage is shown in Figure 12.3.

Song et al. (2007) found that immediately after irradiation, the overall sensory scores of the irradiated and non-irradiated carrot and kale juice were not considerably different. However, the sensory quality of the non-irradiated carrot and kale juice decreased with storage time. According to the authors, “the control samples were unacceptable after 2 days of storage because of the deterioration in quality due to spoilage. In the same study, no significant differences in the amino acid composition between the non-irradiated control and irradiated (3 and 5 kGy) carrot and kale juice were observed. During the storage period (10°C), total AA, AA, and dehydroascorbic acid contents were reduced, and the ascorbic acid of the irradiated carrot and kale juice was higher than that of the non-irradiated at 3 days of storage. Furthermore, irradiated samples stored for 3 days had similar or slightly higher levels of total AA than their non-irradiated counterparts. Moreover, it was found that in the case of carrot and kale juice, radiation resulted in a dose-dependent reduction of the ascorbic acid content. However, the contents of the total AA, including dehydroascorbic acid, were stable up to 3-kGy irradiation dose. Irradiation prolonged their shelf life up to 3 days, whereas the shelf life of the non-irradiated control was limited to only 1 day.”

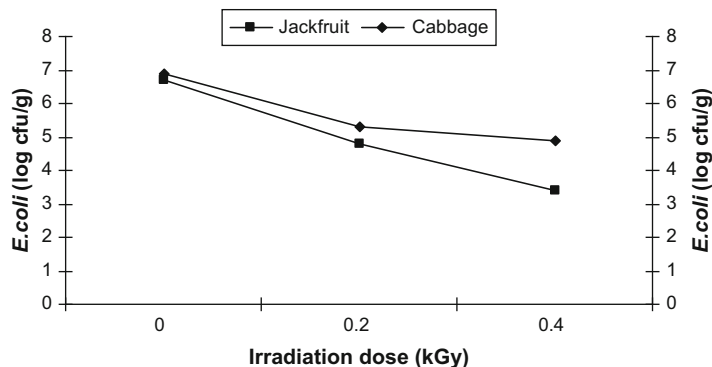


Figure 12.3: Effect of different irradiation doses on *E. coli* population in jackfruit (*Artocarpus heterophyllus*) packed in a polypropylene rigid container (Faridah et al., 2006) and cabbage (*Lactuca sativa* var. capitata) packed in a PE bag (Bibi et al., 2006).

The effect of the two main irradiation parameters (type/dose) on the shelf life and sensory properties of vegetables is displayed in Table 12.6.

12.8 The Microflora of Irradiated Vegetables

Doses of γ -irradiation ranging between 1 and 10 kGy were used to investigate the inactivation of HAV inoculated onto lettuce at ambient temperature. Data analysis with a linear model indicated that a D_{10} value of 2.72 ± 0.05 was required to achieve a 1-log reduction in HAV titer in lettuce (Bidawid et al., 2000).

Four frozen vegetables (broccoli, corn, lima beans, and peas) were γ -irradiated at subfreezing temperatures ranging from -5 to 20°C . The amounts of radiation necessary to reduce the bacterial population by 90% (D_{10} values) for *L. monocytogenes* differed significantly among vegetables at each irradiation temperature. D_{10} values increased significantly with decreasing temperature for all vegetables, with each vegetable displaying a different response pattern. At an irradiation temperature of -5°C , D_{10} values ranged from 0.505 kGy for broccoli to 0.613 kGy for corn. At 20°C , D_{10} ranged from 0.767 kGy for lima beans to 0.916 kGy for peas (Niemira et al., 2002).

Kim et al. (2004) investigated the isolation of enteric bacteria in the fermentation process of kimchi (Korean fermented vegetables) and its radication by γ -irradiation. Viable cell numbers of enteric bacteria were 10^4 CFU/g at the initiation of the fermentation process, gradually reducing during the fermentation period and not detected after 10 days. The enteric bacteria in the early fermentation period of kimchi were eliminated by 2 or 3 kGy of γ -irradiation, but *Lactobacillus* spp. survived and fermentation was maintained. The D_{10} values of total enteric group and *Lactobacillus* spp. were approximately 0.32 and 0.87 kGy, respectively. The three

TABLE 12.6 Effect of Irradiation on Shelf Life and Sensory Properties of Vegetables

| Species | Irradiation Type/ Dose | Temperature | Irradiation Effect on Sensory Properties | Reference |
|---|---|------------------|--|-------------------------------|
| Broccoli, corn, lima beans, peas | 2.5 3.1 kGy | 5°C | No significant changes in texture | Niemira et al., 2002 |
| | 3.9 4.6 kGy | 20°C | Significant softening of peas and broccoli stems but not of corn or lima beans | |
| Broccoli, mung bean sprouts | 1 kGy | 4°C | The appearance, color, texture, taste, and overall acceptability did not undergo significant changes after 7 days of post irradiation storage | Bari et al., 2005 |
| Okra, baby corn, chaom, bird pepper, goat pepper, brinjal, eggplant, bitter cucumber, asparagus, basil | γ irradiation/0.3, 0.6, and 0.9 kGy | 10 \pm 1°C | Organoleptically acceptable after 7 days of storage | Segsarnviriya et al., 2005 |
| Carrot | <2.0 kGy | Room temperature | No significant effect on color, lightness, flavor, sweetness, odor, and taste. During storage, overall acceptability of control samples was not higher than that of samples irradiated with doses <2.0 kGy | Shurong et al., 2006 |
| | <2.0 kGy | 4 7°C | No significant effect on color, lightness, flavor, sweetness, odor, and taste. Overall acceptability of samples irradiated with doses <2.0 kGy was higher than that of non irradiated samples | |
| Tomato | >1.5 kGy >1 kGy >1 kGy | Room temperature | Negative effect on color and lightness Negative effect on taste, sweetness, and flavor Color, taste, sweetness, and flavor significantly lower than those of control samples, especially, taste and flavor | |
| | >2 kGy | Room temperature | Samples were not acceptable | |

(Continued)

TABLE 12.6 Effect of Irradiation on Shelf Life and Sensory Properties of Vegetables—cont'd

| Species | Irradiation Type/ Dose | Temperature | Irradiation Effect on Sensory Properties | Reference |
|--|---------------------------|-----------------|---|-----------------------|
| Carrot (<i>Daucus carota</i> L.) | 2 kGy | — | No change of the organoleptic properties and no effect on the textural properties. A slight increase in sweetness after irradiation | Bandekar et al., 2006 |
| Cucumber (<i>Cucumis sativus</i> L.) | 2 kGy | — | No change of the organoleptic properties and no effect on the textural properties | |
| Conventional chicory | 1.2 kGy | 4°C | Sensorial evaluation showed that they had a better general acceptability when irradiated with at least twice the disinfection dose (1.2 and 2 kGy, respectively) No significant modifications in all the characteristics evaluated | Horak et al., 2006 |
| Conventional soy sprouts | 2 kGy | 4°C | | |
| Alfalfa sprouts | 2 kGy | 4°C | | |
| Mixed salad composed of cherry tomatoes | 1.2 kGy | 4°C | | |
| Organic chicory | 1.3 kGy | 4°C | | |
| Organic rugola | 1.4 kGy | 4°C | | |
| Pineapple (<i>Citrullus vulgaris</i>) in cubes | 1 and 2.5 kGy | — | Sourness was not affected by irradiation | Landgraf et al., 2006 |
| Watermelon (<i>Citrullus vulgaris</i>) in cubes | 1 and 2.5 kGy | — | Sweetness was not affected by irradiation | |
| Carrots (<i>Daucus carota</i>) | 3 kGy | 5°C | The appearance scores were lower for irradiated samples than for controls | Bibi et al., 2006 |
| Tomatoes (<i>L. esculentum</i>) | 3.0 kGy | 5°C | The appearance score was lower for non irradiated samples than for irradiated samples | |
| | 0.5 3.0 kGy | | The non irradiated samples had a lower mean flavor score than the 3.0 kGy irradiated samples | |
| | 0.5 0.5 kGy | | Firmness similar to that of control samples | |
| | 3 kGy | | Samples had the minimum firmness | |
| Cabbage (<i>Lactuca sativa</i> var. <i>capitata</i>) | 0.5 up to 3.0 kGy | 5°C for 14 days | The appearance of irradiated minimally processed cabbage (<i>Lactuca sativa</i> var. <i>capitata</i>) was not affected significantly | |

| | | | | |
|--|----------------------------|------|---|-----------------------------|
| Tomato (<i>Lycopersicon</i> syn. <i>L. esculentum</i>) | >1.5 kGy | — | Significant differences in color, odor, taste, and texture were determined only in the case of watermelon. Rank sums of precut tomato and cantaloupe cubes were not significantly different | Mohacsi Farkas et al., 2006 |
| Melon (<i>Cucumis melo</i>) | >1.5 kGy | — | | |
| Watermelon (<i>Citrullus lanatus</i>) | >1.5 kGy | — | | |
| Tomatoes (<i>Lycopersicon</i> syn. <i>L. esculentum</i>) | 2 kGy | — | Firmness of the samples showed significant softening (tendering) only of watermelon cubes | |
| Melon (<i>Cucumis melo</i>) | 2 kGy | — | | |
| Watermelon (<i>Citrullus lanatus</i>) | 2 kGy | — | | |
| Carrot juice | — | 10°C | Sensory scores of the irradiated and non irradiated carrot and kale juice were not significantly different The color of the control samples became darker Sensory scores of the irradiated and non irradiated carrot and kale juice were not significantly different The irradiated samples maintained their original color over time, whereas the control samples became darker | Song et al., 2007 |
| Kale juice | — | 10°C | | |
| | γ irradiation/3 kGy | 10°C | | |
| | γ irradiation/3 kGy | 10°C | | |

typical enteric bacteria were identified as *Enterobacter agglomerans*, *Salmonella Typhimurium*, and *Alcaligenes xylosoxydans*, and the D_{10} values were 0.38, 0.54, and 0.47 kGy, respectively.

Bari et al. (2005) found that irradiation of broccoli and mung bean sprouts at 1.0 kGy resulted in reductions of approximately 4.88 and 4.57 log CFU/g, respectively, of a five-strain cocktail of *L. monocytogenes*. Reductions of approximately 5.25 and 4.14 log CFU/g were reported for cabbage and tomato, respectively, at a similar dose. The appearance, color, texture, taste, and overall acceptability did not undergo considerable changes after 7 days of post-irradiation storage at 4°C in comparison with control samples.

Bibi et al. (2006) reported that the initial bacterial load in control carrot samples (*Daucus carota*) was 6.3×10^2 CFU/g and reached 6.5×10^5 CFU/g after 14 days of storage. A dose of 1 kGy reduced the bioload to 12.0 CFU/g. After 14 days of storage, only a few colonies could be detected. The samples receiving 2 kGy or higher doses were completely free of bacteria during 14 days of refrigerated storage. The control samples showed 2.7×10^1 CFU/g fungal counts initially, increasing to 1.2×10^4 CFU/g after 14 days of storage. The samples irradiated at a dose higher than 1 kGy were also completely fungi free during the 2 weeks of storage at 5°C. In addition, the initial TBC in cabbage (*Lactuca sativa* var. *capitata*) control samples increased from 1.0×10^3 to 1.0×10^5 CFU/g after 14 days of storage. In the case of irradiated samples, the counts ranged from 7.1×10^1 to 6.3×10^3 CFU/g at 0 days to 4.2×10^4 , 2.4×10^4 , 8.1×10^2 , and 1.5×10^2 CFU/g for 0.5-, 1.0-, 2.0-, 2.5-, and 3.0-kGy irradiated samples, respectively, after 7 days of storage. The bacterial counts of 2-kGy irradiated samples were within the permissible limits. It was also noted that samples irradiated with doses higher than 1 kGy were completely free of coliforms. Only a few colonies were detected after 14 days of storage for 1-kGy treated samples. In the case of fungal counts, a dose of 2.5 kGy gave samples completely free of viable fungal colonies for up to 14 days of refrigerated storage.

Song et al. (2006) investigated the effectiveness of γ -irradiation for inactivating *Salmonella Typhimurium* and *E. coli* in carrot and kale juice stored at 10°C. Viable cells in the non-irradiated samples were 10^7 CFU/ml, but irradiation at 3 kGy showed no viable cell growth of the test organisms at the detection limit of this study (10^1 CFU/ml). *Escherichia coli* was more sensitive to radiation than *Salmonella typhimurium*. The D_{10} values of *Salmonella Typhimurium* in the carrot and kale juice were 0.445 ± 0.004 and 0.441 ± 0.006 kGy, respectively, whereas those of *E. coli* were 0.301 ± 0.005 and 0.299 ± 0.006 kGy.

Shurong et al. (2006) determined the D_{10} values of *E. coli* O157:H7, *Listeria innocua*, and *Salmonella enteritidis*. D_{10} values of *E. coli* O157:H7 inoculated in cherry tomato and fresh precut carrot were 0.08 and 0.13 kGy, respectively. D_{10} values of *Salmonella enteritidis* inoculated in cherry tomato, fresh precut carrot, and a mixture of blanched celery and peanut were in the range of 0.24–0.33 kGy. Irradiation with doses less than 2.0 kGy could ensure

a 5-log reduction of the most resistant examined pathogen, *Salmonella enteritidis*. Moreover, irradiation could effectively control the growth of pathogens during the storage period.

Figures 12.4 and 12.5 display the impact of irradiation on the survival of *E. coli* and coliform bacteria and *Salmonella Typhimurium* and total aerobic bacteria in carrot juice.

Lee et al. (2006) studied the effects of an irradiation treatment for eliminating pathogens on cucumber, blanched and seasoned spinach, and seasoned burdock. The pathogens tested were *Salmonella Typhimurium*, *E. coli*, *Staphylococcus aureus*, and *Listeria ivanovii*. Inoculated viable cells of *Salmonella Typhimurium* and *L. ivanovii* into cucumber and blanched and seasoned spinach were reduced by approximately 4 decimal points with 2 kGy and that of *S. aureus* inoculated into burdock displayed a 4-decimal point reduction with 1 kGy. *Escherichia coli* inoculated into burdock was not detected with 1 kGy. All the bacterial contents of test pathogens into the samples were reduced to lower than detection limit with 3-kGy irradiation. The range of the D_{10} value was 0.28–0.42 among the four previously mentioned pathogens.

Horak et al. (2006) studied the effect of irradiation on conventional and organic chicory (*Chicorium endive*), organic rugola (*Eruca sativa* Mill), soy sprouts (*Glycine max*), alfalfa sprouts (*Medicago sativa*), and a mixed salad composed of cherry tomatoes (*Solanum lycopersicum*), carrots (*Daucus carota* L.), lettuce (*Lactuca sativa*), and cabbage (*Brassica oleracea*) stored at 4°C. The investigated microorganisms were *L. monocytogenes* ATCC 15313, *Salmonella enteritidis* ATCC 13076, and *S. aureus* ATCC 6538P. The most radiation-resistant microorganisms in the products were *L. monocytogenes* in organic chicory and rugola, conventional chicory, alfalfa, and soy sprouts and *S. aureus* in mixed salad. Based on the application of five times the D_{10} determined value, the minimum disinfection doses proposed for the

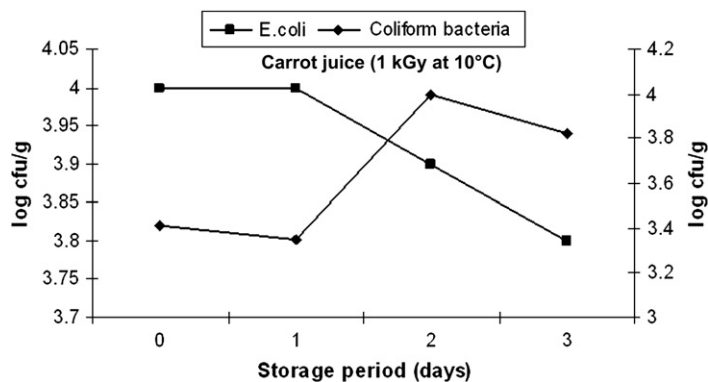


Figure 12.4: Effect of irradiation (1 kGy) on the survival of *E. coli* and coliform bacteria in carrot juice stored at 10°C (Song et al., 2006, 2007).

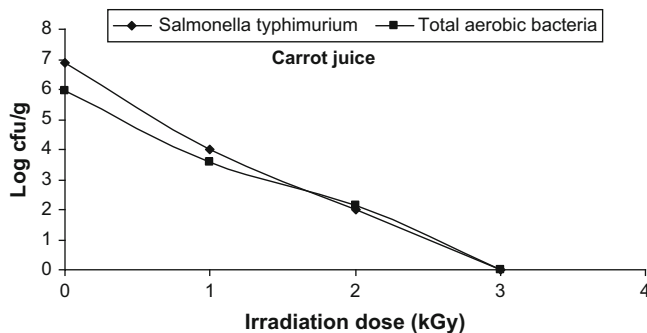


Figure 12.5: Effect of different irradiation doses on the survival of *Salmonella Typhimurium* and total aerobic bacteria in carrot juice stored at 10°C (Day 0) (Song et al., 2006, 2007).

products were 1.2 kGy for chicory and mixed salad, 1.3 kGy for organic chicory, 1.4 kGy for rucula, and approximately 2 kGy for soy and alfalfa sprouts.

D_{10} values of *L. monocytogenes* and *S. aureus* for various agricultural products (chicory, organic chicory, carrots, and lettuce) are shown in Figure 12.6.

According to Landgraf et al. (2006), “storage at refrigeration temperature was found not to be sufficient to control the growth of survived cells of *L. monocytogenes* on irradiated organic watercress. Doses of 1, 2, and 3 kGy reduced the population by approximately 4, 5, and 6 logs, respectively. The non-irradiated samples displayed increasing counts during storage time at 7°C. Similar behavior was reported for samples exposed to 1 kGy. Samples irradiated with 2 and 3 kGy maintained the same population throughout their shelf-life. *Salmonella* population displayed the same pattern as *L. monocytogenes* when inoculated on organic watercress and exposed to 1, 2, and 3 kGy. The population of *Salmonella* on the non-irradiated sample presented a small increase between 14 and 16 days of storage at 7°C, but the population was already very high. It was also found that the D_{10} value for *L. monocytogenes* in arugula varied from 0.37 to 0.48 kGy.” Furthermore, Landgraf et al. (2006) reported that “for shredded iceberg lettuce the D_{10} values for *E. coli* O157:H7 and *Salmonella* spp. were 0.11–0.12 and 0.16–0.23 kGy, respectively.”

Figure 12.7 displays the effect of irradiation on the survival of *L. monocytogenes* in precut tomato and watercress.

Lopez et al. (2006) determined similar D_{10} values for two different strains of *E. coli* (an ATTC and a wild type) in celery (*Apium graveolens*) and cabbage (*Lactuca sativa* var. *capitata*) (0.18–0.23 kGy). The same situation was observed for *L. innocua* in carrots (*Daucus carota* L.), iceberg lettuce (*Lactuca sativa* var. *capitata*), and Toscana (containing chopped iceberg lettuce) and Four Seasons salads (containing a mixture of chopped romaine lettuce, iceberg lettuce, butterhead lettuce, and spinach) (0.19–0.22 kGy). However, a higher D_{10} value was obtained

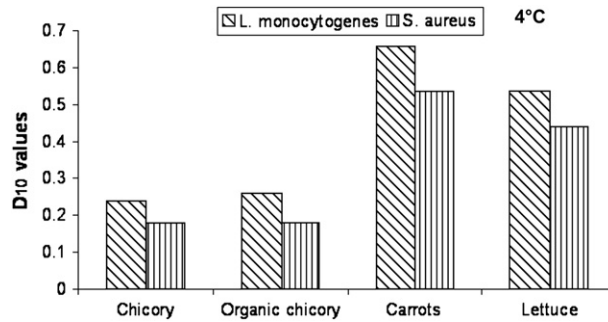


Figure 12.6: D_{10} values of *L. monocytogenes* and *S. aureus* for various agricultural products packaged aerobically at 4°C: chicory and organic chicory (Horak et al., 2006) and carrots and lettuce (Hammad et al., 2006).

for the same microorganism when inoculated in spinach (*Spinacia oleracea*) (0.32 kGy). *Escherichia coli* O157:H7 displayed a greater radio sensibility, presenting a D_{10} value of 0.09 ± 0.01 kGy in both mixed salads.

The D_{10} values of *E. coli* for various agricultural products (celery, cabbage, carrots, and lettuce) packaged aerobically at 4°C are given in Figure 12.8.

The effects of low-dose irradiation on the microbiota of precut tomato (*Lycopersicon* syn. *L. esculentum*) were investigated by Mohacsi-Farkas et al. (2006). Challenge testing with pathogens such as *E. coli* O157:H7 and *L. monocytogenes* was also carried out. Doses of 1–3 kGy were able to reduce considerably the microbiological contamination of tomato. The low-dose irradiation reduced the viable cell count of *L. monocytogenes* by 2 log cycles. A dose of 1 kGy reduced the viable cell number by more than 5 log cycles. *Escherichia coli* was able

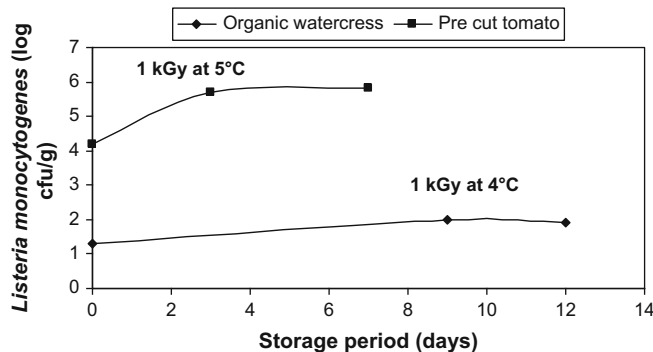


Figure 12.7: Effect of irradiation (1 kGy) on the survival of *L. monocytogenes* in pre-cut tomato and watercress (Landgraf et al., 2006; Mohacsi-Farkas et al., 2006).

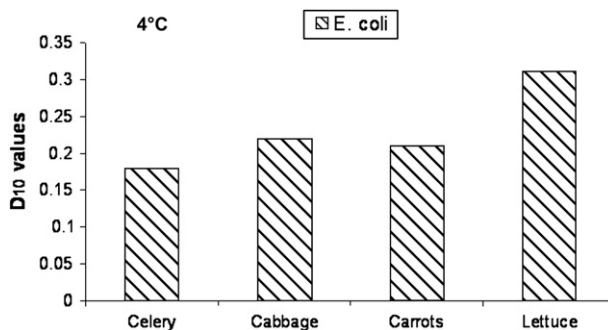


Figure 12.8: D_{10} values of *E. coli* for various agricultural products packaged aerobically at 4°C: celery and cabbage (Lopez et al., 2006) and carrots and lettuce (Hammad et al., 2006).

to grow on tomatoes only at 15°C after 3 days of storage. At refrigeration temperature (5°C), the number of *E. coli* remained stable during 7 days of storage.

Faridah et al. (2006) found that D_{10} values of *L. monocytogenes* were 0.23 kGy in both onion (*Allium cepa*) and cucumber (*Cucumis sativus*), aerobically packaged at $5 \pm 2^\circ\text{C}$. D_{10} values of *E. coli* O157 were lower (0.11 kGy in onion and 0.06 kGy in cucumber) compared to D_{10} values of *L. monocytogenes* in these vegetables. Generally, the total viable count in both onion and cucumber increased during storage. However, the microbial count was lower in the irradiated samples (0.5, 1.5, and 3.0 kGy) compared to the non-irradiated samples. The shelf life of onion and cucumber was at least 14 and 8 days, respectively. Furthermore, data indicated that hardness of cucumber was not affected by the irradiation in the range of 0.5–3.0 kGy. The results also indicated that storage of onion and cucumber for 15 days did not affect this parameter. In addition, irradiation was shown to only slightly affect the color (lightness, redness, and greenness) of the minimally processed onion and cucumber.

Song et al. (2007) reported that the initial populations of the total aerobic bacteria and coliform counts observed in the carrot juice were 10^6 CFU/ml, and those of the kale juice were 10^7 CFU/ml. All the aerobic bacteria and coliforms in the fresh carrot juice were eliminated with irradiation at 3 kGy, and the D_{10} value of the microflora in the carrot juice was found to be approximately 0.5 kGy. However, radiation dose up to 5 kGy could not completely eliminate the bacteria in the fresh kale juice. The D_{10} value was higher than 1.0 kGy in the kale juice.

Figures 12.9 and 12.10 display the impact of irradiation on the survival of *Salmonella Typhimurium* and total aerobic bacteria and *E. coli* and coliform bacteria, respectively, in kale juice. The effects of irradiation on vegetable microflora are summarized in Table 12.7.

12.9 Irradiation and Hurdle Technology of Irradiated Vegetables

Luo et al. (2003) investigated the minimum γ -irradiation doses required to inactivate all spoilage microorganisms, nonspore and spore pathogenic microorganisms, in VP bean curd and pickle. A dose of 10 kGy may inactivate the spoilage microorganisms in bean curd samples, and 15 kGy will inactivate them in pickle. The minimum dose required to inactivate *Salmonella enteritidis* was found to be 1 kGy, whereas a dose of 2 kGy could inactivate *Salmonella enteritidis* in bean curd and *S. aureus* in pickle. *Staphylococcus aureus* in bean curd is inactivated at a dose of 2.5 kGy. A dose of 5 kGy can eliminate *Bacillus cereus* in pickle, with a dose of 7.5 kGy being required for fish and bean curd.

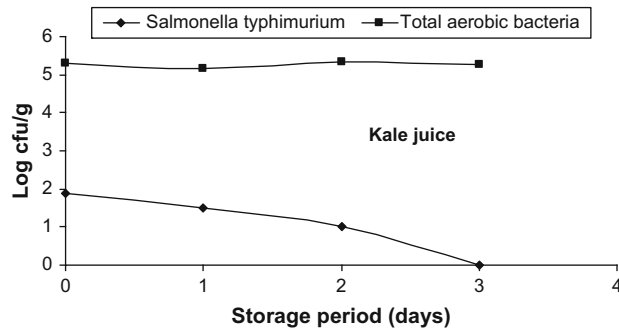


Figure 12.9: Effect of irradiation (2 kGy) on the survival of *Salmonella Typhimurium* and total aerobic bacteria in kale juice during storage at 10°C (Song et al., 2006, 2007).

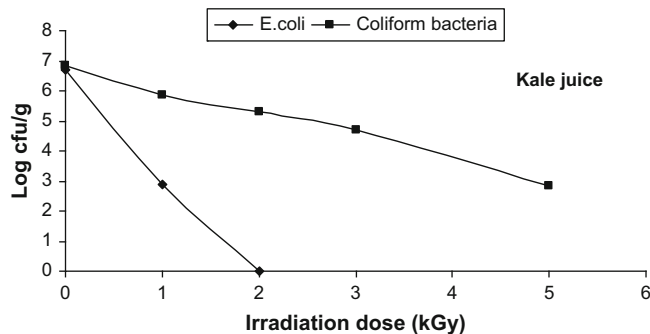


Figure 12.10: Effect of different irradiation doses on the survival of *E. coli* and coliform bacteria in kale juice at Day 0 (Song et al., 2006, 2007).

TABLE 12.7 The Effect of Irradiation on Vegetable Microflora

| Species | Irradiation Type/ Dose | Temperature | Irradiation Effect on Microflora | Reference |
|--------------------------------------|-----------------------------|---------------------|--|----------------------|
| Lettuce | γ irradiation/10 kGy | Ambient temperature | D_{10} value of 2.72 ± 0.05 was required to achieve a 1 log reduction in HAV titer | Bidawid et al., 2000 |
| Broccoli | 0.505 kGy | Irradiated at 5°C | Reduce the bacterial population by 90% (D_{10} values) for <i>L. monocytogenes</i> | Niemira et al., 2002 |
| Corn | 0.613 kGy | Irradiated at 5°C | | |
| Lima beans | 0.767 kGy | Irradiated at 20°C | | |
| Peas | 0.916 kGy | Irradiated at 20°C | | |
| Kimchi (Korean fermented vegetables) | 0.38 kGy | — | D_{10} value of <i>Enterobacter agglomerans</i> | Kim et al., 2004 |
| | 0.54 kGy | — | D_{10} value of <i>Salmonella typhimurium</i> | |
| | 0.47 kGy | — | D_{10} value of <i>Alcaligenes xylosoxydans</i> | |
| | 0.32 kGy | — | D_{10} value of total enteric group | |
| | 0.87 kGy | — | D_{10} values of <i>Latobacillus</i> spp. | |
| Broccoli sprouts | 1.0 kGy | 4°C | 4.88 log CFU/g of a five strain cocktail of <i>L. monocytogenes</i> | Bari et al., 2005 |
| Mung bean sprouts | 1.0 kGy | 4°C | 4.57 log CFU/g of a five strain cocktail of <i>L. monocytogenes</i> | |

| | | | | |
|---|----------------------------|----------------------------|---|-----------------------------|
| Cucumber, blanched and seasoned spinach, seasoned burdock | γ irradiation/1 kGy | — | Reduction of ~ 3 log CFU/g of <i>Salmonella typhimurium</i> | Lee et al., 2006 |
| | γ irradiation/2 kGy | — | 4 log reduction of <i>S. aureus</i> | |
| | γ irradiation/2 kGy | — | 4 log reduction of <i>S. aureus</i> | |
| | γ irradiation/1 kGy | — | 4 log reduction of <i>S. aureus</i> | |
| | γ irradiation/2 kGy | — | <i>Salmonella typhimurium</i> was reduced by ~ 4 log CFU/g | |
| | γ irradiation/2 kGy | — | <i>Salmonella typhimurium</i> was not detected | |
| | γ irradiation/2 kGy | — | <i>Salmonella typhimurium</i> was not detected | |
| | γ irradiation/2 kGy | — | <i>E. coli</i> decreased ~ 4 log CFU/g | |
| | γ irradiation/2 kGy | — | <i>E. coli</i> decreased ~ 4 log CFU/g | |
| | γ irradiation/1 kGy | — | 3 log CFU/g reduction of <i>L. ivanovii</i> | |
| | γ irradiation/2 kGy | — | Reduction of <i>L. ivanovii</i> by ~ 4 log CFU/g | |
| | γ irradiation/3 kGy | — | <i>L. ivanovii</i> not detected | |
| | γ irradiation/3 kGy | — | All the bacterial contents of <i>Salmonella typhimurium</i> , <i>E. coli</i> , <i>S. aureus</i> , and <i>L. ivanovii</i> were reduced to below the limit of detection | |
| | Carrot juice | γ irradiation/3 kGy | 10°C | |
| Kale juice | γ irradiation/3 kGy | 10°C | No viable cell growth of <i>Salmonella typhimurium</i> and <i>E. coli</i> (reduced from 10^7 CFU/ml) | |
| Tomato (<i>Lycopersicon</i> syn. <i>L. esculentum</i>) | 1 kGy | — | Reduction of the viable cell number by more than 5 log cycles | Mohacsi Farkas et al., 2006 |
| | 1 kGy | — | Reduction of <i>L. monocytogenes</i> by 2 log cycles | |
| Soy sprouts (<i>Glycine max</i>) | 2 kGy | 4°C | 5 log cycle reduction of <i>L. monocytogenes</i> | Horak et al., 2006 |
| Alfalfa sprouts (<i>Medicago sativa</i>) | 1.85 kGy | 4°C | 5 log cycle reduction of <i>L. monocytogenes</i> | |
| Mixed salad composed of cherry tomatoes (<i>Solanum lycopersicum</i>) | 1.2 kGy | 4°C | 5 log cycle reduction of <i>S. aureus</i> | |
| Chicory (<i>Chicorium endive</i>) | 1.2 kGy | 4°C | 5 log cycle reduction of <i>L. monocytogenes</i> | |

(Continued)

TABLE 12.7 The Effect of Irradiation on Vegetable Microflora—cont'd

| Species | Irradiation Type/ Dose | Temperature | Irradiation Effect on Microflora | Reference |
|--|---------------------------|-------------|--|-----------------------|
| Organic watercress | 1 kGy | 7°C | Reduction of <i>L. monocytogenes</i> population by ~4 logs | Landgraf et al., 2006 |
| | 2 kGy | | Reduction of <i>L. monocytogenes</i> population by ~5 logs | |
| | 3 kGy | | Reduction of <i>L. monocytogenes</i> population by ~6 logs | |
| Arugala | 0.37 0.48 kGy | | D_{10} value for <i>L. monocytogenes</i> | |
| Shredded iceberg lettuce | 0.11 0.12 kGy | | D_{10} value for <i>E. coli</i> O157:H7 | |
| | 0.16 0.23 kGy | | D_{10} value for <i>Salmonella</i> spp. | |
| Celery (<i>Apium graveolens</i>) | 0.18 ± 0.01 kGy | 4°C | D_{10} value for <i>E. coli</i> ATCC | Lopez et al., 2006 |
| Cabbage (<i>Lactuca sativa</i> var. <i>capitata</i>) | 0.22 ± 0.03 kGy | | D_{10} value for <i>E. coli</i> ATCC | |
| Iceberg lettuce (<i>Lactuca sativa</i> var. <i>capitata</i>) | 0.22 ± 0.03 kGy | | D_{10} value for <i>L. innocua</i> | |
| Carrots (<i>Daucus carota</i> L.) | 0.20 ± 0.02 kGy | | | |
| Spinach (<i>Spinacia oleracea</i>) | 0.32 ± 0.01 kGy | | | |
| Toscana salad (containing chopped iceberg lettuce) | 0.19 ± 0.01 kGy | | | |
| Four Seasons salad (containing a mixture of chopped romaine lettuce, iceberg lettuce, butterhead lettuce, and spinach) | 0.21 ± 0.03 kGy | | | |
| Cherry tomato | 0.08 kGy | | — | |
| Carrot | 0.13 kGy | — | D_{10} value of <i>E. coli</i> O157:H7 | |
| Cherry tomato | 0.24 0.33 kGy | — | D_{10} values of <i>Salmonella enteritidis</i> | |
| Carrot | 0.24 0.33 kGy | — | | |
| Mixture of blanched celery and peanut | 0.24 0.33 kGy | — | | |

| | | | | |
|---|----------------------------|-----------------|---|-------------------|
| Carrot samples (<i>Daucus carota</i>) | 1 kGy | 5°C for 14 days | From 6.3×10^2 CFU/g to 12.0 CFU/g | Bibi et al., 2006 |
| | 2 kGy | | From 6.3×10^2 CFU/g to 0 bacteria during storage | |
| | 2 kGy | | The control samples had 2.7×10 CFU/g fungal counts to complete elimination of any fungi during storage | |
| Cabbage (<i>Lactuca sativa var. capitata</i>) | 1 kGy | | Completely free of coliforms. Few colonies were detected after 14 days of storage of 1 kGy treated samples | |
| | 2.5 kGy | | Free of viable fungal colonies during storage | |
| Carrot juice | γ irradiation/3 kGy | 10°C | All the aerobic bacteria and coliform in the fresh carrot juice were eliminated (population before irradiation 10^6 CFU/ml) | Song et al., 2007 |
| Kale juice | γ irradiation/5 kGy | | Incomplete elimination of bacteria (population before irradiation 10^7 CFU/ml) | |

A series of experiments to examine the effects of γ -irradiation (1, 2, and 3 kGy) on coriander leaves (*Coriandrum sativum* L.) stored in PE sachets at 8–10°C was performed by Kamat et al. (2003). The initial total bacterial and mold counts observed in coriander leaves were 10^6 – 10^8 and 10^3 – 10^4 CFU/g, respectively. All the samples contained *Listeria*, *Yersinia*, and fecal coliforms prior to irradiation. A dose of 1 kGy resulted in a 3 log cycle reduction of bacteria, 1 log kill of yeast and mold, and reduction of coliform to 43 CFU/g. The *Listeria* and *Yersinia* present in the product were eliminated by such a low-dose treatment. The total carotenoid contents, chlorophyll contents as well as its components, chlorophyll a and b, did not change significantly on irradiation (1, 2, and 3 kGy) and subsequent storage.

Lacroix and Lafortune (2004) inoculated grated carrots (*Daucus carota*) with *E. coli* (10^6 CFU/g) and packed under air or under modified atmosphere packaging (MAP) condition (60% O₂, 30% CO₂, and 10% N₂). The packages were then γ -irradiated at doses varying from 0.15 to 0.9 kGy and stored at $4 \pm 1^\circ\text{C}$. *Escherichia coli* counts were periodically evaluated during 50 days of storage. Results showed that at Day 1, an irradiation treatment at a dose of 0.15 kGy reduced by 3 and 4 log the microbial level representing a level of 3 and 2 log CFU/g when samples were irradiated under air and under MAP, respectively. However, a level of 3 log CFU/g was detected in both treated samples after 7 days of storage. When samples were irradiated at the dose of 0.3 kGy, no *E. coli* was detected during the whole storage in samples treated under MAP. When samples were treated under air, a level of 1 or 2 log CFU/g of *E. coli* was detected after 5 days of storage.

Patterson et al. (2006) determined that irradiation (2 kGy) treatment alone or in combination with a decontamination wash [using calcium hypochlorite, eugenol (oil of clove), or oregano oil] did not considerably affect the quality of alfalfa seeds during sprouting. Irradiation (2 kGy) and oregano oil (0.1%) did result in significantly lower total counts during storage of the sprouts for 5 days at 5°C. However, the microbial counts in all cases were higher than log 8 by Day 5 of storage, and all the samples appeared spoiled. *Pantoea* sp. was the dominant bacterium present in all samples. These results suggested that even if the initial microbial quality of the seeds is good (<1 log/g), sufficient microorganisms are present to grow rapidly during the sprouting process, resulting in sprouts with high total counts.

Lacroix et al. (2006) studied carrots (*Daucus carota* L.) stored under MAP (60% O₂, 30% CO₂, and 10% N₂) with an edible coating based on caseinate and whey protein in conjunction with γ -irradiation. Carrots were irradiated at 0.5 or 1 kGy and stored at $4 \pm 1^\circ\text{C}$ for 21 days. According to Lacroix and her co-workers, “ γ -irradiation did not affect significantly the physicochemical properties of the carrots. MAP retarded whitening of uncoated carrots, but this treatment had a detrimental effect on the firmness. Microbiological analysis revealed that for uncoated carrots, doses of 0.5 and 1 kGy applied under air and

MAP reduced, respectively, by 3.5 and 4 log CFU/g and by 4 and 4.5 log CFU/g the content in aerobic plate count (APC). For coated carrots, doses of 0.5 and 1 kGy applied under air and MAP reduced, respectively, by 4 and 4.5 log CFU/g and by 3 and 4.25 log CFU/g the content of APC. The dose (D_{10}) required to reduce *L. monocytogenes* population by 1 log was 0.36 kGy for samples packed under air and 0.17 kGy for those packed under MAP. The effect of an antimicrobial edible coating containing *trans*-cinnamaldehyde combined with MAP and γ -irradiation showed that the coating was able to reduce by 1.29 log CFU/g the content of *L. innocua* in carrots packed under air after 21 days of storage, whereas when packed under MAP, a 1.08 log CFU/g reduction was observed after only 7 days of storage. Moreover, after 7 days of storage, no *L. innocua* was detected in samples treated at 0.5 kGy under air or in samples treated at 0.25 kGy under MAP”.

Landgraf et al. (2006) performed a sensory evaluation for exudate, odor, texture, and color for minimally processed iceberg lettuce aerobically packed in PE bags exposed to radiation doses of 0.0 (control), 0.7, 0.9, and 1.1 kGy. It was reported that doses of 0.7 and 0.9 kGy did not affect the iceberg lettuce attributes. However, a significant difference in the texture was observed with the dose of 1.1 kGy. Therefore, above this dose, irradiation treatment would not be suitable for iceberg lettuce. On Days 0 and 2, irradiated and non-irradiated packaged watercress were similarly assessed even for samples exposed to 3 and 4 kGy. From Day 7 onward, the acceptability of all samples decreased, although on Days 9 and 12 significant differences were observed with respect to 3- and 4-kGy irradiated samples. The acceptability of non-irradiated and 1-kGy irradiated watercress was higher, compared to higher doses, and did not differ significantly during the remaining days of the study. Irradiation treatment of 0.5–2 kGy on lettuce (*Lactuca sativa*) caused a reduction of 3.13–4 log in mesophilic and psychrotrophic counts, respectively. In the case of turnip (*Brassica campestris*), there was a 4.2-log reduction (Trigo et al., 2006a). The irradiation treatment in parsley (*Petroselinum crispum*) caused a reduction of 3 or 4 log cycles in mesophilic and psychrotrophic counts. A dose of 0.5 kGy resulted in reductions of 2.23 and 2.68 log of mesophilic bacterial counts in coriander (*Coriandrum sativum*) and mint (*Mentha spicata*), respectively. With 1 kGy, there was a 3.67- and 2.70-log reduction. A dose of 0.5 kGy in coriander resulted in reductions of 1.52 and 1.72 log for coliforms and Enterobacteriaceae. In mint, the reduction was 3.57 and 3.66 log. Radiation caused a reduction in coliforms and Enterobacteriaceae of 5–7 log in lettuce and 4 log in turnip.

Basbayraktar et al. (2006) concluded that a dose of 1.0 kGy is sufficient to reduce the nonpathogenic and the pathogenic bioload of minimally processed carrots without affecting the sensorial quality. D_{10} values for *L. monocytogenes* and *E. coli* were determined to be 0.29 kGy for both. At 1.0-kGy irradiation, there was an approximately 4-log reduction in *E. coli* and *L. monocytogenes* counts. Furthermore, no *Listeria* and *E. coli* were

recovered from any sample during the storage periods. Treatment with 1 kGy was effective to reduce the pathogens in the shredded carrots. Irradiation had an effect only on pH but no effect on the appearance and texture of sliced-carrot samples. Panelists preferred the irradiated to the non-irradiated sliced-carrot samples regarding odor, taste, and general acceptability. All samples were packed in sterile PE bags. Moreover, it was found that a dose of 1.5 kGy was sufficient to maintain the sensorial quality and the reduction of pathogenic bioload of minimally processed mixed salad. The 5-log reduction in *Salmonella enteritidis* counts and 4-log reduction in *L. monocytogenes* count and lack of adverse effects on sensory attributes revealed that low-dose irradiation can improve food safety of mixed salad.

Mathew et al. (2007) conducted an investigation to extend the shelf life and maintain the quality characteristics of tomatoes (*Lycopersicon esculentum*) under the effect of MAP in low-density PE (LDPE) film pouches, with γ -irradiation at 0–4 kGy and low-temperature ($12 \pm 1^\circ\text{C}$) storage at 90–95% RH. Results revealed that tomatoes packed with LDPE pouches alone as well as treatment with MAP and low doses (1 and 2 KGy) of irradiation showed good storability up to 21 days at $12 \pm 1^\circ\text{C}$ and 90–95% RH with maximum retention of fruit quality characteristics compared to 7 days for openly kept control tomatoes.

The effects of irradiation (type/dose) and hurdle technology on shelf life and the sensory and physical properties of vegetables are given in Table 12.8.

12.10 Conclusions

Application of irradiation to fruits has been performed during the past 10–15 years with remarkable success. In fact, irradiation has minimized pathogen growth, thereby resulting in fruits that are safe to consume. On the other hand, at least in most cases, there were no apparent changes in the total and volatile acid contents between control and fruits irradiated to different low doses during storage for 1 month. Neither the reducing sugar nor the total sugar levels were altered by doses of irradiation used under any of the temperatures during storage for a period of 1 month. In some cases (i.e., oranges), the loss of weight increased with increasing irradiation dose.

Regarding the sensory analysis of fruits and vegetables, insofar as the irradiation dose remained below 0.6 kGy, no change was reported. However, at higher doses (above 0.6 kGy), the sensory changes were considerable, and the consumer could perceive them.

TABLE 12.8 Effect of Irradiation and Hurdle Technology on Shelf Life and Sensory and Physical Properties of Vegetables

| Species | Irradiation Type/Dose | Other Technology | Temperature | Shelf Life | Sensory Properties | Irradiation Effect | Reference |
|--|------------------------------|------------------------------|-------------|------------|--|---|--------------------|
| Sorghum porridge | γ irradiation/ 10 kGy | Cooking (before irradiation) | — | — | — | Cooking did not alter vitamin B ₁ content (0.28 mg/g) of the sorghum porridge, but irradiation decreased it drastically (0.04 mg/g). Cooking did not decrease phytic acid in the sorghum porridge, but irradiation caused a significant decrease. Cooking reduced vitamin B ₁ and C contents of the sorghum relish, and irradiation caused further losses. Cooking did not decrease phytic acid in the sorghum porridge, but irradiation caused a significant decrease. | Duodu et al., 1999 |
| Spinach based relish | γ irradiation/ 10 kGy | Cooking (before irradiation) | — | — | — | | |
| Coriander leaves (<i>Coriandrum sativum</i> L.) | γ irradiation/ 1 kGy | Packaged in PE sachets | 8–10°C | — | The leaves irradiated at 1 kGy and stored for 2 weeks showed 7–8% yellowing compared to 12–15% in unirradiated ones. | 3 log cycle reduction of bacteria, 1 log kill of yeast and mold and reduction of coliform to 43 CFU/g. The <i>Listeria</i> and <i>Yersinia</i> present in the product were eliminated by such a low dose treatment. The initial total bacterial and mold counts observed in coriander leaves ranged between 10 ⁶ and 10 ⁸ CFU/g and 10 ³ and 10 ⁴ CFU/g, respectively. The total carotenoid levels remained unaffected by exposure to 1 kGy dose. | Kamat et al., 2003 |

(Continued)

TABLE 12.8 Effect of Irradiation and Hurdle Technology on Shelf Life and Sensory and Physical Properties of Vegetables—cont'd

| Species | Irradiation Type/Dose | Other Technology | Temperature | Shelf Life | Sensory Properties | Irradiation Effect | Reference |
|---|-----------------------------------|--|------------------------|------------|--------------------|--|--|
| Bean curd and pickle | γ irradiation/ 1.15 kGy | Vacuum packaged bean curd and pickle | — | — | — | The minimum dose required to inactivate <i>Salmonella enteritidis</i> was found to be 1 kGy, whereas a dose of 2 kGy could inactivate <i>Salmonella enteritidis</i> in bean curd and <i>S. aureus</i> in pickle. <i>S. aureus</i> in bean curd is inactivated at a dose of 2.5 kGy. A dose of 5 kGy can eliminate <i>B. cereus</i> in pickle, with a dose of 7.5 kGy being required for fish and bean curd | Luo et al., 2003 |
| Grated carrots (<i>Daucus carota</i>) | γ irradiation/ 0.15 kGy | Packaged in air | 4 ± 1°C for 50 days | — | — | 3 log CFU/g reduction of <i>E. coli</i> (from 10 ⁶ log CFU/g) at Day 1 | Lacroix and Lafortune, 2004 |
| | | Packaged in MAP (60% O ₂ , 30% CO ₂ , and 10% N ₂) | 4 ± 1°C for 50 days | — | — | 4 log CFU/g reduction of <i>E. coli</i> (from 10 ⁶ log CFU/g) at Day 1 | |
| | γ irradiation/ 0.3 kGy | Packaged in air | 4 ± 1°C for 50 days | — | — | 1–2 log CFU/g of <i>E. coli</i> was detected after 5 days of storage | <i>E. coli</i> was not detected during storage |
| | | Packaged in MAP (60% O ₂ , 30% CO ₂ , and 10% N ₂) | 4 ± 1°C for 50 days | — | — | | |

| | | | | | | | |
|---|-----------|---------------------------------|-----------------|--|---|---|---------------------------|
| Shredded carrots | 1.0 kGy | Packaged in sterile PE bags | 5°C for 10 days | — | Panelists preferred the irradiated to the non irradiated sliced carrot samples regarding the odor, taste, and general acceptability | 4 log reduction in <i>E. coli</i> and <i>L. monocytogenes</i> counts. In addition, <i>Listeria</i> and <i>E. coli</i> were not recovered from any sample during the storage periods. Irradiation affected only pH but had no affect on texture of sliced carrots. | Basbayraktar et al., 2006 |
| Mixed salad (radicchio, butterhead lettuce, red lettuce, green lettuce) | 1.5 kGy | Commercially packaged samples | | — | No adverse effects on sensory attributes | 5 log reduction in <i>Salmonella enteritidis</i> counts and 4 log reduction in <i>L. monocytogenes</i> | |
| Soybean sprout | 1.0 kGy | | | — | | 1.0 kGy dose decreased vitamin C content by approximately one third | |
| Lettuce (<i>Lactuca sativa</i>) | 0.5 2 kGy | Packaged in polymeric film bags | 4°C | Shelf life 12 days for 0.5 and 1 kGy (control 8 days) | 3.13 to 4 log reduction in mesophilic and psychrotrophic counts, respectively | — | Trigo et al., 2006a |
| Turnip (<i>Brassica campestris</i>) | | | | Shelf life 15 days for 0.5 and 1 kGy (control 12 days) | 4.2 log reduction in mesophilic and psychrotrophic counts | — | |

(Continued)

TABLE 12.8 Effect of Irradiation and Hurdle Technology on Shelf Life and Sensory and Physical Properties of Vegetables—cont'd

| Species | Irradiation Type/Dose | Other Technology | Temperature | Shelf Life | Sensory Properties | Irradiation Effect | Reference |
|---|-----------------------|----------------------------|-------------|-------------------------------------|--|--------------------|-----------|
| Parsley (<i>Petroselinum crispum</i>) | 0.5 2 kGy | Packaged in polymeric bags | 4°C | — | Reduction of 3 or 4 log cycles in mesophilic and psychrotrophic counts | — | |
| Watercress (<i>Nasturtium officinale</i>) | 0.5 2 kGy | | | Shelf life 7 days (control, 6 days) | 4.69 log reduction in mesophilic and psychrotrophic counts | — | |
| Coriander (<i>Coriandrum sativum</i>) | 0.5 kGy | | | Shelf life 9 days (control, 7 days) | 2.23 log reduction of mesophilic bacterial counts | — | |
| Mint (<i>Mentha spicata</i>) | | | | Shelf life 7 days | 2.68 log reduction of mesophilic bacterial counts | — | |
| Coriander (<i>Coriandrum sativum</i>) | | | | Shelf life 9 days | 1.52 and 1.72 log reduction for coliforms and Enterobacteriaceae, respectively | — | |
| Mint (<i>Mentha spicata</i>) | | | | — | 3.57 and 3.66 log reduction for coliforms and Enterobacteriaceae, respectively | — | |
| Lettuce (<i>Lactuca sativa</i>) | | | | — | 5 and 7 log reduction for coliforms and Enterobacteriaceae, respectively | — | |
| Turnip (<i>Brassica campestris</i>) | | | | — | 4 log reduction in coliforms and Enterobacteriaceae | — | |

| | | | | | | | |
|----------------------------------|------------------------------------|---|---------------------|---|--|---|------------------------|
| Alfalfa seeds | 2 kGy | Oregano oil (0.1%) | 5°C for 5 days | — | — | Resulted in significantly lower total counts. | Patterson et al., 2006 |
| Shredded iceberg lettuce | 0.7 kGy | Aerobically packed in PE bags | — | — | No effect on exudate, odor, texture, and color | — | Landgraf et al., 2006 |
| Shredded iceberg lettuce | 0.9 kGy | — | — | — | No effect on exudate, odor, texture, and color | — | — |
| Shredded iceberg lettuce | 1.1 kGy | — | — | — | Significant difference in the texture | — | — |
| Watercress | — | Packed | — | — | The acceptability of non irradiated and 1 kGy irradiated watercress was higher | — | — |
| | 1 kGy | — | — | — | — | — | — |
| | 3 kGy | — | — | — | — | — | — |
| | 4 kGy | — | — | — | — | — | — |
| Carrots (<i>Daucus carota</i>) | γ irradiation/ 0.5 or 1 kGy | MAP (60% O ₂ , 30% CO ₂ , 10% N ₂) with an edible coating based on caseinate and whey protein | 4 ± 1°C for 21 days | — | Irradiation did not significantly affect the physicochemical properties of the carrots | — | Lacroix et al., 2006 |
| | — | Under air with edible coating based on caseinate and whey protein | 4 ± 1°C for 21 days | — | Protection of firmness | — | — |
| | 0.5 kGy | Under air | 4 ± 1°C for 21 days | — | — | 3.5 log CFU/g reduction in the content in APC | — |
| | 0.5 kGy | MAP (60% O ₂ , 30% CO ₂ , 10% N ₂) | 4 ± 1°C for 21 days | — | — | 4 log CFU/g reduction in the content in APC | — |

(Continued)

TABLE 12.8 Effect of Irradiation and Hurdle Technology on Shelf Life and Sensory and Physical Properties of Vegetables—cont'd

| Species | Irradiation Type/Dose | Other Technology | Temperature | Shelf Life | Sensory Properties | Irradiation Effect | Reference |
|-------------------------------------|---|---|-------------|------------|---|---|-----------|
| Carrots (<i>Daucus carota</i>) | 1 kGy | Under air | 4 ± 1°C for | — | — | 4 log CFU/g reduction in the content in APC | |
| | | MAP (60% O ₂ , 30% CO ₂ , 10% N ₂) | 4 ± 1°C for | — | — | 4.5 log CFU/g reduction in the content in APC | |
| | 0.5 kGy | Under air with edible coating based on caseinate and whey protein | 4 ± 1°C for | — | — | 4 log CFU/g reduction in the content in APC | |
| | | MAP (60% O ₂ , 30% CO ₂ , 10% N ₂) with an edible coating based on caseinate and whey protein | 4 ± 1°C for | — | — | 3 log CFU/g reduction in the content in APC | |
| 1 kGy | Under air with edible coating based on caseinate and whey protein | 4 ± 1°C for | — | — | 4.5 log CFU/g reduction in the content in APC | | |

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|--|----------------------|---|---------------------|--|--|--|----------------------|
| Carrots (<i>Daucus carota</i>) | 1 kGy | MAP (60% O ₂ , 30% CO ₂ , 10% N ₂) with an edible coating based on caseinate and whey protein | 4 ± 1°C for 21 days | — | — | 4.25 log CFU/g reduction in the content in APC | |
| Onion (<i>Allium cepa</i>) | 0.23 kGy 0.11 kGy | Aerobically packaged | 5 ± 2°C | At least 14 days At least 14 days | Hardness not affected by doses up to 3 kGy Hardness not affected by doses up to 3 kGy | <i>L. monocytogenes</i> (D ₁₀ = 0.23 kGy) <i>E. coli</i> O157 (D ₁₀ = 0.11 kGy) | Faridah et al., 2006 |
| Cucumber (<i>Cucumis sativus</i>) | 0.23 kGy 0.06 kGy | | | Shelf life 8 days Shelf life 8 days | — — | <i>L. monocytogenes</i> (D ₁₀ = 0.23 kGy) <i>E. coli</i> O157 (D ₁₀ = 0.06 kGy) | |

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Irradiation of Insects: Disinfestation

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13.1 Introduction

The purpose of a quarantine disinfestation treatment is to prevent the establishment of a pest associated with a commodity to be imported into a country or region where it does not already occur, or where its presence is restricted (Heather, 2004). Traditional treatments, which most commonly involved chemical fumigants, such as ethylene dibromide and methyl bromide, and both hot (43–48°C) and cold (0–3°C) temperatures, work by killing essentially 100% of all stages of quarantined pests that might be present in the commodity. Alternative quarantine treatments for fresh commodities are needed because fumigants are being lost due to health and environmental problems; heat damages many commodities, such as stone and pome fruits and avocados (*Persea americana* Mill.); and cold treatment requires 12 or more days (Hallman and Worley, 1999). Ionizing irradiation was suggested as a possible quarantine treatment 70 years ago, and considerable research to that effect has been done during the past approximately 45 years (Burditt, 1994).

Furthermore, residue-free advantages of irradiation disinfestation over chemical fumigation have been demonstrated repeatedly (Tuncbilek, 1995). Unlike other disinfestation techniques, irradiation does not need to kill the pests to provide quarantine security; therefore, live, but sterile, insects may occur with the exported commodity, making inspection for the target pests redundant as a confirmation of treatment application and efficacy. Moreover, irradiation treatment can be applied to the commodity after packaging (Follett and Griffin, 2006).

13.1.1 Radiotolerance of Insects

Ionizing radiation breaks chemical bonds within individual molecules and between molecules, thereby disrupting normal cellular function in the insect. Insect response to irradiation varies with the insect species and life stage and the absorbed dose received by the insect. Tissues with undifferentiated, actively dividing cells are most susceptible to irradiation. Consequently, eggs

are normally the most susceptible life stage and adults are the most tolerant. Insect gonads and midgut contain mitotically active tissues, and irradiated insects are often sterile and stop feeding soon after treatment (Follett and Griffin, 2006).

Arthropod groups vary in their tolerance to irradiation. Among insects, Diptera, Coleoptera, and Hemiptera tend to be less radiotolerant than Lepidoptera (moths and butterflies), although there is considerable variation among the species that have been tested within these groups. Two of the most radiotolerant insects are the Indian meal moth (*Plodia interpunctella*) and the Angoumois grain moth (*Sitotroga cerealella*), both of which are pests of stored products (Ahmed, 2001; Ignatowicz, 2004). Curculionids were observed to be sensitive to irradiation (Brower and Tilton, 1972). Brown et al. (1972) found that 10 Gy was sufficient to cause sterility in adults of *Sitophilus granaries* (L.).

On the other hand, nematodes require much higher doses than arthropods, and irradiation disinfestations of nematodes may be impractical except for highly tolerant commodities (Hallman, 2000). According to Cogburn et al. (1966), Indian meal moth may have the highest radiotolerance of any arthropod studied. Although Indian meal moth is not of quarantine concern because it is distributed throughout the world, it was studied to determine the limits of radiotolerance of insects (International Consultative Group on Food Irradiation, 1991).

Table 13.1 presents the radiotolerance of insects.

13.2 Literature Review

Kovacks et al. (1986) studied the sensitivity of *Tribolium confusum* (a small flour beetle) to irradiation in a dose range of 0–800 Gy. They found that the insect egg was the most sensitive to radiation, followed by larvae and pupae. A 200-Gy dose of irradiation kills these forms or inhibits their further development. Imagoes do not immediately die after an 800-Gy dose of irradiation; the young imagoes are more sensitive to radiation than the aged ones. A 400-Gy average dose of irradiation is a suitable protection against *T. confusum*.

Mansour (2003) determined the effects of γ -radiation on the fifth-instar codling moth, *Cydia pomonella* (L.), larvae. Mature larvae were exposed to a series of γ -radiation doses ranging from 50 to 250 Gy, and survival to pupae and adults was examined. The results showed that pupation and adult emergence decreased with increasing radiation dose. The results also showed that diapausing larvae were more sensitive to irradiation treatment than nondiapausing larvae, and females were more sensitive than males. A dose of 150 Gy reduced adult emergence to less than 2% in nondiapausing larvae, whereas a dose of 200 Gy completely prevented it. Furthermore, none of the emerging moths exposed to a dose of 150 Gy were females; at the 100-Gy dose, there were less than 14% females. Tests in

TABLE 13.1 Arthropods for which Large-Scale Confirmatory Tests have been Performed to Establish Treatment Efficacy

| Species | Common Name | Dose Applied (Gy) | Stage at which Irradiation was Applied | No. of Arthropods Tested | Reference |
|--------------------------------------|----------------------------------|-------------------|--|--------------------------|-------------------------------|
| <i>Thrips palmi</i> | Orchid palmi | 350 | Adult | 2,500 | Bansiddhi et al., 2004 |
| <i>Cryptophlebia illepada</i> | Koa seedworm | 250 | Larva | 11,526 | Follett, 2004 |
| <i>Cydia pomonella</i> | Codling moth | 200 | Larva | 32,000 | Mansour and Mohamad, 2004 |
| <i>Cylas formicarius elegantulus</i> | Sweet potato weevil | 165 | Adult | 30,655 | Hallman, 2001 |
| <i>Grapholita molesta</i> | Oriental fruit moth | 200 | Larva | 30,000 | Hallman, 2004 |
| <i>Conotrachelus nenuphar</i> | Plum curculius | 92 | Adult | 25,000 | Hallman, 2004 |
| <i>Cylas formicarius elegantulus</i> | Sweet potato weevil | 165 | Adult | 30,000 | Hallman, 2004 |
| <i>Diatraea saccharalis</i> | West Indian sugarcane root borer | 50 | Adult | 220 | Hallman, 2004 |
| <i>Callosobruchus chinensis</i> | — | 100 | Adult | 31,628 | Gao et al., 2004 |
| <i>Anastrepha ludens</i> | Mexican fruit fly | 100 | Larva | 101,794 | Bustos et al., 2004 |
| <i>Anastrepha obliqua</i> | West Indies fruit fly | 100 | Larva | 100,400 | Bustos et al., 2004 |
| <i>Anastrepha serpentina</i> | Sapote fruit fly | 100 | Larva | 105,252 | Bustos et al., 2004 |
| <i>Ceratitis capitata</i> | Mediterranean fruit fly | 150 | Larva | 100,854 | Bustos et al., 2004 |
| <i>Anastrepha ludens</i> | Mexican fruit fly | 69 | Larva | 95,000 | Hallman and Martinez, 2001 |
| <i>Anastrepha striata</i> | Guava fruit fly | 100 | Larva | 13,094 | Toledo et al., 2003 |
| <i>Ceratitis capitata</i> | Mediterranean fruit fly | 250 | Larva | 110,800 | Seo et al., 1974 |
| <i>Ceratitis capitata</i> | Mediterranean fruit fly | 218 | Larva | 70,400 | Seo et al., 1974 |
| <i>Aspidiotus destructor</i> | Coconut scale | 150 | Adult | 32,716 | Follett, 2006 |
| <i>Anastrepha suspensa</i> | Guava fruit fly | 50 | Larva | 100,000 | Gould and von Windeguth, 1991 |
| <i>Tetranychus piercie</i> | Red spider mite | 280 | Adult | 10,000 | Sulaiman et al., 2004 |
| <i>Bactrocera dorsalis</i> | Oriental fruit fly | 150 | Larva | 173,000 | Komson et al., 1992 |
| <i>Bactrocera dorsalis</i> | Oriental fruit fly | 125 | Larva | 55,743 | Follett and Armstrong, 2004 |

(Continued)

Table 13.1 Arthropods for which Large-Scale Confirmatory Tests have been Performed to Establish Treatment Efficacy—cont'd

| Species | Common Name | Dose Applied (Gy) | Stage at which Irradiation was Applied | No. of Arthropods Tested | Reference |
|------------------------------|-------------------------|-------------------|--|--------------------------|---------------------------------|
| <i>Ceratitis capitata</i> | Mediterranean fruit fly | 100 | Larva | 31,920 | Follett and Armstrong, 2004 |
| <i>Bactrocera curcubitae</i> | Melon fly | 150 | Larva | 93,666 | Follett and Armstrong, 2004 |
| <i>Bactrocera tryoni</i> | Queensland fruit fly | 75 | Larva | 24,700 | Rigney and Wills, 1985 |
| <i>Bactrocera jarvisi</i> | Jarvis' fruit fly | 101 | Larva | 153,814 | Heather et al., 1991 |
| <i>Brevipalpus chilensis</i> | False red vine mite | 300 | Adult | 8,042 | Castro et al., 2004 |
| <i>Anastrepha ludens</i> | Mexican fruit fly | 69 | Larva | 95,000 | Hallman and Martinez, 2001 |
| <i>Cydia pomonella</i> | Codling moth | 200 | Larva | >32,000 | Mansour, 2003 |
| <i>Anastrepha ludens</i> | Mexican fruit fly | 249.58 | Eggs and larva | 99,817 | Wolfenbarger and Guenther, 1998 |
| <i>Grapholita molesta</i> | Oriental fruit moth | 200 | Fifth instar larva | 58,779 | Hallman, 2004 |

which more than 100,000 larvae (in the fifth instar) were irradiated in an artificial rearing medium with a dose of 200 Gy resulted in no adult emergence. Similar results were also obtained when more than 32,000 larvae in the same stage were exposed in apple fruit to the same dose. The root weevil (*Diaprepes abbreviatus*) was found to be quite susceptible to radiosterility, and a dose of 50 Gy prevented eclosion of eggs laid by irradiated adults. A dose of 150 Gy prevented adult emergence from mostly third instar papaya fruit flies (*Toxotrypana curvicauda*) naturally infesting papaya fruit (Gould and Hallman, 2004).

Bustos et al. (1992) treated more than 100,000 third instars of each of three species of *Anastrepha*—*ludens*, *obliqua*, and *serpentina*—in mangoes with 100 Gy without any adults developing. Adult emergence in the untreated controls was greater than 83.5%.

Rigney and Wills (1985) found that at 75 Gy, no adult *Bactrocera tryoni* emerged from a total of 24,700 third instars in oranges and avocados. Heather et al. (1991) irradiated 153,800 third-instar *Bactrocera jarvisi* in mangoes at 74–100 Gy with no adult survivors. Haque and Ahmad (1967) found that the lowest dose they used, 55 Gy (37 Gy/min), completely prevented adult emergence of approximately 800 third-instar peach fruit fly, *Bactrocera zonata* (Saunders), infesting guavas. Mean emergence in the control was 95%. Regarding oriental fruit fly, a mean

of 2.25% of adults emerged from larvae irradiated 7 days postinfestation with 50 Gy in mangoes in the Philippines (Manoto et al., 1992).

At a dose of 150 Gy, one adult emerged from $\geq 173,000$ larvae 6 days postinfestation in mangoes in Thailand (Komson et al., 1992). In addition, Vijaysegaran et al. (1992) found that at a dose of 80 Gy, 0.07% of larvae 5 days postinfestation (at 27°C) in carambolas emerged as adults.

Aldryhim and Adam (1999) investigated the lethal and sterilizing responses to γ -irradiation of eggs, larvae, pupae, and 3-day- and 4-week-old adults of *Sitophilus granarius*. Doses were 0, 10, 30, 50, 70, 100, 300, and 500 Gy. Eggs and larvae were unable to develop to adults following doses of 30–500 Gy. Emergence of adults from irradiated eggs and larvae occurred at a dose of 10 Gy. Pupae developed to the adult stage following doses of 10–70 Gy. A dose of 70 Gy at the pupal and 4-week-old adult stages caused sterility. Three-day-old adults were most tolerant to irradiation and required 100 Gy for sterility.

The effect of different irradiation doses on the mortality of adults from irradiated pupae 14 days after irradiation is shown in Figure 13.1.

In a study by Follett (2004), irradiation was explored as a method to prevent adult emergence in, or to sterilize, mango seed weevil. Mixed-age mango seed weevils in mangoes were irradiated with target doses of 50, 100, or 300 Gy and held for adult emergence. The 300-Gy treatments

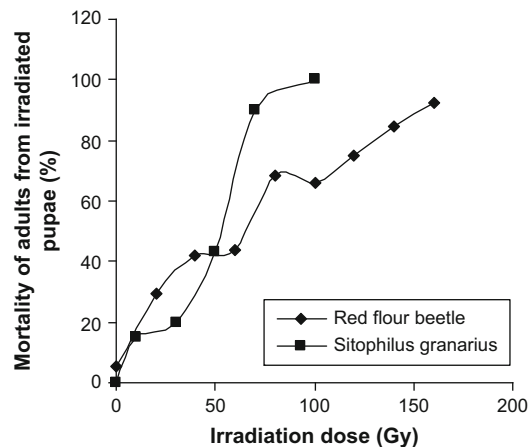


Figure 13.1: Effect of different irradiation doses on the mortality of adults from irradiated pupae (%) 14 days after irradiation: red flour beetle *Tribolium castaneum* (1- or 2-day old pupae) and *Sitophilus granarius* (the age of irradiated pupae not mentioned) (Aldryhim and Adam, 1999; San Juan et al., 2004).

did not prevent adult emergence. Emerging adults from the 100- and 300-Gy treatments were lethargic and short-lived, and they laid no eggs, indicating sterility. Furthermore, it was determined that the most tolerant stage of *Cryptophlebia illepidia* that could potentially occur in harvested fruits is the late (fourth and fifth) instar. No *C. illepidia* larvae receiving an irradiation dose greater than 125 Gy and emerging as adults produced viable eggs, indicating sterility can be achieved at doses less than 250 Gy. Large-scale tests in which 11,256 late instars were irradiated with a target dose of 250 Gy resulted in a pupation rate of only 8.4% and no adult eclosion.

Hallman (2004) studied “irradiation treatment as a method to stop development or reproduction of several insects. Reproduction of 25,000 adult plum curculios (*Conotrachelus nenuphar* [Herbst]) was stopped with 92 Gy. Reproduction of more than 30,000 adult sweet potato weevils (*Cylas formicarius elegantulus* [Summers]) was prevented with 165 Gy. Adult development of more than 30,000 last-instar oriental fruit moths (*Grapholita molesta* [Busck]) was stopped with 200 Gy. Preliminary studies showed that at least 350 Gy was needed to prevent reproduction of late pupae of sugarcane borer (*Diatraea saccharalis* [F.]), southwestern corn borer (*Diatraea grandiosella* Dyar), and Mexican rice borer (*Eoreuma loftini* [Dyar]). More than 400 Gy was required to stop egg hatch and development past first instar from irradiated adult Indian meal moth (*Plodia interpunctella* [Hubner]). No reproduction occurred from 220 adult female West Indian sugarcane root borers (*Diaprepes abbreviatus*) irradiated with 50 Gy.”

Arthur (2004) developed γ -radiation quarantine treatments to control three lepidopteran pests. All stages of *Ecdytoplopha aurantiana* (Lima, 1927; Lep: Tortricidae) and all immature stages of *Tuta absoluta* and *Neoleucinodes elegantalis* were treated with γ -radiation. All stages of *E. aurantiana*, the orange fruit borer, were irradiated in oranges at target doses of 0 (control), 50, 100, 150, 200, 300, 400, 500, and 600 Gy. Immature stages of *T. absoluta* and *N. elegantalis* were irradiated in tomatoes at target doses of 0 (control), 50, 100, 150, 200, 300, 400, and 500 Gy. An irradiation dose of 500 Gy caused 100% mortality in *E. aurantiana* pupae.

Low doses of γ -radiation affected the development of immature stages of the bean weevil (*Acanthoscelides obtectus* Say). When beans infested with eggs were irradiated with 100-Gy or higher doses 1–3 weeks after infestation, no adults emerged. No emergence was also noted when beans were given a dose 300 or 350 Gy at the fourth week after infestation. A dose of 250 Gy and lower doses did not prevent development of the older stages (last instars and pupae) to adults but killed young larvae (Ignatowicz, 2004).

The effect of γ -irradiation on the hatchability of eggs of bean weevil and codling moth is displayed in Figure 13.2.

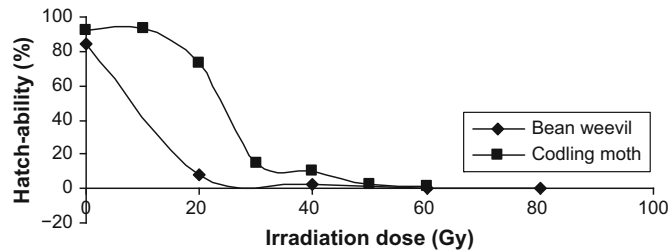


Figure 13.2: Effects of γ -irradiation on the hatchability of eggs of bean weevil *Acanthoscelides obtectus* and codling moth *Cydia pomonella* (Ignatowicz, 2004; Mansour and Mohamad, 2004).

Hayashi et al. (2004) treated four stored product insect pests—*Tribolium castaneum* (Herbst), *Plodia interpunctella* (Hübner), *Callosobruchus chinensis* (L.) and *Sitophilus zeamais* (Mothschulsky)—using “soft electrons” (low-energy electrons) with an energy of 60 keV. Adults of *C. chinensis* survived at 750 Gy but were inactivated having lost the ability to walk at 250 Gy. Soft electrons at 60 keV could not completely inactivate the larvae of *C. chinensis* and smaller larvae (second instars) of *S. zeamais* inside beans and grains because the electrons with low penetration did not reach larvae inside the host commodity. However, soft electrons at 60 keV inactivated eggs, larger larvae (fourth instars), and pupae of *S. zeamais* in rice grains, which indicated that *S. zeamais* was exposed to electrons even inside the grains. Moreover, a dose of 1000 Gy inactivated eggs, larvae, and pupae of *T. castaneum* and *P. interpunctella* and eggs of *C. chinensis*.

Gao et al. (2004) found that for khapra beetle (*Trogoderma granarium*), irradiation doses as low as 48 Gy prevented egg hatch. A 60-Gy dose prevented the development to pupae for young larvae and a 100-Gy dose prevented development for old larvae and diapausing larvae. No successful reproduction was found after irradiating older larvae, pupae, and adults of khapra beetle with a dose of 200 Gy; therefore, the effective quarantine irradiation dose for khapra beetle was 200 Gy. The treatment efficacy at 200 Gy was 99.7% at 95% confidence level (CL). Furthermore, for *Callosobruchus chinensis* (L.), irradiation efficacy at a dose of 100 Gy was higher than 99.95% at 95% CL.

The effects of irradiation on inhibition of egg, larval, and pupal development of the Indian meal moth (*Plodia interpunctella*) and fig moth (*Ephestia cautella*) in hazelnuts were investigated by Akinbingol et al. (2004). Irradiation doses required to inhibit development of eggs of *P. interpunctella* and *E. cautella* were 450 and 300 Gy, respectively. In large-scale tests, irradiation treatment of a composite of immature stages of *P. interpunctella* or *E. cautella* at a dose of 1000 Gy resulted in no adult emergence. Adults emerging from samples irradiated at 250 and 500 Gy produced no viable eggs, indicating sterility.

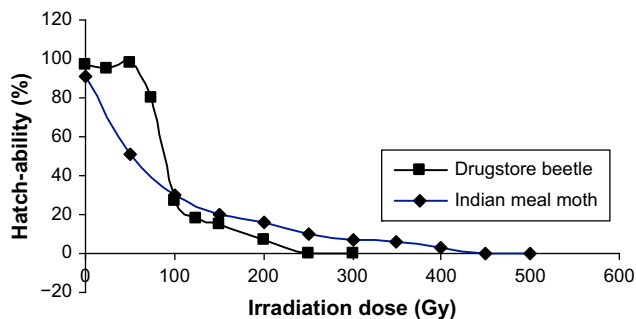


Figure 13.3: Effects of γ -irradiation on the hatchability of eggs of drugstore beetle *Stegobium paniceum* and Indian meal moth *Plodia interpunctella* (Akinbingol et al., 2004; Ignatowicz, 2004).

Figures 13.3 and 13.4 show the effect of irradiation on the hatchability of drugstore beetle and Indian meal moth, Angoumois grain moth, and fig moth.

Zolfagharieh (2004) investigated the impact of irradiation on *Plodia interpunctella* and *Oryzaephilus surinamensis* survival and reproduction in pistachios and dates. Eggs, larvae, pupae, and adults of *P. interpunctella* and *O. surinamensis* were treated with irradiation doses of 50–800 and 50–700 Gy, respectively. Results indicated that an irradiation dose of 700 Gy can control all developmental stages of both species, and the sterilizing doses for adults were 350 Gy for *P. interpunctella* and 85 Gy for *O. surinamensis*.

Effects of irradiation on red flour beetle (*Tribolium castaneum*) eggs, larvae, pupae, and adults were examined by San Juan et al. (2004). Mature eggs were more resistant to irradiation than young eggs; development to adults was prevented at a dose of 80 Gy for 1- to 2-day-old eggs.

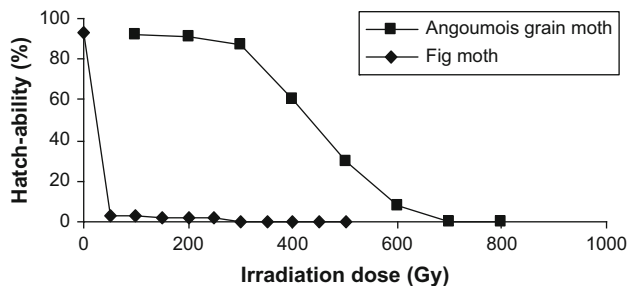


Figure 13.4: Effects of γ -irradiation on the hatchability of eggs of Angoumois grain moth *Sitotroga cerealella* and fig moth *Ephestia cautella* (Ignatowicz, 2004; Akinbingol et al., 2004).

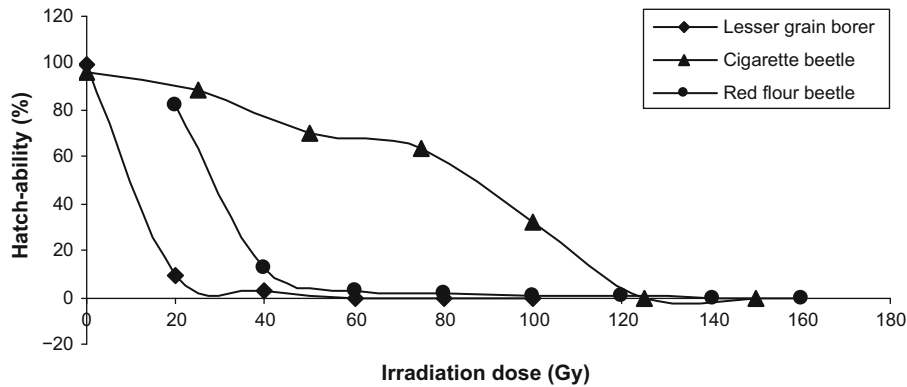


Figure 13.5: Effects of γ -irradiation on the hatchability of eggs of red flour beetle *Tribolium castaneum* (San Juan et al., 2004), cigarette beetle *Lasioderma serricorne* (Ignatowicz, 2004), and lesser grain borer *Rhizopertha dominica* (Ignatowicz, 2004).

Larvae were the most sensitive to irradiation. Pupae were the most resistant to irradiation, and older pupae were more resistant than younger pupae. Development to adults was not prevented in both types of pupae up to 160 Gy. Survivors were not observed after 4 weeks for adults receiving a dose of 100 Gy or higher. Adults from irradiated eggs and larvae were sterile at 60 Gy. For pupae, sterility was achieved at 60 and 120 Gy for the 1- to 2-day-old and 4- to 5-day-old pupae, respectively. Adult sterility was achieved at 120 Gy.

The effects of γ -irradiation on the hatchability of eggs of red flour beetle, cigarette beetle *Lasioderma serricorne*, and lesser grain borer are shown in Figure 13.5.

According to Hu et al. (2004), irradiation experiments with various stages of the citrus rust mite, *Phyllocoptruta oleivora*, showed that eggs were the most sensitive stage; although acute mortality was low, no nymphs were found after irradiation with a dose of 100 Gy. Protonymphs were also sensitive to irradiation, and 100 Gy was the lethal dose. Adults were sterilized with an irradiation dose of 350 Gy, and 450 Gy applied to 1-day-old adults resulted in 100% mortality after 7 days.

Sulaiman et al. (2004) found that irradiating the red spider mite, *Tetranychus piercie*, at a dose of 300 and 400 Gy produced sterile female adults from irradiated protonymphs and deutonymphs, respectively. A lower dose of 200 Gy induced sterility in female adults that developed from irradiated eggs and larvae. Deteriorating effects caused by irradiation treatment were reflected in immature mites by their reduced emergence rate/mortality in subsequent developmental stages. In adults, hatchability of eggs laid by irradiated mites indicated that a dose of 240 Gy was the lowest dose causing sterility in female adults of *T. piercie*. No viable

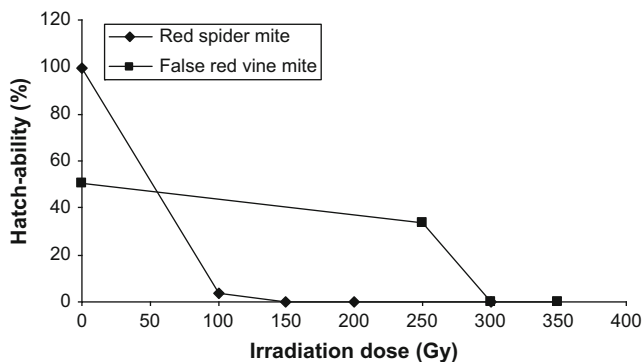


Figure 13.6: Effects of γ -irradiation on the hatchability of eggs of red spider mite *Tetranychus piercie* and false red vine mite *Brevipalpus chilensis* (Castro et al., 2004; Sulaiman et al., 2004).

offspring were produced when 10,000 adult mites were irradiated at 280 Gy. A dose of 350 Gy was required to sterilize *T. piercie* deutonymphs.

Figure 13.6 shows the effects of γ -irradiation on the hatchability of eggs of red spider mite and false red vine mite.

Castro et al. (2004) studied irradiation as a possible quarantine treatment against the false red vine mite, *Brevipalpus chilensis*, on Thompson Seedless grapes. The most resistant stage of *B. chilensis* was the adult. Irradiation doses required to cause 90% mortality of adults, nymphs, and eggs were 1307, 970, and 328 Gy, respectively. The viability of eggs from irradiated adults decreased as irradiation dose increased. At doses between 450 and 600 Gy,

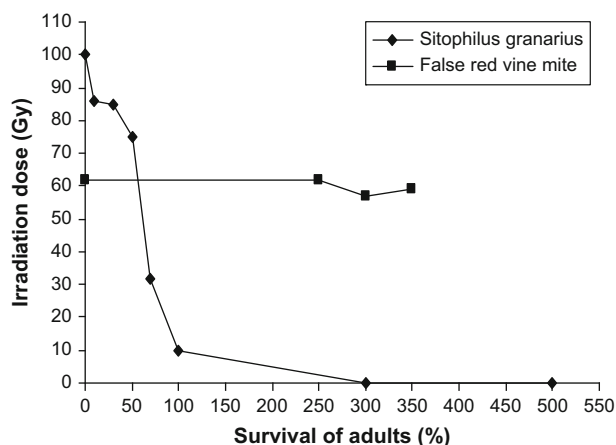


Figure 13.7: Effect of different irradiation doses on the survival of adults of *Sitophilus granarius* and false red vine mite (*Brevipalpus chilensis*) (Aldryhim and Adam, 1999; Castro et al., 2004).

adult females laid eggs but they were not viable. In dose–response tests at 250, 300, and 350 Gy using adult mites on grapes, the minimum irradiation dose that prevented adult reproduction was 300 Gy. A large-scale confirmatory study demonstrated the effectiveness of 300 Gy using 8,042 adult mites. An irradiation dose of 200 Gy combined with 15-day cold treatment (simulating commercial shipping conditions) was also shown to be sufficient to stop reproduction in the mite, and this treatment combination was later confirmed with 5,088 adult mites.

The effect of different irradiation doses on the survival of adults of *Sitophilus granaries* and *Brevipalpus chilensis* is displayed in [Figure 13.7](#).

A combination treatment including an insecticide dip (imidachloprid 10% SL), irradiation (350 Gy), and cold storage (15°C) was developed by [Bansiddhi et al. \(2004\)](#) as part of a systems approach to disinfest good agricultural practices-grown orchids of orchid thrips, *Thrips palmi* Karny. In large-scale confirmatory tests, the combination treatment including irradiation at a dose of 350 Gy was sufficient to prevent development to the next growth stage in immature thrips and sterilize adults of orchid thrips. Irradiation treatment delivered a minimum dose of 300 Gy and a maximum of 380 Gy.

[Hallman and Worley \(1999\)](#) evaluated the tolerance of immature Mexican and West Indian fruit flies, *Anastrepha ludens* (Loew) and *A. obliqua* (Macquart), respectively, to ionizing radiation from a ^{137}Cs source. Although tolerance to irradiation generally increased with increasing stage of development, the insect immediately preceding two developmental milestones (pupariation and larval to pupal molt) was usually more susceptible than 24 h earlier. During the first day of the phanerocephalic pupal stage, the pupa is 40% more tolerant of irradiation than the third instar, whereas the insect 24 h earlier is only 14% more tolerant. Mexican fruit fly third instars inside grapefruits, *Citrus paradisi* Macf., were notably more tolerant of irradiation than third instars in ambient air.

Coconut scale, *Aspidiotus destructor* Signoret (Homoptera: Diaspididae), is a quarantine pest of banana (*Musa* spp.) and many tropical crops. Irradiation was examined as a potential phytosanitary treatment to control coconut scale. Dose–response tests were conducted with second-stage nymphs, adult females without eggs, and adult females with eggs at a series of irradiation doses between 60 and 200 Gy to determine the most tolerant stage. The adult female with eggs was the most tolerant stage. In large-scale validation tests and dose–response tests, a total of 32,716 adult female scales with eggs irradiated with doses between 100 and 150 Gy produced no F₁ adults with eggs. Irradiation treatment with a minimum absorbed dose of 150 Gy should provide quarantine security for coconut scale on exported commodities ([Follett, 2006](#)).

Fisher (1997) stated that “the wide variation in irradiation dosage–sterility relationships reported to date for Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann), in both air and nitrogen gas made it necessary to define these relationships for Mediterranean fruit fly mass reared in Western Australian facilities. Results demonstrated the characteristic increase in sterility with increasing exposure to radiation in both air and nitrogen gas. It was also found that the relationship between irradiation dosage and fertility when irradiation was carried out in air was not parallel to the same relationship in nitrogen gas. The resistance to radiation in nitrogen atmosphere compared with air diminished as irradiation dosage increased. Furthermore, nitrogen offered much greater protection against the sterilizing effects of radiation; a twofold increase in the irradiation dosage was required for sterilization in nitrogen compared with air. The Western Australian Mediterranean fruit fly was 99.5% sterile when pupae were exposed to 76-Gy irradiation dosages in air. The use of nitrogen during irradiation was applied to pupae sterilized for a successful Mediterranean fruit fly eradication program in Western Australia. The average mating competitiveness during the 5-year program was 52% (compared with an expected 25% in air), and the average sterility was 99.4%.”

Follett and Armstrong (2004) studied irradiation quarantine treatment doses for *Bactrocera cucurbitae* (Coquillett), melon fly; *Ceratitis capitata* (Wiedemann), Mediterranean fruit fly; and *Bactrocera dorsalis* (Hendel), oriental fruit fly. An irradiation dose of 150 Gy applied to 93,666 melon fly late third instars in papayas resulted in no survival to the adult stage, indicating that this dose is sufficient to provide quarantine security. Irradiation doses of 100 and 125 Gy applied to 31,920 Mediterranean fruit fly and 55,743 oriental fruit fly late third instars, respectively, also resulted in no survival to the adult stage. Results support a proposed generic irradiation quarantine treatment dose of 150 Gy for all tephritid fruit flies.

Hallman and Martinez (2001) developed a low-dose γ -irradiation quarantine treatment against the Mexican fruit fly, *Anastrepha ludens* (Loew), for citrus fruits. The measure of efficacy of the treatment was prevention of adult emergence from third instars that were reared and treated in Rio Red grapefruit, *Citrus paradisi* Macf. The percentage of Mexican fruit fly adult emergence from grapefruit irradiated with 25, 30, 40, 50, or 60 Gy was 2.5, 1.4, 0.0005, 0, and 0%, respectively.

Hara et al. (2002) found that the green scale, *Coccus v viridis* (Green), could be controlled effectively by irradiation at a minimum absorbed dose of 250 Gy. Reproductive capacity of irradiated gravid adults was reduced greatly, and any resulting offspring were not able to develop beyond the crawler stage. Development of nymphs to the adult stage was not arrested completely nor was development of immature stages eliminated, but all survivors were sterile. Generally, higher doses of irradiation (≥ 400 Gy) caused a more rapid death of all life stages than did lower doses (250 Gy). At 250 Gy, there was prolonged survival of

green scale, with 8.8–11.4% of nymphs and up to 8.8% of crawlers alive 3 months after irradiation. An absorbed dose of 500, 750, or 1000 Gy caused 100% mortality in all stages of the green scale by 7, 6, and 3 weeks post-treatment, respectively. Adults appeared to be more resistant to treatments of 500 Gy or greater. Irradiation doses of 500 Gy or greater prevented development of all stages, hindered production of adult green scales, and caused eventual death.

One of the most destructive postharvest pests of the potato in the warm subtropical and tropical regions is the potato tuber moth *Phthorimaea operculella* (Zeller). It has been reported that irradiation at 10 Gy prevented hatching of eggs and adult emergence from infested tubers stored under tropical ambient conditions (Thomas et al., 1978). Although irradiation at 100 Gy completely inhibited adult emergence in tubers infested with eggs and early larval instars, a dose of 200 Gy was required to obtain the same results in tubers infested with late larval instars (Harwalkar and Rahalkar, 1971). Another study showed that eggs and newly hatched larvae survived doses up to 80 Gy. Immature stages that developed from irradiated eggs showed retardation of development and reduction in size and weight, and the adult moths that emerged were malformed. Females were more sensitive, and all doses delivered to eggs reduced the fecundity of adults that developed from them.

Elbadry and Adry (1965) found that doses of 240–960 Gy given to mature larvae prevented pupation, and lesser doses retarded pupal development. One-day-old pupae succumbed to 60 Gy, whereas normal adults emerged from pupae exposed to eight times that dosage on the eighth day of the pupal stage.

Wolfenbarger and Guenther (1998) reported that “a mean dose of 249.58 Gy ^{60}Co irradiation caused greater than 99.9968% mortality of 99,817 irradiated Mexican fruit fly, *Anastrepha ludens* (Loew), eggs and larvae that infested Ruby Red (also called Webb Red Blush) grapefruit (*Citrus paradisi* MacFayden). Determination was based on estimated larval populations (number of pupae in control fruit) and pupal mortalities (number of adults that eclose). Both ^{137}Cs and ^{60}Co required a greater than 15% dose of irradiation to kill 99.9968% of 21- to 25-day-old larvae in the fruit compared to the dose required to kill eggs and larvae up to 17 days old. The LD_{50} 's of eggs and larvae up to 17 days of age and 21- to 25-day-old larvae were statistically similar based on estimated larval and pupal mortalities. The LD_{50} 's were 93 and 82% less for early stage and mature larvae, respectively, than doses required for 99.9968% mortality. Oriental fruit moth, *Grapholita molesta* (Busck), is a pest of many rosaceous temperate fruits, including pomes (*Malus* spp.) and stone fruits (*Prunus* spp.), in many countries all over the world. In ambient atmospheres, no adults emerged from 58,779 fifth instars (the most radiotolerant stage present in fruit) irradiated with a target dose of 200 Gy (195–232 Gy measured). In atmospheres flushed with nitrogen, 5.3% of adults emerged from 44,050 fifth instars irradiated with a target dose of 200 Gy (194–230 Gy measured), but they died at a faster rate

than control adults and without laying eggs. A dose of 232 Gy (the maximum recorded when 200 Gy was targeted) is recommended to disinfest any fruit of oriental fruit moth under ambient and hypoxic atmospheres.”

Allinghi et al. (2007) found a significant reduction in the female relative performance index with increasing irradiation dose. The tested doses were 0, 40, 70, and 100 Gy. The analysis of induced sterility indicated that treatment with 40 Gy reduces male fertility from approximately 80 to 0.75%, and higher doses produce total sterility. In females, the 40-Gy dose reduces fertility to approximately 2% and higher doses prevent egg laying. The Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann), is one of the most important quarantine pests in the world. In this research, cage-infested “Haden” mangoes in Peru were used, and it was shown that 100 Gy is sufficient to provide a high level of quarantine security against this important pest. A dose of 100 Gy might allow for irradiation of avocados, one of the few fruits that does not tolerate more than 100–200 Gy (Torres-Rivera and Hallman, 2007).

The effects of γ -radiation on all stages of the hide beetle, *Dermestes macularus*, were studied by Seal and Tilton (1986). Eggs of *D. macularus* were more susceptible to γ -irradiation than other stages. Egg radiosensitivity decreased with increasing embryonic development. An absorbed dose of 200 Gy killed the first, sixth, and seventh instars larvae, but the fourth and fifth instars’ larvae were more resistant. Pupae (24 h) treated with 150 Gy failed to eclose, but eclosion was not affected in older pupae. Adults from female pupae irradiated at 72 h with 150 Gy were infertile, but male pupae required more than 200 Gy for sterilization. The average number of eggs per female decreased with increasing doses when either the male or the female of the pair was irradiated as pupae or adults. A dose between 200 and 300 Gy was necessary to provide complete sterility of 24-h-old adults.

The minimum irradiation quarantine treatment doses for arthropods and minimum irradiation quarantine treatment doses for arthropods are summarized in Tables 13.2 and 13.3, respectively.

13.3 Conclusions

Unlike other disinfestation techniques, irradiation does not need to kill the pests to provide quarantine security; therefore, live, but sterile, insects may occur with the exported commodity, making inspection for the target pests redundant as a confirmation of treatment application and efficacy. Another advantage of irradiation treatment is that it can be applied to the food after packaging. Exposure of eggs of red flour beetle, *Anastrepha ludens*, *Phthorimaea operculella*, and Western Australian Mediterranean fruit fly, among others, to γ -irradiation resulted in severe limiting of their hatchability and growth.

TABLE 13.2 Minimum Irradiation Quarantine Treatment Doses for Arthropods

| Species | Common Name | Commodity | Most Tolerant Stage Present in/on Commodity | Minimum Dose Required to Inhibit Development of Immatures | Minimum Dose Required (Gy) to Sterilize Adults | Irradiation Effect | Reference |
|--|----------------------------|----------------------------|---|---|--|---|----------------------------|
| <i>Tribolium confusum</i> | Flour beetle | Wheat germ and wheat bran | Eggs (larvae and pupae followed it) | | | 0.2 kGy dose of irradiation kills these egg larvae and pupae or their further development is inhibited | Kovacks et al., 1986 |
| <i>Diaprepes abbreviatus</i> | Root weevil | | | | 50 | | Gould and Hallman, 2004 |
| <i>Toxotrypana curvicauda</i> | Fruit flies (third instar) | Papaya fruit | | 0.15 kGy | | | |
| <i>Sitophilus granarius</i> | | Wheat grain | 3 Day old adults | 0.03 0.5 kGy | 10 | A dose of 0.07 kGy at the pupal and 4 week old adult stages caused sterility | Aldryhim and Adam, 1999 |
| <i>Aspidiotus destructor</i> Signoret | Coconut scale | Banana (<i>Musa</i> spp.) | Adult female with eggs | | | A total of 32,716 adult female scales with eggs irradiated with doses between 0.1 and 0.15 kGy produced no F ₁ adults with eggs | Follett, 2006 |
| <i>Anastrepha ludens</i> | Mexican fruit fly | Rio Red grapefruit | Adult | 50 Gy (adult emergence from third instars) | | An absorbed dose of 500, 750, or 1000 Gy caused 100% mortality in all stages of the green scale by 7, 6, and 3 weeks post treatment, respectively | Hallman and Martinez, 2001 |

(Continued)

Table 13.2 Minimum Irradiation Quarantine Treatment Doses for Arthropods—cont'd

| Species | Common Name | Commodity | Most Tolerant Stage Present in/on Commodity | Minimum Dose Required to Inhibit Development of Immatures | Minimum Dose Required (Gy) to Sterilize Adults | Irradiation Effect | Reference |
|--------------------------------------|-----------------------------------|----------------------------|---|---|--|---|-------------------|
| <i>Coccus viridis</i> | Green scale | Gardenia and coffee plants | Adult | | At a dose of 250 Gy, reproductive capacity of irradiated gravid adults was reduced greatly and any resulting offspring were not able to develop beyond the crawler stage | At 250 Gy, there was prolonged survival of green scale, with 8.8 11.4% of nymphs and up to 8.8% of crawlers alive 3 months after irradiation. An absorbed dose of 500, 750, or 1000 Gy caused 100% mortality in all stages of the green scale by 7, 6, and 3 weeks post treatment, respectively | Hara et al., 2002 |
| <i>Cryptophlebia illepada</i> | Koa seedworm | Tropical fruits | Late fourth and fifth instar | 250 Gy | | | Follett, 2004 |
| <i>Conotrachelus nenuphar</i> | Plum curculios | Apple | | | 92 | | Hallman, 2004 |
| <i>Cylas formicarius elegantulus</i> | Weevils | Sweet potato | | | 165 | | |
| <i>Grapholita molesta</i> | Oriental fruit moths | Apple | | 200 Gy (last instar) | | | |
| <i>Plodia interpunctella</i> | Indian meal moth | | | 400 Gy | | | |
| <i>Diaprepes abbreviatus</i> | West Indian sugarcane root borers | | | | 50 (female) | | |

| | | | | | | | |
|----------------------------------|-------------------------|-----------------------|-------|---|-----|---|-------------------------|
| <i>Ecdytolopa aurantiana</i> | Orange fruit borer | Orange | | 300 Gy from any stage | 300 | | Arthur, 2004 |
| <i>Tuta absoluta</i> | Tomato worm | Tomato | Pupa | 300 Gy | 200 | | |
| <i>Neoleucinodes elegantalis</i> | Tomato fruit borer | Tomato | Pupa | 400 Gy | 300 | | |
| <i>Trogoderma granarium</i> | Khapra beetle | | | 60 Gy prevented the development to pupae for young larvae and 100 Gy for old larvae and diapausing larvae | 200 | | Gao et al., 2004 |
| <i>Plodia interpunctella</i> | Indian meal moth | Hazelnut | | 450 Gy inhibited development of eggs | | Adults emerging from samples irradiated at 0.25 and 0.5 kGy produced no viable eggs, indicating sterility | Akinbingol et al., 2004 |
| <i>Ephestia cautella</i> | Fig moth | Fig, almond, hazelnut | Larva | 300 Gy inhibited development of eggs and 1000 Gy for immature insects | | Adults emerging from samples irradiated at 0.25 and 0.5 kGy produced no viable eggs, indicating sterility | |
| <i>Plodia interpunctella</i> | | Pistachios and dates | | | 350 | | Zolfaghari, 2004 |
| <i>Oryzaephilus surinamensis</i> | Sawtoothed grain beetle | Wheat products | Pupa | 700 Gy | 85 | | |
| <i>Tribolium castaneum</i> | Red flour beetle | Cocoa | Pupae | 0.08 kGy for 1 or 2 day old eggs | 120 | | San Juan et al., 2004 |

(Continued)

Table 13.2 Minimum Irradiation Quarantine Treatment Doses for Arthropods—cont'd

| Species | Common Name | Commodity | Most Tolerant Stage Present in/on Commodity | Minimum Dose Required to Inhibit Development of Immatures | Minimum Dose Required (Gy) to Sterilize Adults | Irradiation Effect | Reference |
|--------------------------------|----------------------|--|---|--|--|--------------------|------------------------|
| <i>Phyllocoptruta oleivora</i> | Citrus rust mite | Orange | Eggs were the most sensitive stage | | 350 | | Hu et al., 2004 |
| <i>Tetranychus piercie</i> | Red spider mite | Cut foliage and ornamental potted plants | Deutonymph | 350 Gy | 280 | | Sulaiman et al., 2004 |
| <i>Brevipalpus chilensis</i> | False red vine mite | Thompson Seedless grapes | Adult | | 300 | | Castro et al., 2004 |
| <i>Thrips palmi</i> | Orchid thrips | Orchids | | 350 Gy including an insecticide dip (imidachloprid 10% SL) and cold storage (15°C) | 350 Gy including an insecticide dip (imidachloprid 10% SL) and cold storage (15°C) | | Bansiddhi et al., 2004 |
| <i>Sitophilus oryzae</i> | Rice weevil | Rice, wheat, grain | Pupa | 80 Gy | | | Ignatowicz, 2004 |
| <i>Sitotroga cerealella</i> | Angoumois grain moth | Grain | Pupa | 600 Gy | 600 | | |
| <i>Stegobium paniceum</i> | Drugstore beetle | Grain, various plant products | Pupa | 120 Gy | 250 | | |

TABLE 13.3 Minimum Irradiation Quarantine Treatment Doses for Arthropods

| Species | Common Name | Minimum Dose Required (Gy) | Reference |
|--------------------------------------|-------------------------|----------------------------|---------------------------|
| <i>Lasioderma sericorne</i> | Cigarette beetle | 175 (male) 250 (female) | Tilton et al., 1966 |
| <i>Callosobruchus maculatus</i> | Cowpea weevil | 100 | Dongre et al., 1997 |
| <i>Oryzaephilus surinamensis</i> | Sawtoothed grain beetle | 125 | Tuncbilek, 1997 |
| <i>Cylas formicarius elegantulus</i> | Sweet potato weevil | 150 | Dawes et al., 1987 |
| <i>Sitophilus granarius</i> | Granary weevil | 100 | Brown et al., 1972 |
| <i>Sitophilus zeamais</i> | Maize weevil | 100 | |
| <i>Trogoderma variabile</i> | Warehouse beetle | 250 (male) 100 (female) | Brower and Tilton, 1972 |
| <i>Palorus subdepressus</i> | Depressed flour beetle | 400 (male) 400 (female) | Brower, 1973a |
| <i>Tenebrio molitor</i> | Yellow mealworm | 150 (male) 50 (female) | Brower, 1973b |
| <i>Cadra cautella</i> | Almond moth | 300 (male) 300 (female) | Cogburn et al., 1973 |
| <i>Cidia pomonella</i> | Codling moth | 400 (male) | Proverbs and Newton, 1962 |

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Carbohydrates

Ioannis S. Arvanitoyannis

14.1 Introduction

Siddhuraju et al. (2002) highlighted the impact of γ -irradiation on the chemistry of various antinutrients, including non-starch polysaccharides (NSPs) and biological and nutritional qualities of foods and feeds. The potential of irradiation dose levels of up to 10 kGy to reduce various antinutrients was also reviewed. This approach could open avenues for the use of underutilized and nonconventional crops and other agricultural residues as potential additional food and feed sources in the near future. In foods, free radicals are not only formed from the ionization process but also formed as by-products of normal processes and pathological processes leading to diseases (Pryor, 1984). Furthermore, free radicals similar to those induced by irradiation are equally produced by conventional thermal cooking, pasteurization, and microwave heating (Lagunas-Solar, 1995; Pryor, 1984).

Radiation is a very important tool for the modification of polymer materials through degradation, grafting, and cross-linking. Radiation effects on carbohydrates such as chitosan, sodium alginate, carrageenan, cellulose, and pectin were investigated to enhance their use for recycling these bioresources and thereby reduce environmental pollution. These carbohydrates were degraded by irradiation, and biological activities such as antimicrobial activity, promotion of plant growth, suppression of heavy metal stress, and phytoalexins induction were induced. Kume et al. (2002) studied the induction of phytoalexins by using radiation-degraded carbohydrates. The pectic fragments obtained by irradiation with 1000 kGy (10 kGy/h) from ^{60}Co were most effective for induction of glyceollins (a phytoalexin in soybeans) and induced almost the same amount of glyceollins as pectin-PGase. According to Hien et al. (2000), the degraded alginate [viscosity average molecular weight (M_v) ~ 7000 alginate irradiated at 100 kGy] was effectively used either in solution (4%) or powder for growth promotion of rice field. Similar behavior for growth promotion of plants was reported for chitosan, carrageenan, and ligno-cellulose extracts.

Natural polymers are biodegradable and abundant (Bassi et al., 2000; Hirano, 1999). Therefore, a new generation of environmentally friendly materials has emerged and may replace current

sources in industrial applications. Even within the microelectronics industry, there are efforts to produce environmentally safer products that include polymer coatings and composites that are halogen free (Trumble and Brydges, 1998).

14.2 Starch

Starch has received much research interest because it is a major reserve polysaccharide of green plants and it can be isolated through various simple extraction processes. Starch affects the structure, texture, and consistency of many foods. Starch modification is often a prerequisite for its usage by the food manufacturing industry to improve pasting properties and cold storage stability. Most of the currently employed modification techniques (acid or enzymatic treatments) are complicated and time-consuming, whereas radiation processing has been found to provide a low-cost and environment-friendly alternative (Bhat and Karin, 2009).

14.2.1 Wheat

Thermal studies using differential scanning calorimetry (DSC) were carried out by Ciésła and Eliasson (2003) to investigate the effect of γ -irradiation (conducted in the solid state) on the structure of amylose–lipid complex in wheat starch. Suspensions of the control and the wheat starch irradiated with 30-kGy γ -rays were examined over various courses of heating and cooling at rates of 2.5 and 10°C/min. Differences between DSC traces between the control and the irradiated samples were more clearly detected over cooling than over heating because of the higher resolution of thermal effects. The differences between endothermal effects of gelatinization recorded in the control and the irradiated starch were larger in the case of high-concentration suspensions.

Differences were detected with DSC between gelatinization and amylose–lipid complex transition occurring in suspensions of control and irradiated with 30 kGy wheat flour characterized by a dry matter:water ratio of approximately 1:1, with the results dependent on the heating rate (Ciésła, 2003). A decrease in T_{\max} occurred after irradiation of both wheat and rye flour (from 69.3 to 59.3°C for 0 and 30 kGy, respectively). The lower values of the initial gelatinization temperature were found for the irradiated wheat flour samples compared to those for the control samples. On the contrary, in the case of rye flour, when no additional preliminary step in viscosity progress occurred, an increase in the initial temperature of gelatinization was found after irradiation. Based on comparison of the results obtained using DSC and the Brabender viscograph, it was concluded that irradiation slightly affected the crystalline ordering, and the crystalline regions are probably more resistant to radio-depolymerization than are the amorphous ones. The effect of irradiation dose on viscosity and thermal properties (T_{\max}) of wheat and rye flour batches is shown in Figure 14.1.

Transition of the amylose–lipid complex occurs in all the irradiated samples at a lower temperature compared to the non-irradiated starch (for dense gels in the first cycle at 0 kGy, T_p was 99.7°C, whereas at 30 kGy T_p was 95.8°C). A further thermal treatment triggered a decrease of the transition temperature in the irradiated samples, with no increase observed for the non-irradiated ones. Irradiation hindered the occurrence of retrogradation in dense gels but encouraged the process in watery gels. Modification of the amylose–lipid structure in wheat starch and, in particular, a decrease of the complex symmetry were reported after irradiation with doses of 5–30 kGy by Ciésła and Eliasson (2007). It was suggested that the decreasing T_p values of the amylose–lipid complex transition, in every subsequent heating/cooling cycle, might be a reliable indicator of the previously performed irradiation.

Wang and Yu (2009) compared the effect of γ -irradiation on the physicochemical properties of flour and starch granule structure of wheat to non-irradiated wheat. The moisture content of wet gluten and titratable acidity of wheat flour were significantly altered by γ -irradiation. Gamma irradiation had a substantial effect on the titratable acidity of wheat. In fact, as the irradiation dose increased progressively from 0.6 to 3 kGy, the titratable acidity values increased 4.9, 15.2, 25.6, and 30% with respect to the non-irradiated wheat flour values [15.31 mg sodium hydroxide (NaOH)/100 g]. This result might be attributed to the grain deterioration, resulting in an increase of free fatty acid and phosphate levels (Hanft and Koehler, 2005). Gamma treatment also deformed the starch granules of wheat grain and their breakage augmented as the dose of γ -irradiation increased, apparently resulting in an increase of small starch granules.

Semi-pilot scale storage studies on irradiated prepacked whole wheat flour revealed that there was no adverse effect of irradiation and storage up to 6 months for whole wheat flour treated at doses up to 1 kGy on total proteins, fat, carbohydrates, vitamin B₁ and B₂ content, color index, sedimentation value, dough properties, total bacterial count, and mold count (Marathe et al., 2002). Storage of wheat flour resulted in slight increases in moisture, free fatty acids, damaged

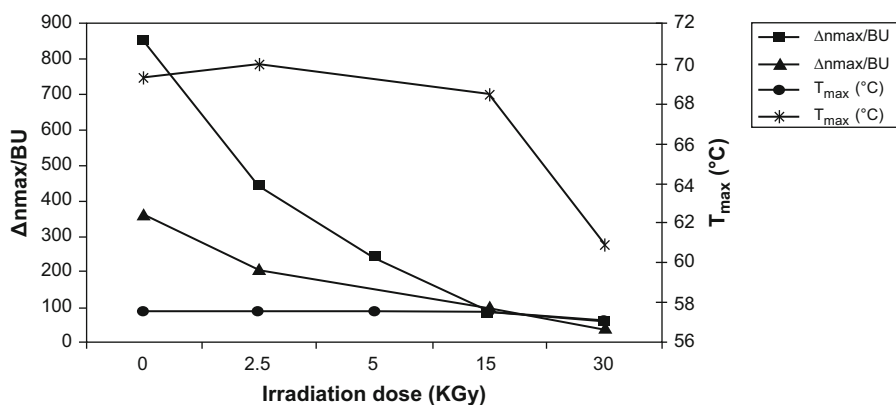


Figure 14.1: The effect of irradiation dose on viscosity and thermal properties (T_{max}) of wheat and rye flour batches (Ciésła, 2003).

starch, reducing sugars and a slight decrease in gelatinization viscosity (Figure 14.2). Irradiation at 0.25 kGy was sufficient to extend the shelf life of up to 6 months without any change in nutritional and functional attributes. Chapatias made from irradiated starch (0.25 kGy) were preferred, even after 6 months of storage, to the control.

Dolińska et al. (2004) subjected the grains of the Polish winter wheat variety Begra to γ -radiation (grain harvested in 1996) within the dose range of 0.05–10 kGy and microwave heating (MW) (grain harvested in 1997) from 28 to 98°C. It was shown that application of γ -radiation can kill or reduce insects that attack grains and reduce microbial contamination.

14.2.2 Potato

The morphological, thermal, and pasting properties of starch separated from potatoes of three varieties (Kufri Chandramukhi, Kufri Jyoti, and Kufri Chipsona-2) treated either with CIPC [isopropyl *N*-(3 chlorophenyl) carbamate] or γ -irradiation (^{60}Co , 0.1 and 0.5 kGy) and subsequently stored at 8, 12, and 16°C for 90 days were investigated by Rajarathnam et al. (2007). The irradiation of potatoes with 0.5 kGy resulted in starch with significantly lower peak, trough, and breakdown viscosity compared to starch from potatoes treated with either CIPC or 0.1 kGy irradiation. The irradiation of potatoes with 0.5 kGy resulted in a significant increase in setback and pasting temperature. Fourier transform infrared spectroscopy (FT-IR) spectra revealed that the starch from irradiated potatoes displayed a significant decrease in the intensity of the C–H stretch region between 2800 and 3000 cm^{-1} and a slight broadening of O–H stretch (3000–3600 cm^{-1}) in starches from irradiated potatoes.

Shishonok et al. (2007) investigated “the supermolecular structure of potato starch modified by e-beam irradiation. It was shown that the treatment of starch in air at doses from 110 to 440 kGy

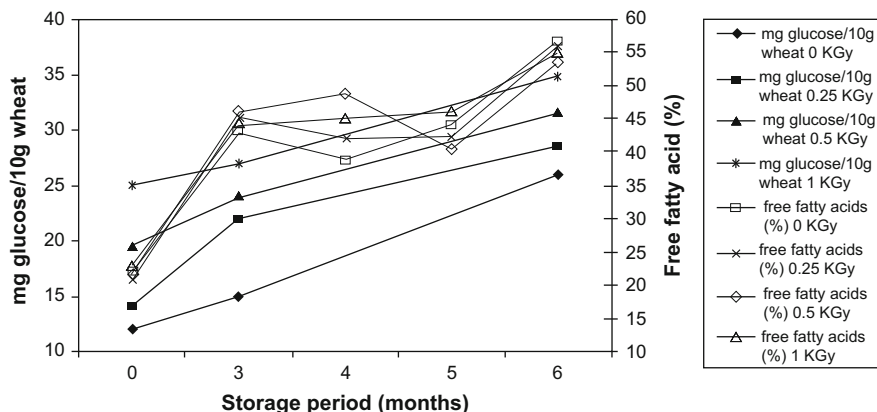


Figure 14.2: Free fatty acids and reducing sugars in irradiated wheat flour versus storage time (Marathe et al., 2002).

was accompanied by its amorphization and degradation of macromolecules, whereas an increase in the number of oxidized groups was insignificant and grain morphology remained unchanged. The flow of the gel of unirradiated starch was characterized by non-Newtonian behavior. The solutions of all irradiated samples exhibited a dramatic (by two orders of magnitude) fall in dynamic viscosity. The degree of crystallinity and of polymerization after irradiation resulted in enhancement of starch solubility in cold water from 5 to 70%. The amorphization and chain degradation in potato starch increased its solubility in cold water from 10 to 68% for the range 110–440 kGy.”

Sweet potato [*Ipomoea batatas* (L.) Lam.] roots of two Hawaii-grown clones were treated with 0.1–0.6 kGy X-ray irradiation, and their quality characteristics were evaluated before and after cooking. Root moisture content, surface color, and glucose and fructose concentrations were not affected by irradiation treatment. Firmness decreased at higher doses for red-skin, yellow-flesh roots but not for white-skin, purple-flesh roots. Irradiation had the greatest effect on sucrose concentrations, which increased linearly in response to doses as starch concentrations decreased. A sensory panel perceived sweet potato roots treated with 0.6 kGy irradiation as sweeter than control roots. Panelists found that overall acceptability was the same for control and 0.6-kGy treated roots for both clones (Wall, 2004).

14.2.3 Corn/Maize

Rombo and co-workers (2004) studied the effect of irradiation on the molecular properties of starch in maize and bean flours. Increasing irradiation dose caused an increased proportion of β -(1,3)- and β (1,4)-bonded starch in bean and maize flours. Size-exclusion high-performance liquid chromatography showed that higher irradiation doses led to a reduction in the molecular size of amylopectin in both bean and maize starches, which presumably involved debranching and an increase in the production of short, straight-chain molecules. With increased irradiation dose, there was an increase in the crystallinity of the amylopectin fraction of the bean starch due to β -bonding and amylopectin depolymerization. It is noteworthy that increased crystallinity of starches, confirmed with X-ray diffraction techniques, had already been reported in irradiated foods by McArthur and D'Appolonia (1988). These two factors and their interrelated effects were probably responsible for the observed slight reduction in maize and bean porridge starch digestibility. The impact of irradiation dose on the thermal properties (T_0 and ΔH) of irradiated maize and bean flours is displayed in Figure 14.3.

Chung and Liu (2009) found that the carboxyl content and amylose leaching of γ -irradiated corn starch increased and the swelling factor decreased with increasing radiation dose. The apparent amylose content decreased gradually from 28.7% for native starch to 20.9% for 50-kGy irradiated starch. The proportion of short amylopectin branch chains [degrees of

polymerization (DP) 6–12] increased and the longer branch chains (DP > 37) decreased with increasing radiation dose. The relative crystallinity and the degree of granule surface order decreased from 28.5% and 0.63 in native starch to 26.9% and 0.605 in 50-kGy irradiated starch, respectively. Pasting viscosity and gelatinization temperatures decreased with an increase in radiation dose. At high dose (50 kGy), melting of amylose–lipid complex in DSC thermogram was not observed. The rapidly digestible starch content decreased slightly up to 10 kGy but increased at 50 kGy. The resistant starch (RS) content decreased slightly at 2 kGy and then increased up to 50 kGy. The slowly digestible starch content showed the opposite trend to RS content.

Corn, potato, and drum-dried corn starch were exposed to X-ray and e-beam irradiation treatment at doses of 10, 50, and 100 kGy. The disintegration properties of these starches were compared using α -lactose monohydrate tablets containing 5% (w/w) starch as disintegrant (De Kerf et al., 2001). Irradiation caused fragmentation of the amylopectin fraction, thereby leading to lower molecular weight and merging with the amylose fraction and higher solubility (Figures 14.4. and 14.5), in agreement with previous studies by Rayas-Solis (1987) and Sokhey and Chinnaswamy (1993), unless cross-linking of amylose chains was initiated (Esteves et al., 1997).

14.2.4 Cassava

Bertolini et al. (2001) investigated the effect of UV and γ -irradiation on the free radical formation of cassava starch. The electron spin resonance patterns of the cassava starch samples after UV or γ -radiation showed different shapes (either two main signals AA' and BB' or a main BB' signal) depending on water content and storage time after irradiation. UV and γ -irradiation both significantly decreased starch intrinsic viscosity from 177 ml/g for non-irradiated to 126

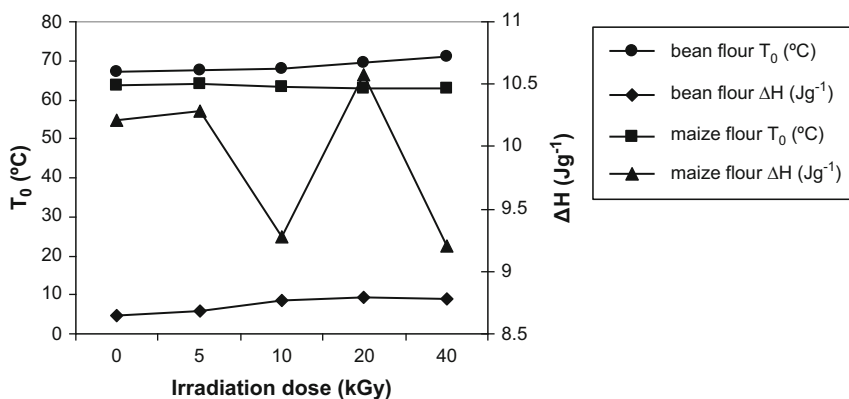


Figure 14.3: Thermal properties (T_0 and ΔH) of starches in irradiated maize and bean flours versus irradiation dose (Rombo et al., 2004).

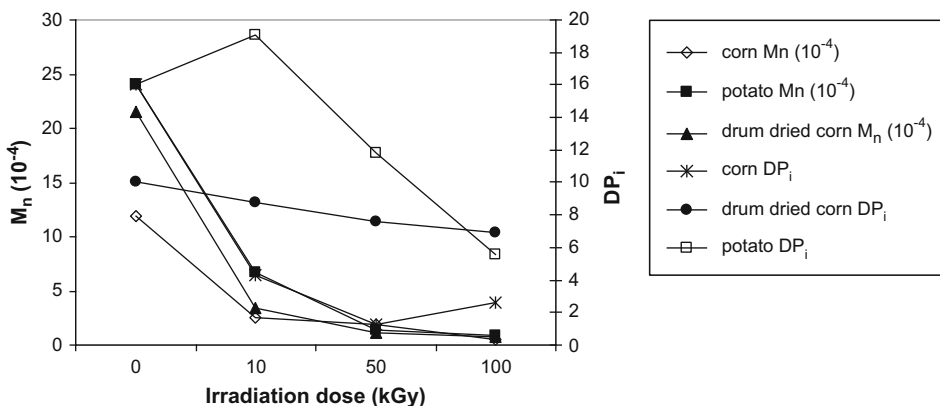


Figure 14.4: Molecular weight distribution (M_n and DP_i) of X-ray irradiated corn, potato, and DDCS against irradiation dose (De Kerf et al., 2001).

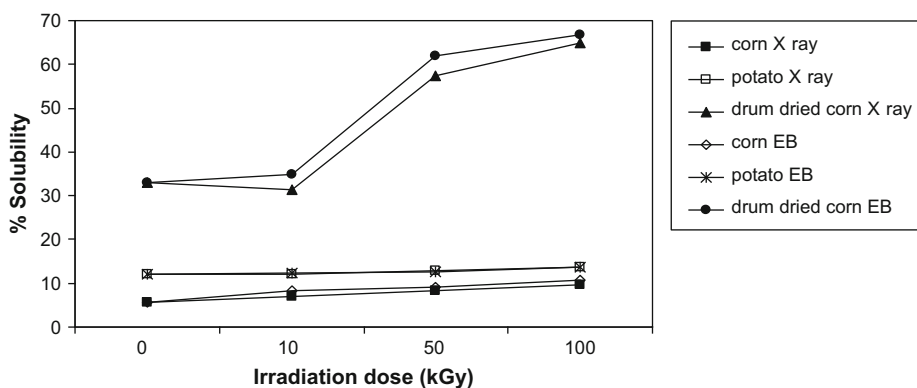


Figure 14.5: Percentage solubility ($n = 2$) of corn, potato, and DDCS versus various X-ray irradiation doses (De Kerf et al., 2001).

and 131 ml/g for UV and γ -irradiated, respectively. Starch acidification made the depolymerization effect even more pronounced.

14.2.5 Banana

Wall (2007) determined fruit quality and ripening of Dwarf Brazilian bananas (*Musa* sp., group AAB) after X-ray irradiation for disinfestation of quarantine pests. Bananas were treated with irradiation doses of 0, 200, 400, 600, or 800 Gy, stored for 7 days at 14°C, and ripened at 20°C. Irradiation neither extended banana shelf life nor affected soluble solids content, but titratable

acidity decreased with increasing dose. Starch and total sugar concentrations were similar for control and irradiated fruit at all doses. However, sucrose contents decreased linearly as dose increased, whereas glucose and fructose concentrations increased, indicating an acceleration of sucrose hydrolysis in treated bananas. Irradiation retarded peel softening but not pulp softening for winter-harvested fruit and had a minimal effect on peel and pulp firmness of summer-harvested fruit. For irradiated fruit, the respiratory climacteric rates decreased relative to control fruit, but CO₂ and ethylene production increased 1 day after irradiation stress. Summer-harvested fruit were also damaged at the 600-Gy dose for distal fruit only.

14.2.6 Chickpeas

Changes in physical and chemical properties of chickpeas γ -irradiated with ⁶⁰Co at doses of 0–50 kGy were investigated by [Graham et al. \(2002\)](#). Irradiation between 0 and 20 kGy had no significant effect on the hydration capacity of the chickpeas. However, increasing the dose from 20 to 50 kGy significantly decreased the hydration capacity due to leaching of soluble compounds from the cotyledon to the water. There was an improvement in cooking quality (defined as degree of softness) with increased irradiation (5–50 Gy). These improvements, compared with the zero irradiation treatment, revealed a reduction in compression of 3, 21, 36, 41, and 49% for 5, 10, 20, 30, and 50 kGy, respectively. The impact of irradiation dose on compression force (a measure of cooking quality) and peak viscosity of chickpeas is displayed in [Figure 14.6](#).

14.2.7 Rice

Although γ -irradiation at dosages of 0.2–2 kGy effectively controlled insects in packed aromatic milled rice (KDML-105), it also induced undesirable changes in some physico-chemical properties of the rice, such as decreased cooked rice hardness and an increase in water absorption and total solids in cooking water. Alterations of the granular structure of starch, recorded with scanning electron microscopy (SEM), affected the texture of the cooked rice. Moreover, irradiation led to an increase in yellowness (*b** value), an increase in lipid oxidation (thiobarbituric acid), a decrease in volatile compounds (ACPY, 2-acetyl-1-pyrroline), and changes in the color and aroma of irradiated cooked rice. Sensory analysis panelists responded to these changes with lower perception of sensory qualities (greatest drop for odor and overall acceptability), as shown in [Figure 14.7](#). It is advisable to use maximum doses of less than 1 kGy to disinfest aromatic rice ([Sirisoontaralak and Noomhorm, 2006](#)).

[Zuleta et al. \(2006\)](#) investigated the effect of minimal doses of γ -irradiation to reduce microbial loads (⁶⁰Co; doses of 0, 1.5, and 3 kGy) on flour from three rice cultivars with different amylose

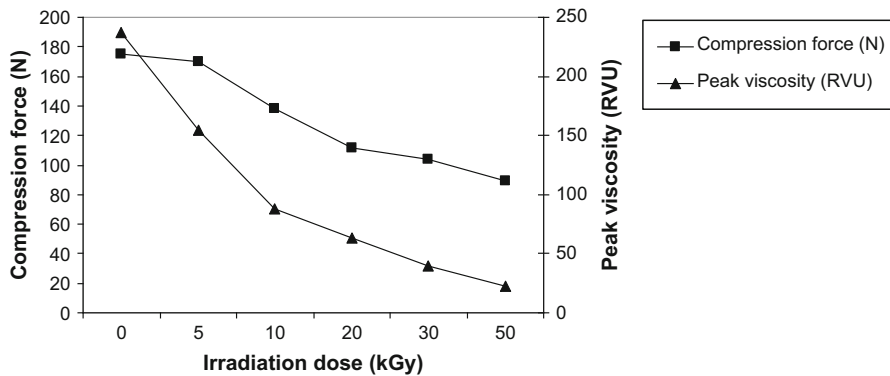


Figure 14.6: Compression force (measure of cooking quality) and peak viscosity of chickpeas versus irradiation dose (Graham et al., 2002).

contents (ACs) grown in Argentina: RP₂ (AC 25%), Yeruá (Y; AC 19%), and Higokumochi (H; AC 5%). Results showed that γ -irradiation affected rice functional and nutritive characteristics proportionally to the dosage used. With 3 kGy, for RP₂, Y, and H, respectively, original digestibility values increased 37.5, 60, and 76%; gel viscosity decreased 52, 77, and 90%; and syneresis increased 0, 193, and 546%. Amylopectin was the starch fraction most affected, as displayed by SEM.

Yu and Wang (2007) investigated the effect of γ -irradiation [0 (non-irradiation), 2, 5, 8, and 10 kGy, with dose rate of 1 kGy/h] on microstructures of rice inner endosperm, which was greater than the effect on microstructures of outer endosperm. Apparent amylose content and gel consistency were affected by irradiation pretreatment (2.9–12 and 28.8–42%, respectively). Apparent amylose content decreased and gel consistency increased with

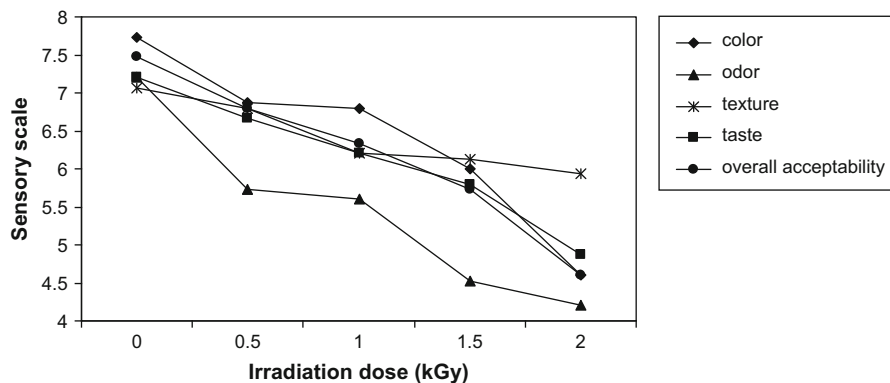


Figure 14.7: Effect of γ -irradiation on the sensory qualities of aromatic rice (KDML-105) (Sirisoontaralak and Noomhorm, 2006).

increasing dose. In addition, six major parameters of starch pasting curve—peak viscosity (PKV), hot pasting viscosity (HPV), cool pasting viscosity (CPV), setback (CPV - PKV), breakdown (PKV - HPV), and peak time—were considerably decreased with the increasing dose by different velocity. These changes were also due to the breakage of starch granules caused by γ -irradiation.

Three types of rice cultivars (*indica*, *japonica*, and hybrid rice) with similar intermediate apparent amylose content (AAC) as well as early *indica* rice cultivars with different amounts of AAC were selected for studying the effects of γ -irradiation on starch viscosity, physico-chemical properties, and starch granule structure (Wu et al., 2002). Four major parameters determined with a rapid visco analyzer—peak viscosity, hot pasting viscosity, cool pasting viscosity, and setback viscosity—were considerably decreased with increasing dose levels. Gamma irradiation reduced the amylose contents in the cultivars with low AAC and intermediate AAC and in glutinous rice, but it had no effect on the high AAC cultivar. No visible changes in gelatinization temperature were detected after irradiation, but the peak time was reduced with the dose levels. Gel consistency significantly increased in the tested cultivars, especially in the high AAC *indica* rice (from 28 to 80 mm). The starch granules were slightly deformed with γ -irradiation, suggesting that γ -irradiation can be effectively used for improving rice or cooking quality.

Bao et al. (2005) investigated the physical and structural characteristics of rice flour and starch obtained from γ -irradiated white rice. Pasting viscosities and the enthalpy changes of the rice flour and starch decreased considerably with increased irradiation dosage. Gel permeation chromatography analysis revealed that the ratio of amylopectin to amylose decreased significantly with increased radiation dosage. The changes recorded in thermal properties [T_0 , T_p , and T_c (onset, peak, and conclusion temperature, respectively)] were slight, varying between 0 and 1.3°C. The crystallinity increased in irradiated starch and decreased in irradiated flour; with regard to the native ones, this could probably be attributed to cleavage of amylopectin molecules at the amorphous regions. The weight-average molecular weight (M_w) and gyration radius (R_z) of amylopectin analyzed using high-performance size-exclusion chromatography equipped with multiangle laser-light scattering and refractive index (detector) decreased gradually from 1.48×10^9 (M_w) and 384.1 nm (R_z) of native rice starch to 2.36×10^8 (M_w) and 236.8 nm of 9-kGy irradiated starch (Figure 14.8).

14.2.8 Alginate

Alginate with an M_w of approximately 900 kDa and mannuronate:guluronate ratio of approximately 1:3 was irradiated by ^{60}Co γ -rays in aqueous solution at doses up to 200 kGy (Luan et al., 2009). The irradiated alginate with M_w of approximately 14.2 kDa was found to have a positive influence for growing plants—namely, chrysanthemum, lisianthus, and limonium—in tissue culture barley and soybean (Luan et al., 2003). The irradiated oligoalginate

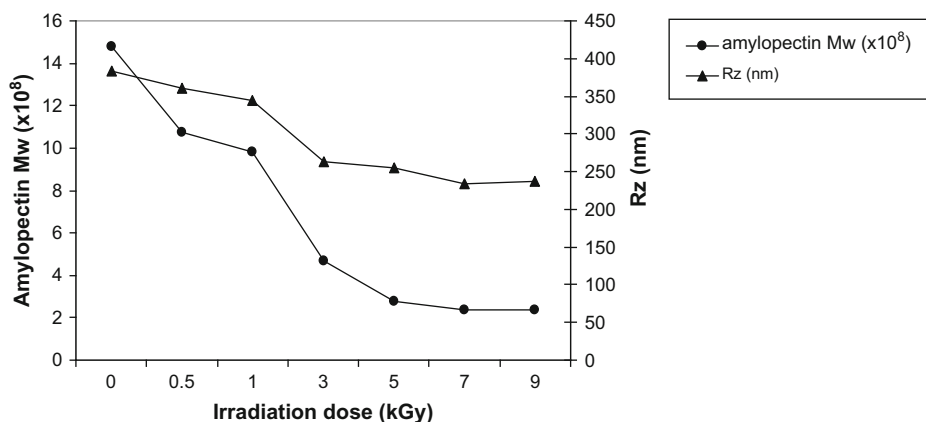


Figure 14.8: Weight-average molecular weight (M_w) of amylopectin and gyration radii of amylopectin (R_z) of the rice starch obtained from γ -irradiated white rice (Bao et al., 2005).

fraction with M_w ranging from 1 to 3 kDa displayed the strongest effect on the growth and development of the previously mentioned plants at low concentration (20 ppm). It was suggested that oligoalginate with M_w in the range 1–3 kDa is a trigger for the growth and development of plants.

The growth-promotion behavior of sodium alginate (SA) on vegetable (red amaranth, *Amaranthus cruentus* L.), 3% aqueous solution, was studied by irradiating with γ -irradiation of various total doses (12.5–50 kGy) at a dose rate of 3.5 kGy/h. The viscosity of the irradiated SA was found to decrease from 10^4 to 10^3 orders. Red amaranth was cultivated in 18 different individual plots, and SA solution (150 ppm) was applied on red amaranth after 10 days on seedlings at every 6-day interval. The irradiated SA of 37.5 kGy at 150 ppm solution showed the best performance. Dry matter of red amaranth significantly increased at 37.5 kGy on irradiated alginate treatment, which was approximately 50% higher than that of the untreated samples (Mollah et al., 2009).

14.2.9 Barley

The impact of MW irradiation (800 W) for 3, 5, and 7 min on dry matter (DM), crude protein, and starch degradation of barley grain was investigated by Sadeghi and Shawrang (2008). Duplicate *in situ* bags of untreated or irradiated barley grain were incubated in the rumen of four nonlactating Holstein cows for up to 48 h. Irradiation for 3 min had no effect, but irradiation for 5 and 7 min decreased the DM degradability. MW irradiation increased the washout fraction and decreased the potentially degradable fraction and degradation rate of starch. Irradiation for 5 min did not affect the effective starch degradability, but irradiation for 3 and 7 min increased and decreased it, respectively.

14.2.10 Dates

Moroccan dates *Phoenix dactylifera* L. cv. Boufegous were treated with 0.6, 0.9, and 1.8 kGy of γ -irradiation and subsequently stored at ambient temperatures. After 8 months of storage, the treatment increased the ash content but decreased amino acids content. Irradiation at 0.9 kGy significantly increased glucose and total sugars contents after 8 months of storage. Although after 4 months of storage a significant reduction in the starch content was displayed, reduction was recorded for both irradiated and non-irradiated dates. The starch values decreased from 1.46 to 0.90% dry basis for controls and from 1.32 to 0.86% for samples treated at 1.8 kGy. The results also indicated that the treatment at 0.6, 0.9, and 1.8 kGy in conjunction with prolonged storage resulted in significant variation in the amounts of hydrochloride-soluble pectin (HSP). The HSP amounts decreased in all samples with increasing storage time (Azelmat et al., 2006). The impact of storage time on amino acids and starch content of irradiated dates is displayed in Figure 14.9.

14.2.11 Cowpea

Abu et al. (2006) reported that γ -irradiation as low as 2 kGy significantly modified all cowpea starch pasting and functional properties studied. Irradiation at 2 kGy caused a significant increase in water absorption capacity of cowpea starch due to irradiation-induced damage or degradation of cowpea starch to simpler molecules such as dextrans and sugars—that is, depolymerization due to irradiation application. Similar results were reported by Wu et al. (2002). Application of DSC revealed an increase in the primary germ tube of cowpea starch, possibly indicating a decrease in crystallinity with increasing irradiation dose. In contrast,

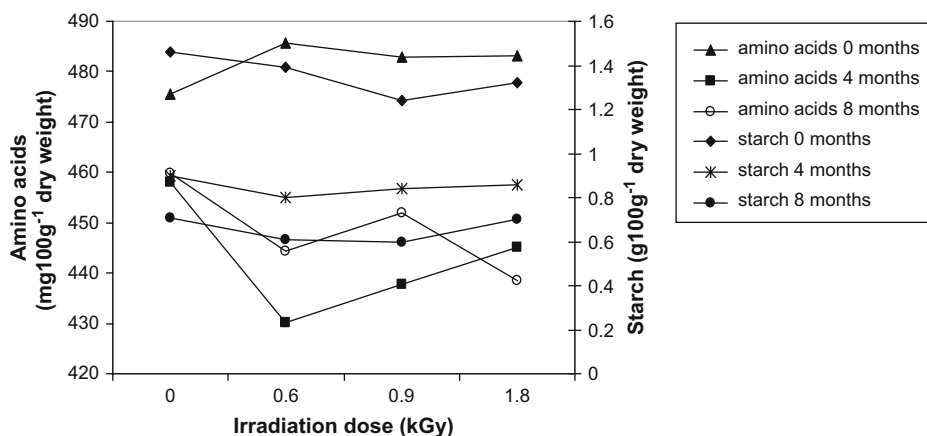


Figure 14.9: Irradiation effects on chemical properties of Boufegous dates during storage at $18 \pm 4^\circ\text{C}$ (Azelmat et al., 2006).

SEM and FT-IR show that cowpea starch granule physical properties and surface crystallinity, respectively, are not affected by γ -irradiation up to 50 kGy.

The effects of irradiation (2, 10, and 50 kGy) on swelling index and gel strength are shown in Figure 14.10, and the effects of irradiation on gelatinization enthalpy and peak gelatinization temperature of starch isolated from cowpea flours are shown in Figure 14.11.

The impact of irradiation on physical properties of starches is summarized in Table 14.1.

14.3 Carbohydrate Modification

The irradiation of cellulose triacetate (CTA) e-beam in the dose range of 10–200 kGy revealed that (1) the decomposition onset shifted to higher values, a clear indication of higher thermal stability, and (2) at low doses (10–80 kGy) the melting temperature (T_m) decreased considerably from 323 to 306°C because of the generation of defects that affect the crystals. However, at higher doses (80–200 kGy) the T_m increased to 319°C due to an increase in lamellae thickness. Similar behavior was recorded for the onset value of decomposition (T_0), which was 177, 149, and 192°C for 0, 80, and 200 kGy, respectively (Figure 14.12). It was also reported that the color intensity ΔE greatly enhanced with increasing e-beam dose and was accompanied by a significant increase in the blue color component (Nouh et al., 2008).

The effect of γ -irradiation dose (101 and 80 J/kg) on structural and electrochemical parameters of three cellophane membranes (with different contents of regenerated cellulose) was studied by de Lara et al. (2006). According to the experimental results, γ -radiation led to a reduction in salt permeability, which strongly depended on the membrane cellulose content (between 20 and 40% for 10 J/kg dose), whereas a much lower reduction occurred when the two different

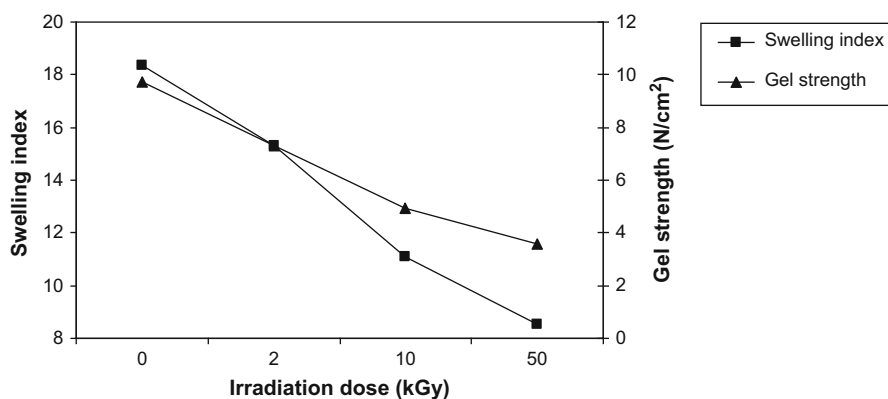


Figure 14.10: Effect of irradiation (2, 10, and 50 kGy) on functional properties (swelling index and gel strength) of starch isolated from cowpea flours (Abu et al., 2006).

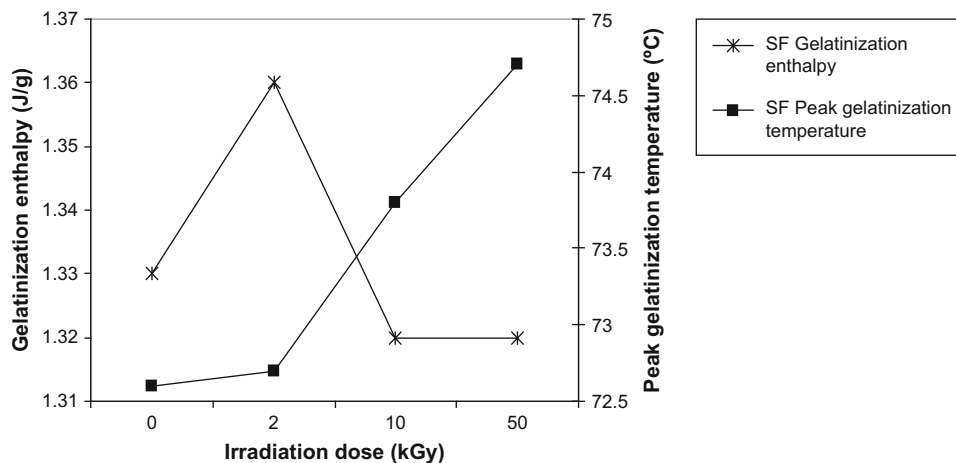


Figure 14.11: Effect of irradiation dose (0–50 kGy) on gelatinization enthalpy and peak gelatinization temperature of starch isolated from irradiated cowpea flours (SF) and pastes (SP) (Abu et al., 2006).

radiation doses for a given sample were compared. Exposure to a low radiation dose (10 J/kg) resulted in cross-linking of polymer chains.

Electrical and structural modifications in the matrix of cellulose membranes produced by γ -irradiation with a dose of 80 Gy were determined based on changes in the electrochemical parameters. Membrane irradiation reduced salt permeability and increased the cationic permselectivity to salt diffusion and membrane potential. However, X-ray photoelectron spectroscopy (XPS) analysis did not reveal any chemical changes in the membrane but a decrease of carbon concentration due to environmental contamination. The irradiation decreased the membrane fouling with bovine serum albumin (BSA) (Vazquez et al., 2005).

Borsa et al. (2003) developed cross-linked cellulose molecules by means of high-energy irradiation. Cross-linking of cellulose was greatly enhanced with swelling [NaOH and tetramethylammonium hydroxide (TMAH)], carboxymethylation, and coating with water-soluble carboxymethyl cellulose. Samples (10 kGy) were irradiated in wet state of the fabric because the mobility of cellulose molecules is much higher in the presence of water, which is advantageous for the development of cross-links. Irradiation in dry state was associated with a low number of cleavages because of the many cross-links that developed. On the contrary, in wet state, higher mobility led to approximately the same number of cleavages for NaOH or even higher number for TMAH. Fewer cleavages were reported for untreated sample, almost the same for NaOH treated, and many more for TMAH treated in the wet state compared to the dry state. When the structure was modified with cross-linking, an increase in the absorbance was assigned to the intermolecular hydrogen bonds (FT-IR), and a decrease of fiber swelling was reported.

TABLE 14.1 Effect of Irradiation on Physical Properties of Starches

| Type of Starch | Irradiation Type/Dose | Physical Properties | References |
|------------------------------------|---|---|--|
| Wheat starch amylose lipid complex | γ irradiation/ 30 kGy | T_p increased from 58.5 to 60.2°C after irradiation T_0 increased from 53.7 to 56.5°C after irradiation ΔH decreased from 12.9 to 9.6 Jg ⁻¹ after irradiation | Ciésla and Eliasson, 2003 |
| Wheat and rye flour | γ irradiation/ 30 kGy | T_{max} decreased from 69.3 to 59.3°C | Ciésla, 2003 |
| Wheat starch amylose lipid complex | γ irradiation/5 30 kGy | T_p decreased from 99.7 to 95.8°C | Ciésla and Eliasson, 2007 |
| Wheat flour and starch granule | γ irradiation/ 0.6 3 kGy | Moisture content of wet gluten altered Titratable acidity of wheat flour increased from 4.9 to 30% | Wang and Yu, 2009 |
| Whole wheat flour | γ irradiation/ 0.25 1 kGy | No adverse effect on total proteins, fat, carbohydrates, vitamin B ₁ and B ₂ content, color index, sedimentation value, dough properties, total bacterial count, and mould count Slight decrease in viscosity and moisture | Marathe et al., 2002 |
| Potatoes | γ irradiation/ 0.1 and 0.5 kGy | Significantly lower peak, trough, and breakdown viscosity Setback and pasting temperature increased. Intensity of the C H stretch decreased from 2800 and 3000 cm ⁻¹ | Rajarathnam et al., 2007 |
| Potatoes | e beam irradiation/ 110 440 kGy | Strong drop in dynamic viscosity Degree of polymerization of amylopectin and amylose decreased Solubility in cold water increased from 10 to 68% | Shishonok et al., 2007 |
| Sweet potato | γ irradiation/ 0.1 0.6 kGy | No effect on root moisture content, surface color, and glucose and fructose concentration The alcohol insoluble solids and the starch concentrations of raw roots decreased | Wall, 2004 |
| Maize and bean flours | γ irradiation/ 2.5 kGy | Reduction in amylopectin molecular size Increase in crystallinity of amylopectin fraction | McArthur and D'Appolonia, 1988; Rombo et al., 2004 |
| Corn | γ irradiation/2, 10, and 50 kGy | Carboxyl content increased Amylose leaching decreased from 28.7 to 20.9% Swelling factor decreased Crystallinity and the degree of granule surface decreased from 28.5 to 26.9% and from 0.631 to 0.605, respectively Pasting viscosity and gelatinization temperatures decreased | Chung and Liu, 2009 |

(Continued)

Table 14.1 Effect of Irradiation on Physical Properties of Starches—cont'd

| Type of Starch | Irradiation Type/Dose | Physical Properties | References |
|-----------------------------------|---|---|----------------------------------|
| Corn, potato, and drum dried corn | γ irradiation and e beam irradiation/10, 50, and 100 kGy | Solubility of corn increased from 5.6% (0 kGy) to 9.6% (100 kGy) Solubility of drum dried corn increased from 33% (0 kGy) to 64.9% (100 kGy) | De Kerf et al., 2001 |
| Cassava | UV and γ irradiation/772 J/cm ² and 8.1 kGy | Viscosity decreased from 177 ml/g for non irradiated to 126 ml/g | Bertolini et al., 2001 |
| Banana | γ irradiation/0, 200, 400, 600, or 800 Gy | Titrateable acidity decreased Sucrose contents decreased Glucose and fructose concentrations increased Minimal effect on peel and pulp firmness Respiratory climacteric rates decreased CO ₂ and ethylene production increased | Wall, 2007 |
| Chickpeas | γ irradiation/0 50 kGy | No significant effect on hydration capacity (HC) between 0 and 20 kGy, but significant decrease (107 to 98%) in HC at 50 kGy Viscosity decreased from 235 to 150 RVU for 0 and 2 kGy, respectively | Graham et al., 2002 |
| Rice | γ irradiation/0.2 2 kGy | Cooked rice hardness decreased from 1.74 to 1.09 kgf Water absorption and total solids increased from 2.24 to 2.91 g/g and 0.79 to 1.76 g/100 g, respectively Texture decreased from 7.07 to 5.93 Yellowness increased from 9.72 to 14.66 Lipid oxidation increased from 2.84 to 4.42 nmol/g Appearance decreased from 7.53 to 5 Color and aroma decreased from 7.73 to 4.60 and 400 to 330 ng/g, respectively Taste decreased from 7.20 to 4.87 Odor and overall acceptability decreased from 7.20 to 4.20 and from 7.47 to 4.60, respectively | Sirisoontarak and Noomhorm, 2006 |
| Flour from three rice cultivars | γ irradiation/0, 1.5, and 3 kGy | Functional and nutritive characteristics were affected Original digestibility values increased from 37.5 to 76% Syneresis increased from 193 to 546% | Zuleta et al., 2006 |

Table 14.1 Effect of Irradiation on Physical Properties of Starches—cont'd

| Type of Starch | Irradiation Type/Dose | Physical Properties | References |
|----------------------------|---|--|----------------------------------|
| Rice | γ irradiation/ 2, 5, 8, and 10 kGy | Amylose content increased from 2.9 to 12% Gel consistency increased from 28.8 to 42% | Yu and Wang, 2007 |
| Rice | γ irradiation/ 0–1 kGy | Peak viscosity, hot pasting viscosity, cool pasting viscosity, and setback viscosity were considerably decreased No visible changes in gelatinization temperature Gel consistency increased from 28 to 80 mm | Wu et al., 2002 |
| Rice, flour, and starch | γ irradiation/ 9 kGy | Enthalpy decreased from 7.5 to 3.8 J/g (flour) and 12.1 to 10.8 J/g (starch) Amylopectin and amylose decreased from 14.77×10^8 to 2.36×10^8 and from 3.85×10^5 to 3.66×10^5 , respectively Crystallinity of starch increased from 36 to 38%, and that of flour decreased from 31.6 to 25% M_w decreased from 1.48×10^9 to 2.36×10^8 R_z decreased from 384.1 to 236.8 nm Carbohydrate contents increased from 36 to 56% T_0 of flour increased from 57.7 to 59.9°C T_p of flour decreased from 64.9 to 64.5°C T_c of flour decreased from 71.6 to 70.4°C | Bao et al., 2005 |
| Alginate | γ irradiation/ 200 kGy | M_w ranged from 1 to 3 kDa | Luan et al., 2003, 2009 |
| Alginate | γ irradiation/ 12.5–50 kGy | Viscosity decreased from 10^4 to 10^3 Dry matter of red amaranth converted at 150 ppm | Mollah et al., 2009 |
| Barley | MW irradiation/ 800 W | Washout of dry matter fraction increased from 0.558 to 0.587 Degradation of dry matter fraction decreased from 0.340 to 0.291 | Sadeghi and Shawrang, 2008 |
| Dates | γ irradiation/ 0.6, 0.9, and 1.8 kGy | Amino acids content decreased from 483.23 to 438.5 mg/100 g dry weight (1.8 kGy) Titratable acidity decreased from 0.2 to 0.14 g malic acid/100 g dry weight (1.8 kGy) Total sugars contents increased from 81.58 to 87.43 g/100 g dry weight HSP amount decreased | Azelmat et al., 2006 |

(Continued)

Table 14.1 Effect of Irradiation on Physical Properties of Starches—cont'd

| Type of Starch | Irradiation Type/Dose | Physical Properties | References |
|----------------|-----------------------------------|---|-----------------------------------|
| Cowpea | γ irradiation/1 and 50 kGy | Water absorption capacity of cowpea flours increased from 1.70 to 1.90 Oil absorption capacity of cowpea flours increased from 0.78 to 1.10 Swelling index of cowpea flours decreased from 18.37 to 8.53 Gel strength of cowpea flours decreased from 9.73 to 3.57 n/cm ² Peak viscosity of cowpea flours decreased from 1689 to 211 | Abu et al., 2006; Wu et al., 2002 |

Zhao and Mitomo (2008) found that e-beam irradiating solid-state and low concentrated solution resulted in degradation and a high concentrated solution state that was favorable for cross-linking. X-ray diffraction analysis revealed that the cross-linked dihydroxypropyl (DHP)-chitosan paste was more amorphous than the original DHP-chitosan. The order of peak area of these samples was as follows: original DHP-chitosan > DHP-chitosan paste > cross-linked DHP-chitosan. Crystalline peaks decreased greatly after lactic acid treatment in paste, implying the decrease of intermolecular hydrogen bonding, whereas there was a strong decrease after cross-linking, indicating the formation of gel network structure. The swelling of polyvinyl alcohol (PVA)/carboxymethylated (CM)-chitosan blend hydrogels prepared by irradiation and cross-linked CM-chitin and CM-chitosan blends against irradiation dose is shown in Figure 14.13.

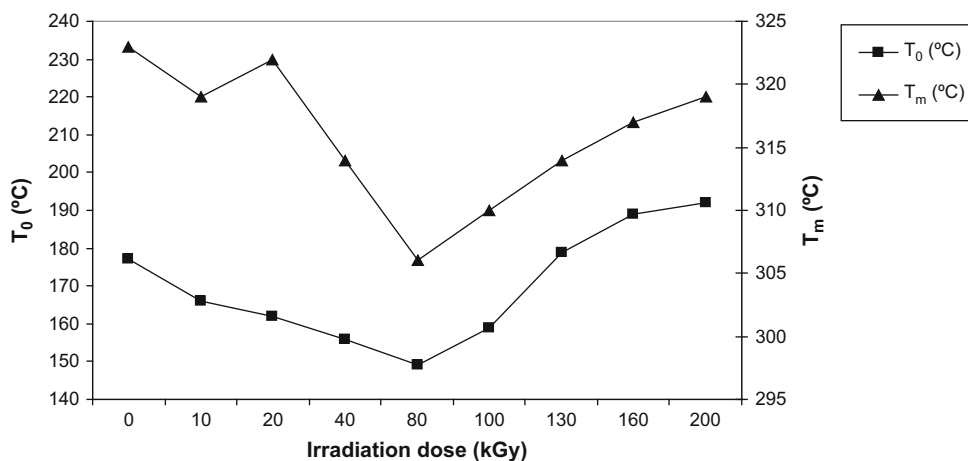


Figure 14.12: Thermal properties [onset temperature of decomposition T_0 (°C) and melting temperature T_m (°C)] for CTA samples as a function of the e-beam dose (Nouh et al., 2008).

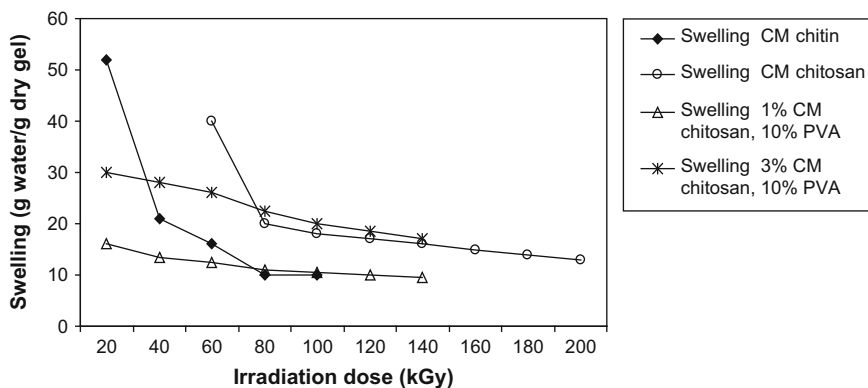


Figure 14.13: Effect of irradiation dose on the swelling of PVA/CM-chitosan blend hydrogels prepared by irradiation (Zhao et al., 2003) and cross-linked CM-chitin and CM-chitosan (Zhao et al., 2008).

Newer types of cross-linked chitin derivatives (carboxymethylchitin and carboxymethylchitosan) were synthesized with e-beam radiation (1–200 kGy), and the sorption of Cu(II) ions onto these cross-linked chitin derivatives was investigated. Sorption kinetic studies indicated the rapid removal of Cu(II) ions from the aqueous solutions. Moreover, isothermal sorption data revealed that Cu(II) was removed by these cross-linked carboxymethylated chitin derivatives with high efficiency. The uptake of Cu(II) ions was 161 mg/g on cross-linked carboxymethylchitosan at pH 5.5. Low pH was shown to be favorable for Cu(II) desorption. The Cu(II) ions were desorbed from the cross-linked matrix rapidly and completely after a treatment in a diluted HCl solution (Zhao et al., 2003).

Tahtat and co-workers (2007) investigated the effect of γ -irradiation on the N-deacetylation of chitin to form chitosan. Chitin from crab shells was irradiated up to 20 kGy and N-deacetylated in aqueous NaOH solution (40 and 60% w/w) at 60 and 100°C for 60 min. The degree of N-deacetylation (DD) of non-irradiated and irradiated samples was determined by the infrared band ratio method. It was found that a higher extent of N-deacetylation was achieved for the chitin samples irradiated up to a dose of 20 kGy compared to non-irradiated chitin. The DD values of non-irradiated and 20-kGy irradiated chitin by N-deacetylation at 60°C with 40% NaOH for 60 min were found to be 38 and 60%, respectively. The increase in DD by irradiation was interpreted to be a result of a reduction in chitin molecular weight. Low-dose irradiation of chitin has provided the possibility of its N-deacetylation into chitosan at much milder reaction conditions. Radiation-induced enhancement of N-deacetylation was found to be mostly due to reduction in the molecular weight of irradiated chitin.

Transparent starch-based plastic sheets were prepared by irradiation of compression-molded starch-based mixture in physical gel state with e-beam at room temperature. After irradiation, the ductility and tensile strength (TS) of the sheets were improved (from 45 to 58 MPa for TS) due to the chemical reactions (which was demonstrated by determination of gel fraction

and DSC profiles) between starch macromolecules under the action of ionizing radiation. Addition of glycerol to starch proved to be an excellent plasticizer so that the ductility of starch sheets greatly improved (elongation at break increased from 0 to 50%). The TS of dry starch-based plastic sheets increased further, and the TS then either leveled off or decreased slightly. PVA was incorporated into starch-based sheets, and with increasing PVA content, the TS of dry starch/PVA blend plastic sheets decreased from 28 to 16 MPa, whereas the elongation at break increased from 6 to 30% (Zhai et al., 2003).

Wu and Song (2006) prepared low-viscosity carboxymethyl corn starch with the reaction of γ -irradiated starch with monochloroacetic acid in the presence of alkali. Although the viscosity decreased with an increase in irradiation dose, the viscosity increased with increasing dose rate (for an increase in dose rate from 3 to 15 Gy/min, viscosity increased from 65 to 250 mPa s) and degree of substitution (DS). Gamma irradiation can activate the starch to react with monochloroacetic acid, and the higher the irradiation dose, the higher the DS and the reaction efficiency. The final product, carboxymethyl starch (CMS), had low viscosity at high concentration, and the higher the irradiation dose, the closer the rheological behavior to a Newtonian liquid. The applications of irradiation on carbohydrate modification are summarized in Table 14.2.

The impact of irradiation dose on the quality indices (percentage ACC and gel consistency) of irradiated rice is displayed in Figure 14.14.

14.4 Chitin/Chitosan

Radiation technology can be effectively utilized to process natural polymers such as chitin/chitosan that occur in abundance. Although chitin and chitosan have unique characteristics in terms of solution properties, membrane formation, and metal chelation, their applications are still limited due to the low solubility in water, and there is a strong need to enhance both their solubility and their water uptake for various applications (Chmielewski et al., 2005). Radiation processing (either directly or grafting) of carbohydrates can induce modifications in molecular weight, hydrophobicity, and mechanical properties. Radiation of natural polysaccharides (chitin, chitosan, carrageenan, and alginates) can enhance bioactivities such as growth promotion of plants, suppression of heavy metal stress on plants, and anti-microbiological activities (Kume, 2000).

Yang and co-workers (2007) investigated the effects induced by three different sterilization methods (steam, γ -radiation, and ethylene oxide) with different doses or sterilization times by means of FTIR spectroscopy, X-ray diffraction, and assessments of molecular weight and degree of deacetylation. The results revealed that the steam sterilization greatly darkened the color of chitosan, especially at an irradiation dose higher than 10 kGy (only 20% of MW remained after 25 kGy). The sharp decrease in MW of chitosan exposed to irradiation induced

TABLE 14.2 Impact of Irradiation Application on Carbohydrate Modification

| Carbohydrate | Irradiation Type/Dose | Physical Properties | Reference |
|-------------------------------|--|---|-----------------------|
| Cellulose triacetate | e beam irradiation/ 10 200 kGy | T_m decreased considerably from 323 to 306°C (10 80 kGy) T_m increased up to 319°C (80 200 kGy) Increase in blue color intensity from 3.8 to 8.10 | Nouh et al., 2008 |
| Cellophane membranes | γ irradiation/ 101 and 80 J/kg | Reduction in salt permeability from 1.33 to 1.10×10^{-6} m/s Increase in the negative character of cellophane membranes | de Lara et al., 2006 |
| Matrix of cellulose membranes | γ irradiation/ 80 Gy | Reduction in salt permeability from 2.30 to 1.41×10^{-6} m/s Cationic permselectivity was increased | Vazquez et al., 2005 |
| Cellulose molecules | γ irradiation/ 10 kGy | Increase in the absorbance of cellulose's hydroxyl groups from 42 to 115% for CMC fiber + CMC sol Decrease of fiber swelling | Borsa et al., 2003 |
| DHP chitosan | e beam irradiation/ 1 kGy | Crystalline peaks decreased | Zhao and Mitomo, 2008 |
| N deacetylation of chitin | γ irradiation/ 20 kGy | Increase in degree of N deacetylation Reduction in molecular weight from 130 to 71 kDa Intrinsic viscosity decreased from 298 to 199 ml/g | Tahtat et al., 2007 |
| Dry starch/PVA blend | e beam irradiation/ 30 70 kGy | TS increased from 45 to 58 MPa (due to the chemical reactions) %E increased from 0 to 50% (due to the chemical reactions) TS decreased from 28 to 16 MPa (when the amount of glycerol was 30% in starch based sheet) %E increased from 6 to 30% (amount of glycerol was 30% in starch based sheet) | Zhai et al., 2003 |
| Carboxymethyl corn starch | γ irradiation/ 3 15 Gy | Viscosity increased from 65 to 250 mPa s | Wu and Song, 2006 |

radical formation occurring randomly at any carbon atoms of the chitosan base units and thereby splitting 1–4 glycosidic bonds, causing main chain scission.

Hewajulige et al. (2009) investigated the potential use of γ -irradiated chitosan for control of the anthracnose disease-causing organism *Colletrichum gloesporioides*, and extension of storage life of papaya varieties Rathna and Red Lady. These researchers extracted chitin from shrimp waste was converted into chitosan and used as an antifungal treatment against fungal strains isolated from both papaya varieties. Chitosan in powder form and as 1% solution was irradiated

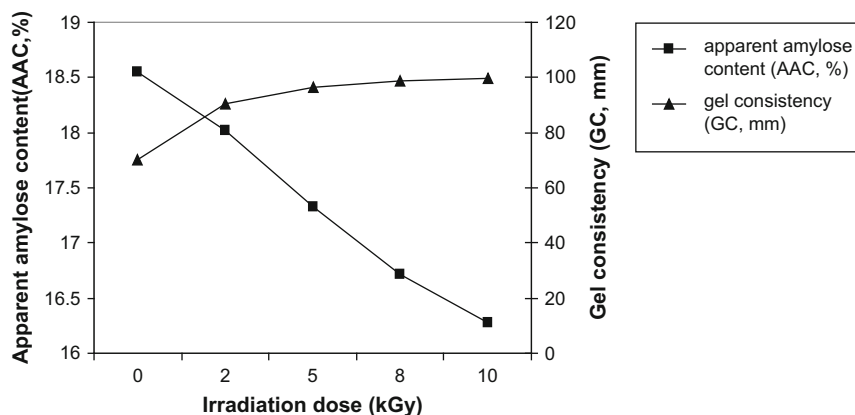


Figure 14.14: Effect of irradiation dose on the quality indices of irradiated rice (Yu and Wang, 2007).

with doses of 5, 10, 25, 50, 75, 100, and 150 kGy of ^{60}Co γ -rays in order to enhance antifungal activity. The fungal strains were selected via a series of *in vitro* experiments using potato dextrose agar (PDA). A complete inhibition of growth in both fungal strains was observed on PDA plates incorporated with 1% chitosan solution at all irradiated doses compared to the control (distilled water). The plates incorporated with non-irradiated chitosan (0 kGy) and inoculated with the fungus isolated from Red Lady papaya showed slight mycelial growth of both fungal strains, and 1% chitosan solution (in 10% acetic acid) irradiated at the lowest dose (5 kGy) was selected for *in vivo* experiments on storage life extension of papaya fruits.

Zainol et al. (2009) irradiated chitosan powder with γ -rays of 10, 25, 50, and 100 kGy. The γ -rays induced a noticeable change in color tone intensity of chitosan. FT-IR analysis confirmed that the chain scission reaction occurred as a result of γ -ray exposure through the depolymerization mechanisms. The DD of chitosan measured using FT-IR revealed a negligible effect due to the exposure of γ -ray radiation. Further investigation of the viscosity average molecular weight (M_v) showed a reduction of M_v from 577 kDa of pure chitosan to 458, 242, 159, and 106 kDa for 10, 25, 50, and 100 kGy of γ -radiated chitosan, respectively. Moreover, the TS and percentage elongation (%E) at break and stress-strain curves showed a similar decreasing trend with increasing dosage of γ -ray, as shown in Figures 14.15 and 14.16.

Mahlous et al. (2007) extracted chitin from irradiated and non-irradiated prawn shells in an attempt to optimize the deproteinization and demineralization processes, such as the concentrations of alkali and acidic media, the reaction times, and temperatures. The optimal irradiation dose for reducing the deproteinization time by a factor of three compared with non-irradiated samples was 25 kGy. Optimal conditions for chitin extraction were as follows:

1. For deproteinization: Irradiation dose, 25 kGy; 1 N NaOH; reaction temperature, 85°C; reaction time, 1 h.

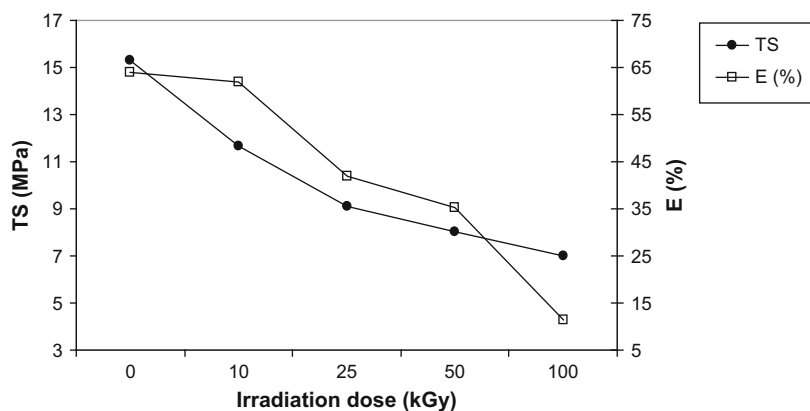


Figure 14.15: Tensile strength (TS) and elongation at break (%E) of chitosan powders versus irradiation dose (Zainol et al., 2009).

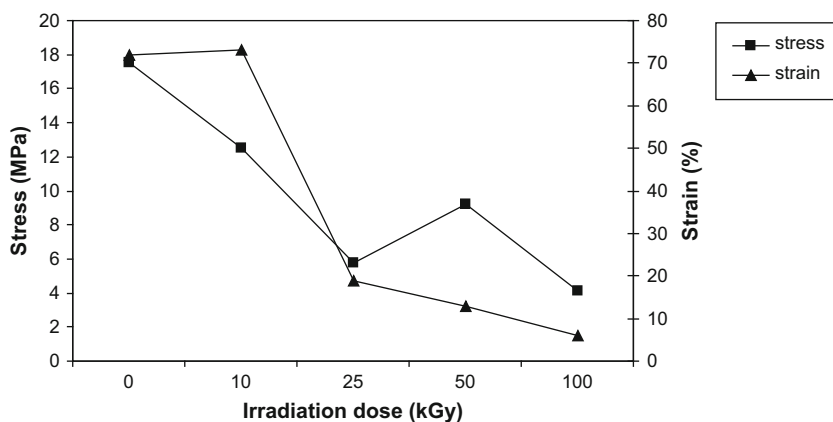


Figure 14.16: Typical stress-strain curves for chitosan film at different dose of γ -ray exposure (Zainol et al., 2009).

2. For demineralization: Irradiation dose, 25 kGy, 1 N NaOH; room temperature, $23 \pm 1^\circ\text{C}$; reaction time, 3 h.
3. For deacetylation: 60% NaOH irradiation at 25 kGy; treatment temperature, 100°C ; reaction time, 2 h.

Under the previously mentioned conditions, DD reached 93%.

DHP-chitosan, despite its many applications, is hardly soluble in water. Therefore, Zhao and Mitomo (2008) introduced some further modifications of the polymer using e-beam radiation.

Diluted lactic acid was used to improve the solubility of DHP-chitosan, and then the effects of e-beam radiation on the DHP-chitosan in solid state and solution state were investigated. It was found that solid state and low concentrated solution state resulted in degradation, whereas highly concentrated solution state was favorable for cross-linking.

The information available on antioxidant activity of CTS and its derivatives is limited and contradictory, and it was initially obtained from *in vitro* models (Je et al., 2004a,b; Xing et al., 2004). Antioxidant effects of CTS *in vitro*, depending on its molecular antioxidant activity of oligomers, in comparison with high-molecular-weight CTS have been reported (Xing et al., 2004, 2005). However, these results are not in agreement with *in vivo* findings (Chiang et al., 2000).

Rao et al. (2005) investigated the shelf life of intermediate-moisture (IM) meat products using a combination of hurdles, such as reduced a_w , active edible coating of chitosan, and irradiation. They reported that “the antioxidant activity of chitosan increased upon irradiation without significantly affecting its antimicrobial property. The a_w of meat products such as mutton sheek kebabs and steak bacon was first reduced to 0.85 ± 0.02 . The products were then coated with chitosan and irradiated (4 kGy). No viable bacteria or fungi were detected in chitosan-coated, irradiated products. In contrast, IM meat products that were not subjected to γ -radiation showed visible fungal growth within 2 weeks. The chitosan-coated products showed lower thiobarbituric acid reactive substances (TBARS) than the noncoated samples for up to 4 weeks of storage at ambient temperature.”

A synopsis of applications of irradiation on the properties of chitin/chitosan is given in Table 14.3.

14.5 Cellulose

Földvary et al. (2003) reported that both radiation and treatment with alkali solution (NaOH or TMAH) caused loss of weight in cotton cellulose (CC). Exposure of CC to radiation initiated scissions in the cellulose chains, and further treatment with aqueous alkaline solutions led to dissolution of some small fragments. This degradation was confirmed by the weight loss, dissolution experiments, and the decrease in degree of polymerization (Takács et al., 1999, 2000, 2001).

The physical properties of the cellulose fabric treated with MW irradiation at 40 and 50°C for 1–30 min were investigated by Hou et al. (2008). The TS of the treated cellulose with MW irradiation was higher and increased further with treating temperature and time, whereas the %E at break decreased (Figure 14.17). The tearing strength of the treated cellulose fabric with MW irradiation also increased with treating temperature and time, and it was much higher than that of the untreated sample. Recorded changes of physical properties were mainly due to the increase in the crystallinity of the cellulose fabric treated with MW. Thermal analysis (DSC)

TABLE 14.3 Applications of Irradiation on Chitin/Chitosan

| Chitin/Chitosan | Irradiation Type/Dose | Physical Properties | Reference |
|-----------------|---|---|-----------------------|
| Chitosan | γ irradiation and ethylene oxide/10 and 25 kGy | Decrease in M_w from 5.69 to 5.60×10^{-5} Degree of deacetylation increased from 91.1 to 91.5% Color of chitosan altered | Yang et al., 2007 |
| Chitosan powder | γ irradiation/10, 25, 50, and 100 kGy | Noticeable color tone intensity change Reduction of M_v from 577 to 106 kDa Degree of deacetylation decreased from 74.37 to 70.44% TS decreased from 15.33 to 7 MPa %E decreased from 63.96 to 11.41% | Zainol et al., 2009 |
| DHP chitosan | e beam irradiation/1 kGy | Cross linking increased | Zhao and Mitomo, 2008 |
| Chitosan | γ irradiation/4 kGy | Reduction of a_w to 0.85 Antioxidant activity increased No viable bacteria or fungi Lower TBARS | Rao et al., 2005 |

revealed that the enthalpies (endothermic peak) of cellulose fabrics increased proportionally to the irradiation time and temperature, probably due to an increase in crystallinity.

Vázquez and co-workers (2008) investigated the modifications initiated by different types of ionizing radiation and thermal treatment on transport, chemical, and structural parameters of polymeric (regenerated cellulose) membranes. XPS analysis did not reveal any significant chemical changes on membrane surfaces as a result of the treatments, whereas IR spectra

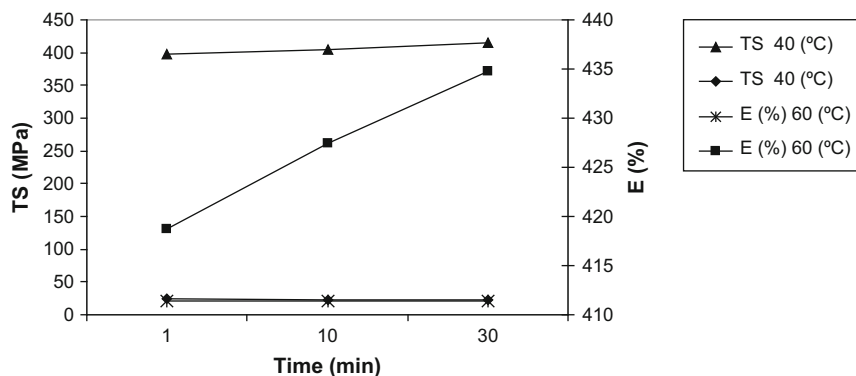


Figure 14.17: Tensile strength (TS) and percentage elongation (%E) of the cotton fabrics untreated and treated with MW irradiation versus time (1–30 min) (Hou et al., 2008).

suggested a reorganization of hydrogen bonds and/or a generation of radical species for the γ -irradiated samples. Differences in salt permeability were attributed to the expansion/compression of the polymer chains.

Cotton cellulose was swollen in aqueous solutions of NaOH and TMAH, respectively, in the presence of air. After neutralization and drying, samples were irradiated in open air (3, 10, and 20 kGy) in dry form (water content ~8–10%). Degrees of polymerization (DP) and FT-IR spectra were determined as a function of base concentration (Tóth et al., 2003). DP and FT-IR data strongly suggested irradiation cross-linking was assisted by the enhanced mobility of molecular chains in the amorphous part of treated cellulose. The effect of preswelling was more significant for TMAH-treated samples. These results were considered to be an additional confirmation for higher swelling ability of TMAH compared to NaOH.

Katsumate and co-workers (2007) investigated the effect of γ -irradiation dose (0–100 kGy) on the resistance of sapwood (*Cryptomeria japonica*) to biological attacks [termites (*Coptotermes formosanus* Shirami) decay due to the fungi *Fomitopsis palustris* and *Trametes versicolor*]. It was clearly demonstrated that the amount of wood consumed by *Coptotermes formosanus* increased with doses of γ -irradiation [from 80 to 120 termite consumption rate ($\mu\text{g}/\text{termite day}$) for 0 and 100 kGy, respectively]. In contrast, γ -irradiation did not exhibit any remarkable effect on the decay susceptibility of wood. These results suggested that the decreased cellulose DP by γ -irradiation contributed to an increase in feeding activity of the termites, whereas the matrix of the cell wall did not undergo any substantial changes, thereby resulting in the consistency of decay resistance. It was thus suggested that γ -irradiated wood has strong potential as matrix (substrate) in bait systems.

According to Cody et al. (2009), “scanning transmission X-ray microscopy and micro carbon X-ray absorption near edge spectroscopy (C-XANES) can effectively provide quantitative information regarding the distribution of the biopolymers cellulose, hemicellulose, and lignin in vascular plant cell walls. Polysaccharides are susceptible to soft X-ray irradiation-induced chemical transformations that may complicate spectral analysis. The primary chemical effect of soft X-ray irradiation on cellulose acetate involved mass loss coincident with deacetylation, whereas a lesser amount of vinyl ketone formation also occurs. Reduction in irradiation dose via defocusing doses enabled high-quality pristine spectra to be obtained. Radiation-induced chemical modification studies of oak cell wall revealed that cellulose and hemicelluloses are less labile to chemical modification than cellulose acetate.”

Stoica-Guzun et al. (2007) attempted to quantify tetracycline transport through irradiated and non-irradiated bacterial cellulose membranes. A mathematical model that also considers the possibility of drug adsorption on bacterial cellulose matrix was proposed based on experimental observations. The values of two parameters (D_m and K_a) were identified by fitting experimental data with theoretical results. In the case of irradiated membranes, an abrupt decrease of diffusion coefficient was observed. The same variation was observed for adsorption

constant rate. The increase in irradiation dose had practically no effect on these two parameters. If bacterial cellulose is used as matrix encapsulation for different drugs, the application of radiation (between 5 and 25 kGy) for the drug release can be retarded.

Lee et al. (2007) irradiated (with doses of 1–2 kGy) the mycelia in order to induce the lignocellulolytic mutants of *Pleurotus ostreatus*. Five strains were isolated by the criteria of clamp connection, fruiting body formation, growth rate, and activities of extracellular enzymes. All isolated strains were able to form the fruiting bodies and grew similarly to the control. The extracellular enzyme activities in liquid media of isolated strains were up to 10 times higher than that of the control. Genetic similarities of the isolated strains ranged from 64.4 to 93.3% of the control. From these results, it seems that the genetic diversity of *P. ostreatus* could be changed and useful strains could be induced by γ -ray radiation to recycle or reuse biowastes.

The applications of irradiation on cellulose properties are summarized in Table 14.4.

14.6 Blends of Natural Polymers

Senna et al. (2007) produced foamy low-density polyethylene/plasticized starch (LDPE/PLST) blends at different compositions in the presence of azodicarbonamide (ACA) compound as foaming agent. The LDPE/PLST blends both before and after e-beam irradiation were analyzed in terms of chemical properties, bulk density, and structure morphology. The TS and %E at break of the unfoamed LDPE/PLST blends increased with increasing e-beam dose up to 30 kGy and then tended to decrease irrespective of the blend composition. Both TS and %E at break in a blend containing 30% PLST were shown to decrease considerably with increasing irradiation dose (Figure 14.18). Both the soil burial test and SEM micrographs confirmed the growth of microorganisms over all the blend sheets. The blend was completely damaged after 2 months of burial.

Ruckert and co-workers (1999) employed allylurea (AU) as a reactive additive for obtaining grafted plasticized films with stabilized physical properties. Potato starch was mixed with AU [30–50 parts per hundred (pph)] in a mixer operating at 125°C. Freshly prepared thermoplastic films of appropriate thickness were exposed to 175-kV e-beam radiation to induce covalent grafting of AU by a free radical process. The glass transition region for the samples treated with a 200-kGy dose decreased to approximately 20°C, whereas the films treated with a 400-kGy dose exhibited a glass transition slightly above 25°C. The latter result is consistent with the observed higher brittleness of heavily irradiated samples. Urea and AU act as plasticizers of destructurized starch but exhibit limited compatibility with the polysaccharide. Radiation doses as high as 1400 kGy are required for complete allyl group conversion.

Lee et al. (2008) evaluated the effect of irradiation on the reduction of viscosity and the increase of solid content of cereal porridge. Four cereals—wheat, rice, maize (the normal starch type),

TABLE 14.4 Applications of Irradiation on Cellulose

| Cellulose | Irradiation Type/Dose | Physical Properties | Reference |
|---|--|---|---------------------------|
| Cellulose | MW irradiation/800 W/1 30 min | TS increased from 397 to 415.3 N %E decreased from 24.255 to 21.842 mm Wrinkle recovery angle increased from 183.8 to 186.2 Cellulose fabric increased Increase in crystallinity from 74.27 to 79.33% Enthalpies increased | Hou et al., 2008 |
| Regenerated cellulose | γ irradiation and ionizing radiation/30 60 Gy | No changes on membrane surfaces Differences in salt permeability | Vázquez et al., 2008 |
| Cotton cellulose | γ irradiation/3, 10, and 20 kGy | Major changes in swelling | Tóth et al., 2003 |
| Cellulose | γ irradiation/0 and 100 kGy | No remarkable effect on decay susceptibility of wood Increase in feeding activity of the termites Matrix of the cell wall did not undergo any substantial changes | Katsumate et al., 2007 |
| Cellulose membranes | γ irradiation/5 and 25 kGy | Decrease of diffusion coefficient | Stoica Guzun et al., 2007 |
| Lignocellulolytic mutants of <i>Pleurotus ostreatus</i> | γ irradiation/1 2 kGy | Change in genetic diversity | Lee et al., 2007 |

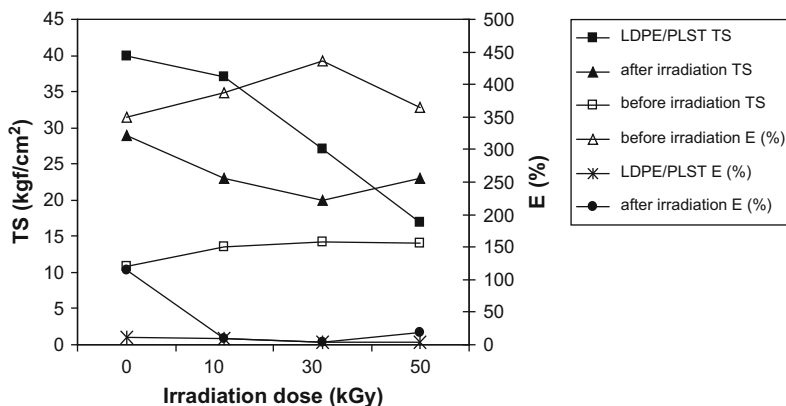


Figure 14.18: Tensile strength (TS) and percentage elongation (%E) of LDPE/PLST (80/20) blend before and after e-beam irradiation at various doses (Senna et al., 2007).

and waxy rice—were used. The porridge with 3000 cP was individually prepared from cereal flour, γ -irradiated at 20 kGy, and tested. Gamma irradiation of 20 kGy caused the highly viscous and rigid cereal porridge to have a semi-liquid consistency. The solid contents of all porridges increased with irradiation compared with non-irradiated ones. No significant differences in starch digestibility were observed in all cereal porridge samples. The results indicated that γ -irradiation might be helpful for improving the energy density of cereal porridge with acceptable consistency. High viscous and rigid porridges of cereals turned into semi-liquid consistencies by γ -irradiation at 20 kGy.

Changes in TS and %E of the starch-based film with different irradiation doses and locust bean gum (LBG) concentrations were reported by Kim et al (2008). The TS of all the starch-based films (12.0 ± 1.89 MPa) increased with the addition of LBG. After irradiation, the TS of S (no LBG added) displayed no differences, whereas the TS of SG2 [1.5% (w/v) LBG added] gave the highest at 3 kGy (Figure 14.19). An increase in LBG from 0.75 to 1.5% also had a major impact on TS after irradiation, in agreement with findings by Zhai et al. (2003).

14.6.1 Chitosan/Starch

Zhai and co-workers (2004) prepared starch–chitosan blend films with e-beam irradiation of compression-molded starch-based mixture in physical gel state at room temperature. Without irradiation, an intact, smooth starch–chitosan blend film was formed after drying naturally at room temperature. The TS of films increased largely after incorporating 20% chitosan into the starch film. Twenty percent chitosan was the maximum value used in starch–chitosan mixture in this experiment. Elongation at break increased substantially with the content of chitosan. No obvious change in elongation at break with the dose was found. The effect of

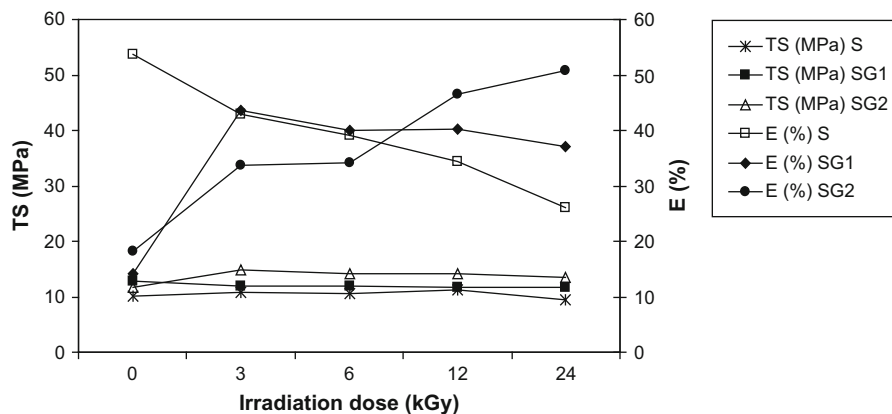


Figure 14.19: Tensile strength (TS) and percentage elongation (%E) of γ -irradiated starch-based films against irradiation dose (0–24 kGy) (Kim et al., 2008).

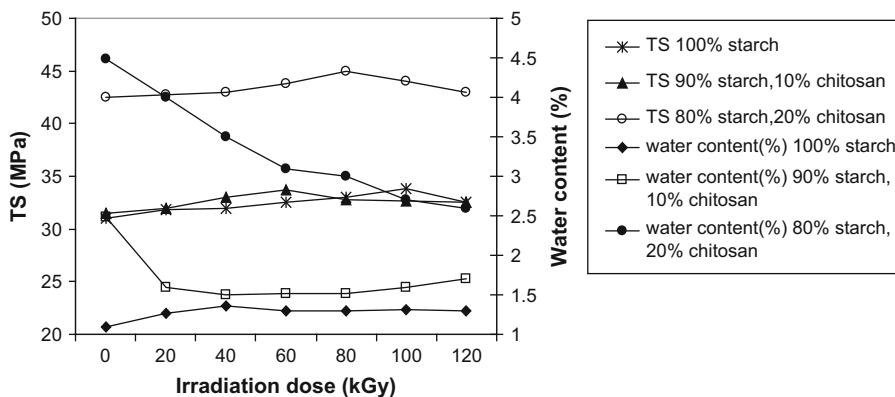


Figure 14.20: The impact of irradiation dose on tensile strength (TS) and percentage water content of blend films after having been dried naturally at room temperature (Zhai et al., 2004).

irradiation dose on TS and percentage water content of starch–chitosan films is shown in Figure 14.20.

The effects of irradiation on the physical properties of blends of natural polymers are presented in Table 14.5.

14.7 Blends of Synthetic Polymers

14.7.1 Polypropylene/Starch

Bagheri (2009) investigated γ -irradiated samples containing photo-initiators (PIs) (Irgacure 184, Irgacure 651, benzoinethylether, benzophenone, and ferric stearate) with and without corn starch at 0–60 kGy by UV spectrophotometer and FT-IR. A linear decrease in the wavelength of the absorbance maximum of each aromatic PI was observed with increasing dose. The inclusion of PI in the sample (although among the aromatic PIs there was no significant difference) reduced the embrittlement point (brittle fracture) due to oxidation. However, ferric stearate showed higher effectiveness than the other PIs. The reduction in embrittlement dose can be explained by the pro-degradant effect of the PIs, especially at early stages of γ -irradiation. Ferric stearate and Irgacure 184 showed the highest and lowest effect, respectively. The impact of absorbed dose (0–60 kGy) on the carbonyl index ($A_1 1721 \text{ cm}^{-1}/A_2 2720 \text{ cm}^{-1}$) starch-filled polypropylene samples is shown in Figure 14.21.

14.7.2 PVA/Chitosan

PVA/water-soluble chitosan (ws-chitosan) hydrogels were prepared with a combination of γ -irradiation and freeze thawing (Yang et al., 2008). Gamma irradiation reduced the

TABLE 14.5 Application of Irradiation on Blends of Natural Polymers

| Blends of Natural Polymers | Irradiation Type/ Dose | Physical Properties | References |
|--|--|---|--|
| Polyethylene/ plasticized starch | e beam irradiation/ 30 kGy | TS decreased from 40 to 17 kgf/cm ² %E decreased from 111 to 4% | Senna et al., 2007 |
| Allylurea | e beam irradiation/ 200, 400, and 1400 kGy | Higher brittleness Limited compatibility with polysaccharide | Ruckert et al., 1999 |
| Four cereals—wheat, rice, maize (the normal starch type), and waxy rice | γ irradiation/20 kGy | Solid contents increased No significant differences in starch digestibility Improvement of the energy density of cereal porridge with acceptable consistency Highly viscous and rigid por ridges of cereals turned into semi liquid consistencies | Lee et al., 2008 |
| Locust bean gum | γ irradiation/3 kGy | TS decreased from 10.04 to 9.41 MPa %E decreased from 53.72 to 26% Change in HunterLab values | Kim et al., 2008; Zhai et al., 2003 |
| Starch/chitosan blend | e beam irradiation/ 30 kGy | TS of starch/chitosan increased from 31.5 to 32.5 MPa %E of starch/chitosan increased from 20 to 33% The content of water of starch/ chitosan decreased from 2.48 to 1.7% | Zhai et al., 2004 |

crystallinity of PVA, whereas freeze thawing increased it. ws-Chitosan disrupted the ordered association of PVA molecules and decreased the thermal stability of both physical blends and hydrogels. Hydrogels based on PVA, ws-chitosan, and glycerol were developed by pure γ -irradiation and γ -irradiation followed by freeze thawing, respectively. The larger G' value for hydrogels made by irradiation compared to the FT-produced hydrogels followed by irradiation indicated that the FT process inhibited the formation of chemical cross-linking.

A series of well-miscible hydrogels were prepared from PVA and CM-chitosan with e-beam irradiation at room temperature. The mechanical properties and equilibrium degree of swelling improved considerably after adding CM-chitosan into PVA hydrogels. After irradiation, the melting points and melting enthalpies of PVA/CM-chitosan blend gel decreased due to the

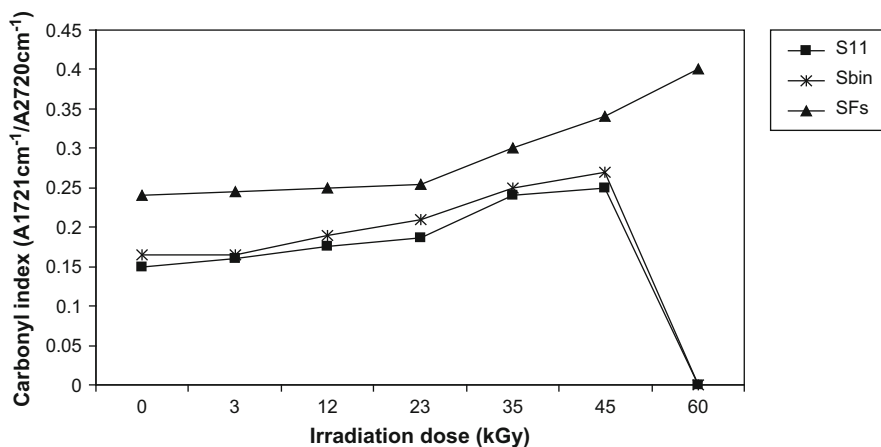


Figure 14.21: Effect of absorbed dose (0–60 kGy) on the carbonyl index (A_1 1721 cm^{-1}/A_2 2720 cm^{-1}) starch-filled polypropylene samples containing 0.5 w% photo-initiators (Bagheri, 2009).

cross-linking of PVA under irradiation (from 219 to 208.5°C and from 27 to 23.4 J/g for T_m and ΔH_m , respectively). FT-IR and DSC spectra of the prepared gels after extracting sol revealed that there was a grafting measured via the optical density method. The blend hydrogels exhibited satisfactory antibacterial activity against *Escherichia coli*, even when the CM-chitosan concentration was only 3 wt% (Zhao et al., 2003). The impact of the percentage CM-chitosan content on TS and %E at break of PVA/CM-chitosan blends is displayed in Figure 14.22.

14.7.3 PVA/Starch

Blends of sago starch (SS) and PVA were irradiated with doses ranging from 10 to 30 kGy, and foams were produced from these irradiated blends using a microwave. The recorded pronounced increase in gel content (from 1 to 95%) with increasing irradiation dose indicated the cross-linking of PVA. Blends showed a gradual increase in gel strength up to the dose of 25 kGy. A gradual increase in gel strength was observed for irradiated aqueous PVA, indicating that SS/PVA blends were rather harder than irradiated PVA (implying that this could be potentially attributed to sago starch cross-linking). This cross-linking was further confirmed by means of SEM micrographs, which revealed the development of fracture patterns on the surface of the starch granules (Wongsuban et al., 2003). The impact of irradiation dose on the gel content of SS/PVA blends and cross-linking of DHP-chitosan is shown in Figure 14.23.

Mohdy (2007) prepared starch-based plastic films with e-beam irradiation of starch and PVA in a physical gel state at room temperature. The gel fraction of the starch/PVA films increased with both the radiation dose and the PVA content in the plastic film and decreased with increasing glycerol concentration. The TS of the films decreased at high starch ratios in

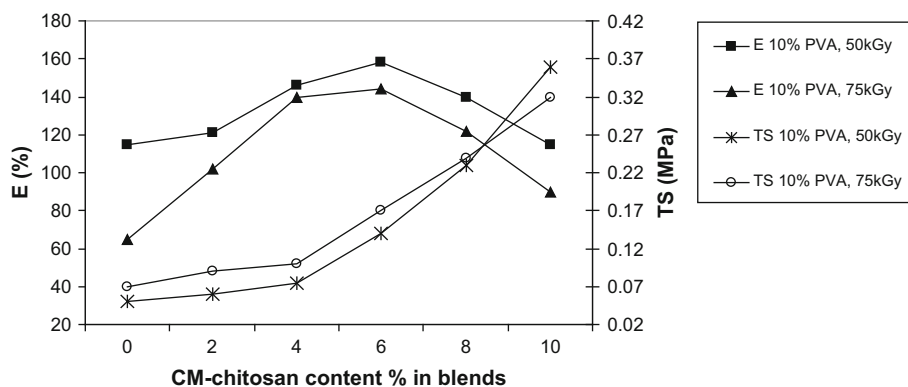


Figure 14.22: The effect of various CM-chitosan content percentages on tensile strength (TS) and percentage elongation (%E) at break of PVA/CM-chitosan blend hydrogels prepared with irradiation (Zhao et al., 2003).

the starch-based mixture because of the lower cross-linking degree of starch, as shown in Figure 14.24. The TS of films decreased with increasing glycerol concentration, but %E at break increased up to approximately 400% at a 20% glycerol concentration and then it leveled off and decreased slightly. The TS of the starch-based plastic films increased with increasing irradiation dose and PVA ratio in the polymer blend, but it decreased at high ratios of PVA (starch:PVA = 10:90 and 0:100) at 40 kGy. The TS increased with dose due to the chemical cross-linking in the mixture of PVA and starch. The TS of starch-based plastic films was improved by the blending of PVA with starch and irradiation modification; this may have been due to the formation of hydrogen bonds or chemical interactions between the -OH groups of PVA and the -OH groups of starch.

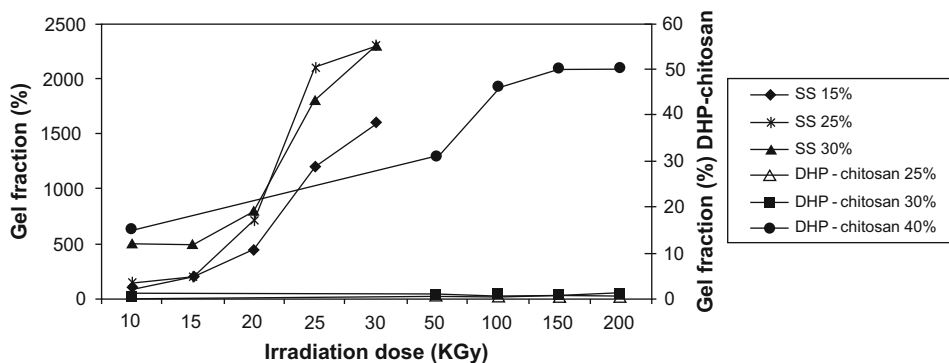


Figure 14.23: Effect of irradiation dose on the gel content of SS-PVA blends (Wongsuban et al., 2003) and concentration on cross-linking of DHP-chitosan (Zhao et al., 2008).

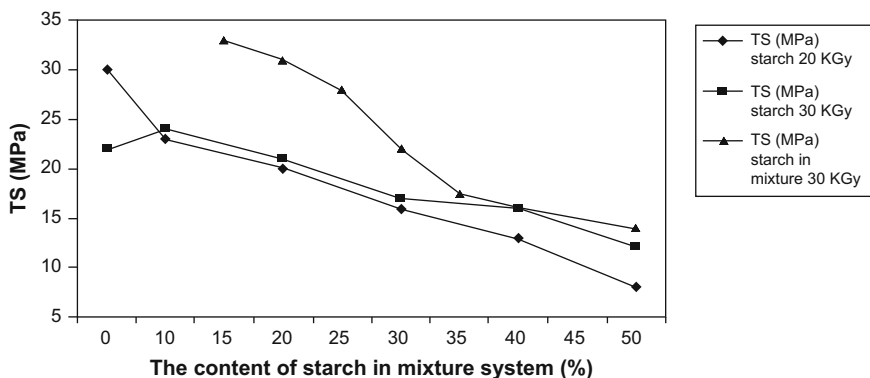


Figure 14.24: The change of tensile strength (TS) of dry starch-based sheets with the content of starch in mixture (Zhai et al., 2003) and the effect of various starch compositions on the TS in the presence of glycerol at different irradiation doses (polymer concentration 7.5% w/v) (Mohdy, 2007).

14.7.4 Carboxymethyl Starch/Cellulose

Said (2007) investigated the physical properties of ternary miscible blends based on various ratios of PVA, polyacrylamide (PAM), and carboxymethyl cellulose (CMC) prepared with solution casting in the form of thin films. The structure–property behavior of the ternary PVA/PAM/CMC blends, before and after exposure to various doses of e-beam irradiation, was investigated with FT-IR spectroscopy, SEM, XRD, and stress–strain curves. Said summarized the effect of e-beam irradiation on the structural properties as follows:

1. The IR spectra of pure polymers or their blends confirmed that the binding was through hydrogen bonding.
2. The XRD patterns showed that the peak position for the ternary blends decreases with increasing ratio of CMC in the blend.
3. The peak intensity and broadness largely increased after e-beam irradiation.
4. Reduction in the domain size clearly indicated the compatibility of different components in the blends. After e-beam irradiation, the compatibility within the blends containing lower ratios of CMC was higher than that in the blends with higher contents of CMC.
5. The stress at break decreased for the blends containing higher ratios of CMC or PAM at a dose of 50 kGy.

The mechanical properties (TS and %E) of pure polymers and their blends at different ratios before and after γ -irradiation to various doses are shown in Figure 14.25.

14.7.5 Cellulose/Chitosan

Chitosan cross-linked cellulose fibers were prepared by [Alonso et al. \(2009\)](#) in an attempt to employ nontoxic procedures to confer antimicrobial properties to cellulose fibers. Citric acid was used as cross-linker and NaH_2PO_4 as catalyst in previously UV-irradiated cellulose fibers, and further heat dried-cure process and washing with acetic acid (0.1 M) resulted in maximum incorporation of chitosan of 27 mg/g of functionalized textile. Thermogravimetric analysis clearly demonstrated the improvement of thermal stability of the cross-linked material with regard to cellulose and chitosan. The UV irradiation induced morphological changes, such as less entangled cellulose fibers, thereby enhancing the chitosan incorporation. The biomass and spore germination percentage of *Penicillium chrysogenum* and colony-forming units per milliliter for *E. coli* diminished considerably on the composite materials compared to raw cellulose fiber.

14.7.6 Hydrogels

[Zhao and Mitomo \(2009\)](#) prepared a series of environmentally friendly hydrogel films from DHP-chitosan using irradiation technique without any bifunctional cross-linking compounds. DHP-chitosan irradiated at highly concentrated solution (>10%, paste-like state) was found to introduce cross-linking structure. It was shown that a concentration of 40% solution was the most effective for cross-linking. TS increased with increased absorbed dose at an early stage; after reaching a maximum of 0.2 MPa for 50 kGy, it decreased to approximately 0.05 MPa for 200 kGy. This effect is due to the increasing cross-linking density

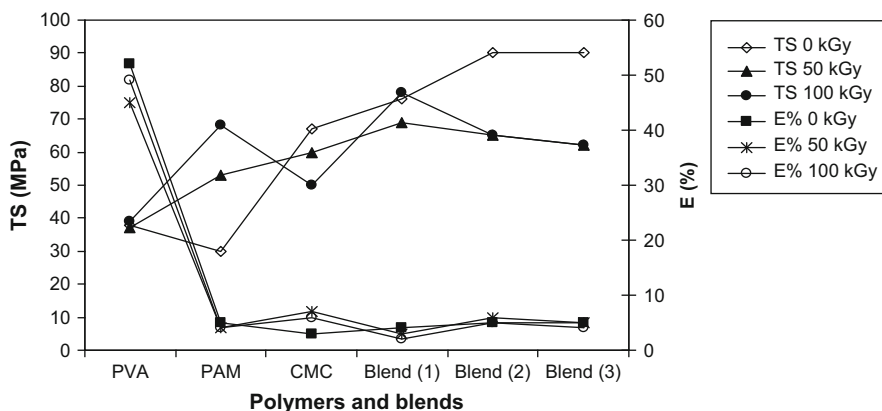


Figure 14.25: Tensile strength (TS) and percentage elongation (%E) of pure polymers and their blends at different ratios before and after γ -irradiation to various doses. Blend 1 PVA/PAM/CMC equal ratio from each polymer; blend 2 PVA/PAM/CMC (40/20/40); and blend 3 PVA/PAM/CMC (40/40/20) ([Said, 2007](#)).

at an early stage, and after reaching a maximum, higher absorbed doses led to degradation and destruction of the network structure. The gel strength of DHP-chitosan was similar to that of other polysaccharides hydrogels such as CM-cellulose and CM-chitin/chitosan cross-linked with irradiation (Zhao et al., 2003). Elongation at break of cross-linked polymers decreased with increasing absorbed dose. The weight loss of the gel samples with or without the enzyme after 120 h incubation increased to approximately 33 and 14%, respectively.

The gelatinized maize starch/acrylic acid (AAc) hydrogels were synthesized with co-polymerization of AAc and gelatinized maize starch in aqueous medium by means of γ -irradiation. Both irradiation dose and starch/AAc blend composition substantially affected the swelling of the obtained hydrogels and altered their gel content. An increase in AAc polymer in the starch/AAc blend resulted in an increase in the gel content. The starch/AAc polymer of composition (10/90) displayed the maximum swelling value. The swelling of starch/AAc at different compositions in NaCl solution was lower than that in distilled water. The maximum water absorption obtained for starch/AAc hydrogels in distilled water was 200g/g, for neutralized starch/AAc hydrogels it was 350 g/g, and it was 15 and 43 g/g in distilled water and NaCl solution, respectively. It was envisaged that this particular hydrogel could potentially find applications as superabsorbent materials for industrial and agricultural purposes (El-Mohdy et al., 2006).

14.7.7 Miscellaneous

Gonzalez et al. (2002) investigated the irradiation of a mixture of glycopolysaccharides and proteins isolated from *Phaseolus vulgaris* beans mixed with glycerol and water as plasticizers with doses of 25, 50, and 100 kGy under two conditions: (1) before the compression molding process and (2) after mixtures were molded. When the maximum dose (100 kGy) was applied to mixtures before the molding process, the plastic product obtained displayed a deformation reduction of 62%, whereas the water absorption capacity increased by 20%.

Polysaccharides from seaweeds, fucoidan and laminarin, were irradiated with γ -rays, and their structural changes and antioxidative activities were investigated by Choi et al. (2009). Application of γ -irradiation to fucoidan resulted in a considerable decrease of MW (217, 37, 15, and 10 kDa for 0, 10, 30, and 50 kGy, respectively), whereas in the case of laminarin the decrease was far less pronounced (23, 9.5, 8.8, and 8 kDa for 0, 10, 20, and 30 kGy, respectively). The UV spectra of irradiated polysaccharides revealed considerable increases in the numbers of carboxyl and carbonyl groups and double bonds. DPPH radical scavenging ability and reducing power of the γ -irradiated polysaccharides were substantially higher than those non-irradiated, as shown in Figure 14.26.

The applications of irradiation on blends of synthetic/natural polymers are summarized in Table 14.6.

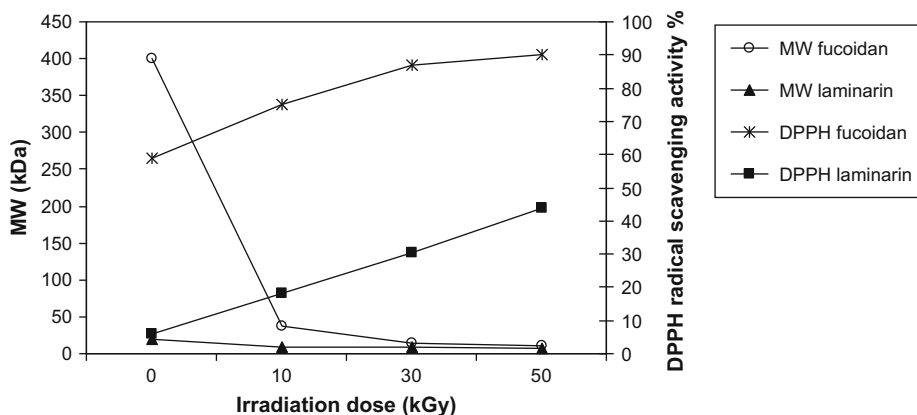


Figure 14.26: The effect of irradiation dose (0–50 kGy) on molecular weight (MW) and DPPH radical scavenging activities of two polysaccharides fucoidan and laminarin (Choi et al., 2009).

14.8 Conclusions

It is evident from ongoing research worldwide that there will be an ever-increasing industrial demand for modified starches using an inexpensive, safe, and economically viable method. In this regard, radiation processing, being a physical method, will prove to be a good alternative to chemical modifications. Combination treatments of irradiation with other physical treatments such as X-rays, infrared rays, and ultrasound could be explored to improve cross-linking (Bhat and Karin, 2009).

Currently employed conventional processing methods are relatively ineffective for the reduction or removal of antinutritional factors, especially for the hydrolysis of NSPs. In particular, irradiation levels up to 10 kGy, which are acceptable for food irradiation, seem to be effective in inactivating antinutrients such as protease inhibitors, lectin, phytic acid, nonstarch polysaccharides, and oligosaccharides without altering the nutritional quality of the food (Siddhuraju et al., 2002).

There is a great need for development of biodegradable polymers that are environmentally friendly and eventually converted to CO_2 and H_2O by bacterial degradation in the soil. Using the technique for radiation cross-linking of poly- ϵ -caprolactone, radiation cross-linking of CMC was tested with a degree of substitution (DS, which is the number of carboxymethyl groups replaced from three OH groups in the unit) from 0.7 to 2.2. It was assumed that high-radiation cross-linking of CMC was induced by the formation of CMC radicals in the intermediate products of water radiolysis (Kume et al., 2002).

The exposure of chitosan films coated on Al/Si substrates to oxidative surface reactions resulted in a surface that is more hydrophilic, richer in carbonyl-containing molecules, and has a lower molecular weight than the bulk material. The deposition of chitosan films onto

TABLE 14.6 Application of Irradiation on Blends of Synthetic Polymers

| Blends of Synthetic Polymers | Irradiation Type/ Dose | Physical Properties | References |
|------------------------------|---|--|------------------------|
| Polypropylene/ starch | γ irradiation/ 0 60 kGy | Carbonyl index (A_1 1721 cm^{-1} / A_2 2720 cm^{-1}) increased from 0.15 to 0.24 Ferric stearate increased Irgacure 184 decreased Wavelength absorption of the samples was in the range of 200 400 nm | Bagheri, 2009 |
| PVA/chitosan | γ irradiation/ 30 kGy | Reduction of crystallinity of PVA Increase freeze thawing Thermal stability decreased | Yang et al., 2008 |
| PVA/CM chitosan | e beam irradiation/1 kGy | Melting points decreased from 219 to 208.5°C Melting enthalpies decreased from 27 to 23.4 J/g | Zhao et al., 2003 |
| PVA/starch | MW irradiation/ 10 30 kGy | Increase in gel content from 1 to 95% Increase in gel strength from 500 to 2300 g/cm^2 | Wongsuban et al., 2003 |
| PVA/starch | e beam irradiation/ 20 40 kGy | Gel fraction of the starch/PVA films increased with the irradiation dose and PVA content and decreased with increasing glycerol concentration PVA content decreased TS decreased from 30 to 8 MPa %E increased to approximately 400% at a 20% glycerol concentration ΔH_m decreased from 16.94 to 12.12 J/g T_m increased from 203.16 to 207.50°C | Mohdy, 2007 |
| CMS/cellulose | e beam irradiation/50 kGy | Peak intensity and broadness largely increased TS increased from 37 to 62 MPa %E decreased from 45 to 5% | Said, 2007 |
| Cellulose/chitosan | UV irradiation/254 nm with times of exposure of 4, 8, and 20 h | Improvement of thermal stability of the cross linked material Entanglement of cellulose fibers | Alonso et al., 2009 |

Table 14.6 Application of Irradiation on Blends of Synthetic Polymers—cont'd

| Blends of Synthetic Polymers | Irradiation Type/ Dose | Physical Properties | References |
|---|--|--|--|
| DHP chitosan hydrogels | e beam irradiation/ 100 kGy | Increase in cross linking TS increased at an early stage and then decreased %E increased from 65 to 90% Swelling decreased from 120 to 43 g water/g dry gel Weight loss of the gel samples with/without enzyme increased | Zhao and Mitomo, 2009; Zhao et al., 2003 |
| Starch/AAC hydrogels | γ irradiation | Swelling of the obtained hydrogels was altered Increase in gel content from 22 to 59% | El Mohdy et al., 2006 |
| Glycopolysaccharides and proteins mixed with glycerol and water | γ Radiation/25, 50, and 100 kGy | Water absorption capacity increased by 20% TS decreased by 20% | Gonzalez et al., 2002 |
| Polysaccharides from seaweeds | γ irradiation/0, 10, 30, and 50 kGy | Considerable decrease of M_w from 217 to 10 kDa Increases in the numbers of carboxyl and carbonyl groups DPHH radical scavenging increased from 59 to 90% | Choi et al., 2009 |

AI-coated silicon wafers produced films with more ordered chitosan structure. Surface analysis of modified films by XPS indicated that the hydroxyl groups as well as the amine segments appeared not to participate in surface degradation reactions by either UV/ozone or oxygen plasma at the exposure times employed (Matienzo and Winnacker, 2002).

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Irradiation of Edible Films of Plant and Animal Origin

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15.1 Introduction

In the beginning, each food came in its own natural, biodegradable, edible film. But ever since the biblical Adam took his first bite of the apple and noticed that the uneaten portion turned brown after a few minutes, humankind has sought effective substitutes for nature's coating in order to keep those uneaten portions fresh for future consumption. Sometime after Adam and Eve got kicked out of the Garden of Eden, plastic wrap was invented, and like everything else outside of the garden, it was less than perfect.

Sobral et al. (2001)

Edible films can be prepared from protein, polysaccharide, and lipid materials. Among them, protein-based edible films are the most attractive. These films have impressive gas barrier properties compared with those prepared from lipids and polysaccharides. However, the poor water vapor resistance of protein films and their lower mechanical strength in comparison with synthetic polymers limit their application in food packaging (Bourtoom, 2009).

Moreover, edible films or coatings can be used to prevent food exposure to a host of conditions that can cause changes in food quality and safety. Current edible films have limited uses because of their physical characteristics. For example, lipid-based films have good moisture barriers but poor mechanical strength (see <http://www.ibridgenetwork.org/umass>).

Edible films and coatings play an important role in the quality, safety, transportation, storage, and display of a wide range of fresh and processed foods. Edible films and coatings, while preventing moisture loss and maintaining quality, prevent spoilage and microbial contamination of foods (Carvalho et al., 2008).

The functional efficiency of edible films and coatings strongly depends on the nature of film components and physical structure. Therefore, lipids or hydrophobic substances such as resins,

waxes, or some insoluble proteins are most efficient for retarding moisture transfer. On the contrary, water-soluble hydrocolloids, like polysaccharides and proteins, are not very efficient barriers against water transfer. Moreover, hydrocolloids usually impart better mechanical properties to edible films and coatings than do lipids and hydrophobic substances (Debeaufort and Voilley, 1995).

Due to ecological concerns, there has been a renewed interest in natural and compostable materials, and issues such as biodegradability and environmental safety are becoming increasingly important. Tailoring of new products within a perspective of sustainable development or eco-design is a philosophy that is being applied to increasingly more materials. This is why components such as natural fibers and biodegradable polymers are considered as “interesting”—environmentally safe—alternatives for the development of new biodegradable composites (Arvanitoyannis, 1999, 2008; Arvanitoyannis and Kassaveti, 2008).

Anker et al. (2002) noted that whereas “European countries have devised an incentive to reduce packaging in the form of a packaging tax, the land-a-plenty United States is cranking out more varieties of packaging than ever before.”

Kim and co-workers (2006) stated, “Edible films have potential in a number of different areas. They can coat food surfaces; separate different components; or act as casings, pouches, or wraps. They can preserve product quality by forming oxygen, aroma, oil, or moisture barriers; carrying functional ingredients, such as antioxidants or antimicrobials; and improving appearance, structure, and handling.”

15.2 Edible Films of Plant Origin

In the 1990s, there was a remarkable increase in research efforts for the development of biopolymer films and coatings from protein, polysaccharides, and lipid materials. The qualities of renewability, degradability, and edibility make such films particularly suitable for food and non-food packaging applications. Moreover, wide commercialization of biopolymer films would provide a value-added innovative use for traditional agricultural commodities as a source of film-forming materials (Park et al., 1995).

There has been ongoing interest in the development of films and coatings, including edible packaging materials, from renewable biopolymers. Opportunities for adding value to underutilized agricultural materials and concerns regarding the potentially adverse environmental impact of synthetic packaging materials are two major drivers of such interest. The terms “films” and “coatings” are often used interchangeably. Normally, films are stand-alone, self-supporting structures that are preformed and then placed on or between food components (Sothornvit et al., 2002).

In general, the purpose of edible films and coatings is to inhibit the migration of moisture, gases, aromas, and lipids; to carry food ingredients; and/or to improve the mechanical integrity

or handling characteristics of foods. Proteins, which are abundantly available from sustainable resources of plant or animal origin, can be used as raw materials for the formations of edible films and coatings (Cuq et al., 1995).

Corn, wheat, soybean, and cottonseed are the prevalent types of plant from which proteins with film-forming ability are obtained. Nevertheless, there are other plant proteins, of limited availability, that may be of interest due to a unique property they impart to films or an advantage with regard to film formation. Limited availability may be due to relatively low production of the protein source or limitations in recovering the protein as a co-product from a process (Yong Cho et al., 2002).

15.2.1 Effect of Irradiation on Starch

The effect of γ -irradiation in conjunction with addition of locust bean gum (LBG) on the properties of the starch-based films was investigated. The film casting solution including corn starch, LBG (0, 0.75, and 1.5% w/v), polyvinyl alcohol (PVA), sucrose, and glycerol was irradiated at 0, 3, 6, 12, and 24 kGy. Tensile strength (TS) of the starch-based films increased with addition of LBG. After irradiation, the TS of S (no LBG added) and SG1 (0.75% w/v, LBG added) did not show any differences, whereas the TS of SG2 (1.5% w/v, LBG added) showed the highest at 3 kGy. Water vapor permeability (WVP) of the starch-based film decreased significantly by irradiation (from 6.46 to 4.35×10^{-4} g/m² s Pa) (Lee et al., 2005b).

Starch-based plastic films were prepared by e-beam irradiation (doses of 20, 30, and 40 kGy) of starch and PVA in a physical gel state at room temperature. The TS of the starch-based plastic films increased (from 8 to 30 MPa) with increasing irradiation dose and PVA ratio in the polymer blend, but it decreased (from 14 to 11 MPa) at high ratios of PVA (starch/PVA = 10:90 and 0:100) at 40 kGy. The effect of the starch/PVA composition and irradiation dose on the elongation at break of the dry starch-based plastic films shows that the elongation increased with increasing PVA and decreasing starch content in the polymer blend, but it decreased (from 620 to 390%) with high ratios of PVA (starch/PVA = 10:90 and 0:100) at 20 and 40 kGy (Hulleman et al., 1998).

Three alkali lignin samples (one from sugar-cane bagasse and two from wheat straw) were compared in terms of structure and reactivity when incorporated within a starch matrix submitted to e-beam irradiation (200 and 400 kGy) for cross-linking purposes. Films with a 60:40 starch:lignin ratio as well as control films made from pure starch were prepared by a casting technique in an aqueous medium. Moreover, chromatographic analyses of phenolic fractions provided evidence that condensation/oligomerization reactions involving phenolic compounds take place within the starch matrix (Gierer et al., 2001).

Starch/chitosan blend films were prepared by irradiation of compression-molded starch-based mixture in physical gel state with e-beam irradiation (doses of 30, 50, and 70 kGy) at room temperature. The TS of the films increased (from 42 to 45 MPa) largely after incorporating 20% chitosan into starch film. The content of water adsorbed in starch/chitosan blend films increased with increasing chitosan but decreased slightly with irradiation dose. The elongation at break of starch/chitosan blend films increased (from 20 to 30%) after drying naturally at room temperature (50 kGy) (Zhai et al., 2001).

The mechanical properties of the γ -irradiated starch-based films are shown in Figure 15.1.

The aging of hydrated wheat starch-based materials was followed as a function of time for different systems. In particular, one aspect of retrogradation—the development of crystallinity—was analyzed in order to study the effect of a specific cross-linking treatment of starch films induced by UV irradiation. The decrease in elongation was 75% for the untreated sample compared to 40% for the cross-linked one. Aging tended to eliminate the difference due to the cross-linking treatment. Stress and modulus increased during storage, but samples showed different aging kinetics depending on the cross-linking treatment (Delville et al., 2002).

Lourdin et al. (1997) used allylurea (AU) as a reactive additive for obtaining grafted plasticized starch films with stabilized physical properties. Potato starch was mixed with AU (30–50 parts per hundred) at 125°C. Freshly prepared thermoplastic films of appropriate thickness were exposed to 175-kV e-beam irradiation for inducing covalent grafting of AU by a free radical process. The glass transition region for the samples treated with a 200-kGy dose decreased to approximately 20°C, whereas the films treated with a 400-kGy dose exhibited a glass transition slightly above 25°C.

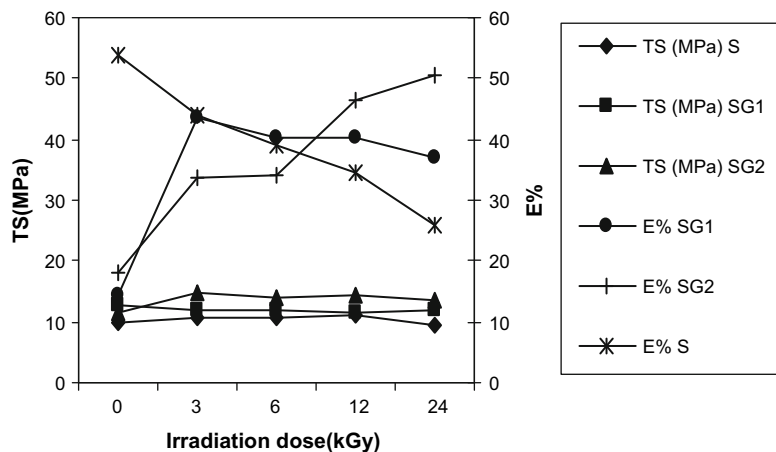


Figure 15.1: Mechanical properties of the γ -irradiated starch-based films (Zhai et al., 2001). S, no locust bean gum (LBG) addition; SG1, 0.75% (w/v) LBG was added; SG2, 1.5% (w/v) LBG was added.

Acrylamide was grafted on the surface of starch-filled low-density polyethylene and low-density polyethylene films by the mutual irradiation technique at doses from 0.75 to 5 kGy. The effect of dose, solvents, and dihydroxybenzoquinone on the degree of grafting was studied with Fourier transform infrared spectroscopy (FT-IR) and the weight measurement method of extracted films at a constant monomer concentration (10% w/w). The decrease in grafting level after the maximum cannot be reasonably explained by degradation of the grafted polymer. This might be due to the formation of osmotic cells (Cohn et al., 1984; Hoffman and Ratner, 1979).

Corn starch has been used for the surface modification of a cast polypropylene (CPP) polymer surface using benzophenone (BP) as photoinitiator. The modified polymer surfaces were characterized with X-ray photoelectron spectroscopy, water contact angle (CA), and scanning electron microscopy (SEM). It was found that the optimal conditions for preparing corn starch-modified CPP film are concentrations of 0.03 g/l for corn starch and 1.0 g/l for BP, with a photointensity of 12.0 mW/cm² for a time of 8 min. The CA of the CPP surface was reduced from 105.0° to a minimum of 66.3° after modification with corn starch (Huang et al., 2004).

Figure 15.2 displays the impact of different irradiation doses on the starch/PVA films.

15.2.2 Effect of Irradiation on Chitosan

Chitosan powder was irradiated with predetermined doses of γ -ray (⁶⁰Co) of 10, 25, 50, and 100 kGy, respectively. However, it is interesting to note that the slope of the stress–strain curve in the elastic region increases with increasing dosage of γ -ray irradiation. The TS decreased when the irradiation dose (0, 10, 25, 50, and 100 kGy) increased. For example, when the dose of irradiation was 10 kGy, the TS was 15.33 MPa, whereas when the dose was 100 kGy the TS was

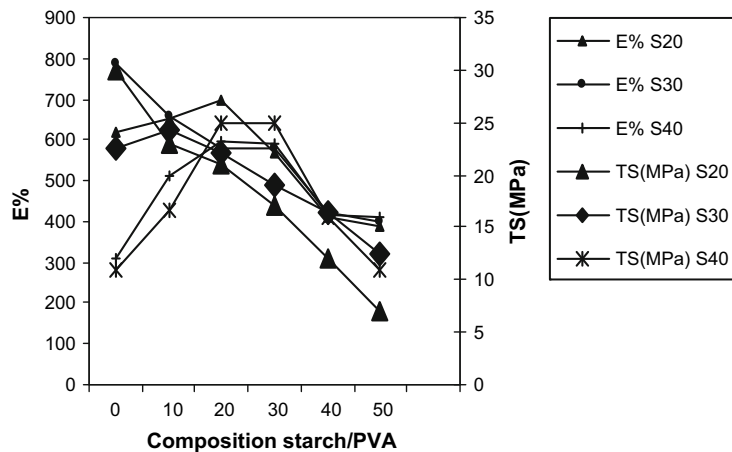


Figure 15.2: Effect of various starch/PVA glycerol compositions on the tensile strength (TS) and elongation of break (E%) of their corresponding films at different irradiation doses (adapted from Abd El-Kader et al., 1993).

7 MPa. The elongation at break decreased (from 63.96 to 11.41%) as long as the radiation dose increased (Zainol et al., 2009).

The effect of irradiation treatment on TS and percentage elongation of chitosan and soybean films is shown in Figure 15.3.

Sionkowska et al. (2006) investigated the thermal and mechanical properties of collagen/chitosan blends before and after UV irradiation using thermal analysis and mechanical (Instron) techniques. Air-dried collagen, chitosan, and collagen/chitosan films were exposed to UV irradiation (wavelength 254 nm) for different time intervals. Ultimate tensile strength (UTS) and ultimate percentage elongation (%UE) decreased after UV irradiation of the blend. The weight losses for collagen/chitosan blends with ratios of 70:30 and 50:50 were similar to the weight losses before and after 8 h of UV irradiation. The blend containing 30% collagen and 70% chitosan showed greater weight loss after irradiation than the non-irradiated samples. UTS after 8 h of UV irradiation was much higher than that for low concentrations of chitosan in the blend. The %UE of the collagen film decreased after 2, 4, and 8 h of UV irradiation. The %UE of chitosan decreased rapidly after 2 h of UV irradiation. After 8 h of UV irradiation, the ultimate percentage of elongation was lower than that for the non-irradiated specimens for all the blends.

Figure 15.4 displays the effect of irradiation on elongation and Young's modulus of the collagen/chitosan blend.

The effect of solar radiation on two natural polymers, collagen and chitosan, as well as collagen/chitosan blends in the form of thin films was studied with UV-visible and FT-IR spectroscopy. It was observed later that the intensity of solar radiation began to increase starting at approximately 9:30 a.m. to the altitude of sun position until a maximum value of total solar radiation of approximately 1000 W/m^2 at approximately noon. The intensity of UVA and UVB radiation around noon was approximately 7 W/m^2 . The enhanced presence of a coil structure

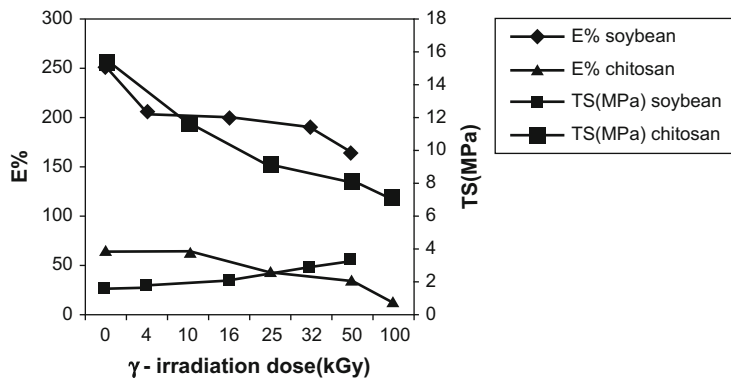


Figure 15.3: Effect of γ -irradiation treatment on tensile strength and elongation of soybean and chitosan films (Lee et al., 2005a; Zainol et al., 2009).

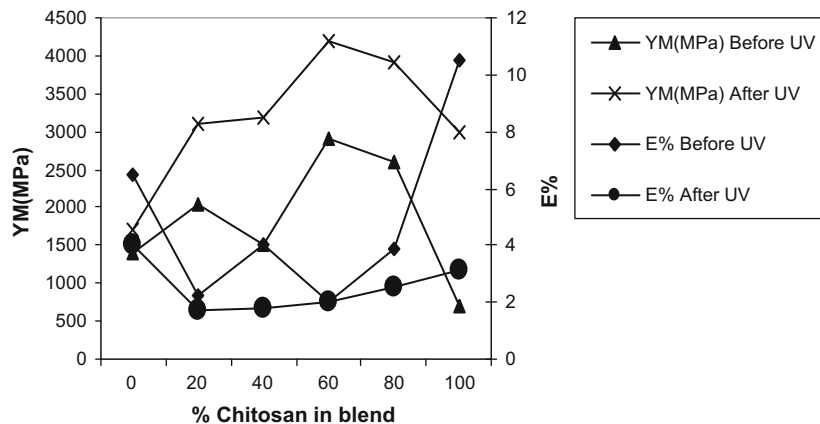


Figure 15.4: The effect of UV irradiation on ultimate percentage of elongation (%E) and Young's modulus (YM) of chitosan in collagen/chitosan blends (adapted from Sionkowska et al., 2005).

and the progressive loss of the helical character of collagen brought about an overall increase in the scattering level of the sample (Sionkowska et al., 2005).

Chitosan was prepared from chitin using a deacetylation process. The molecular weight and degree of deacetylation of chitosan were determined by viscosity and infrared spectroscopy, respectively. Chitosan films were grafted with 2-hydroxyethylmethacrylate (HEMA) using a ^{60}Co γ -irradiation technique. The changes in physicochemical properties of modified films due to graft level of HEMA onto chitosan were determined. The tensile properties of modified films decreased with increasing graft level. The grafted films displayed improved thermal stability (Singh and Ray, 1998).

Chitosan has potential biomedical applications that may require the final products to be sterilized before use. The γ -irradiation of purified and highly deacetylated chitosan fibers and films at sterilizing doses (up to 25 kGy) caused main chain scissions. The viscosity average molecular weight of the polymer decreased with increasing irradiation dose, with the radiation yields of scission being 1.16 in air and 1.53 in anoxia. Pre-irradiation application of a negative pressure of 100 kPa disrupted the network structure, which may have contributed to the greater irradiation yield obtained by chitosan fibers in anoxia (Lim et al., 1998).

Chitosan films were modified with He^+ , N_2^+ , O_2^+ , and Ar^+ ion beam irradiation. Takahashi et al. (2006) investigated the relationship between the surface properties of the film and cell adhesion. The results of FT-IR and Raman studies indicated the formation of new carbon structures and new functional groups by ion beam irradiation. Chitosan film irradiated with each ion at fluence of 1×10^{15} ions/cm² exhibited excellent cell adhesion. It was concluded that cell adhesion increased for the formation of new carbon structures and new functional groups with ion beam irradiation.

15.2.3 Effect of Irradiation on Cellulose

Composite films were prepared from the aqueous dispersions of starch with microcrystalline cellulose using glycerol as plasticizer and irradiated under UV light using sodium benzoate as photosensitizer. With increasing time of photoirradiation, the swelling degree decreased, and it reached a plateau level after 20 min of irradiation. The increase in modulus of 5, 10, and 15 wt% cellulose-reinforced samples irradiated for 30 min was found to be approximately 72.41, 42.5, and 32%, respectively, in comparison to their corresponding control ones. The elongation (%) values were found to decrease with increasing content of cellulose fiber and time of photoirradiation (Kumar et al., 2005).

The changes in microstructural parameters in hydroxypropyl methylcellulose polymer films irradiated with 8 MeV e-beam were studied using the wide-angle X-ray scattering method. The changes in polymer network with different dose rates were quantified in terms of microstructural parameters. The value of enthalpy decreased with increasing dose rate, which corresponds to the state with lower ordered polymer network (Somashekar and Somashekarappa, 1997).

A simple two-beam interferometric technique was used to measure the absolute (built-in) birefringence in cellulose triacetate film plates. By means of a least squares fitting to the Cauchy dispersion formula, the quantum parameters of cellulose triacetate were deduced. The dispersion of the induced birefringence due to γ -irradiation, at the visible region of the spectrum, was determined. At short wavelengths and small radiation doses, the birefringence exhibited similar values due to a major increase in the refractive index associated with a highly varying dispersion (El-Diasty, 2004).

The effect of UV irradiation on enzymatic degradation of highly substituted cellulose acetate (CA) was investigated. The degradability of CA by cellulase decreased with increasing degree of substitution (DS) of CA. UV irradiation resulted in a decrease in molecular weight of CA and did not affect DS. Under UV irradiation for 1 or 7 days, no significant degradation of CA by cellulase was observed. On the other hand, CA under UV irradiation for 30 days displayed 23% weight loss in the sterilized 0.1 M acetate buffer. UV irradiation resulted in the enhancement of solubility and degradability of CA (Ishigaki et al., 2000).

15.2.4 Effect of Irradiation on Soybean

To evaluate whether microwave irradiation of soybean oil provides viscosity and lubricity characteristics that differ from those of other heat processes, heat-bodied and microwave-irradiated soybean oils were produced over a range of viscosities. Increasing the microwave temperature to 200°C for 20 min increased viscosity over the oil microwave irradiated at 150°C for 10 min. Increased viscosity after microwave irradiation was previously reported for olive and sunflower oils (Albi et al., 1997). The oxidized oil would be expected to have higher

molecular weight, which favors higher temperatures of solidification (Hagemann, 1988; Larsson, 1994).

To elucidate the effect of γ -irradiation (0, 4, 16, 32, and 50 kGy) on the physicochemical properties of soy protein isolate (SPI) films, the molecular and mechanical properties of the films were examined after γ -irradiation of the film-forming solution at various radiation doses. The TS value was 3.24 MPa for 50 kGy, compared with 1.59 MPa for the control. The percentage elongation at break (%E) decreased with increase in radiation dose. The %E for 50 kGy was 164, whereas the %E for the control was 249. The WVP of SPI films significantly decreased (from 7 to 5.5×10^{-2} g/m² h Pa) when irradiated (Vachon et al., 2000).

Different concentrations of ferulic acid were added to film-forming solutions when preparing SPI-based edible films. Moreover, the properties of the film were further improved when ferulic acid was oxidized by hydrogen peroxide. When the level of ferulic acid increased to 200 mg/100 g, the TS and percentage elongation at break decreased slightly. Ferulic acid did not significantly decrease the vapor permeability of the SPI films, and increased WVP at higher levels (Oudgenoeg et al., 2001).

Films were cast from heated, alkaline aqueous solutions of soy protein (5 g/100 ml water) and glycerin (50% w/w of protein). Control and UV irradiated (13.0, 25.9, 38.9, 51.8, 77.8, or 103.7 J/m²) films were evaluated for TS, elongation at break (E), WVP, and Hunter L^* , a^* , and b^* color values. TS increased ($P < 0.05$) linearly and %E decreased linearly with UV dosage. WVP was not affected ($P > 0.05$) by UV irradiation. UV treatment was shown to increase the yellowish coloration of films (increased $+b^*$ values) (Gennadios et al., 1998).

Soybean protein isolate was used to investigate the formation of edible protein films through an enzymatic cross-linking method with a purified microbial transglutaminase (MTG) produced from an effective, laboratory-produced, strain *Streptomyces* sp. WZFF.L-M1, followed by the addition of glycerol and suitable heating and drying treatments. Cheaper partially purified skimmed soybean protein powder (SSP) and whey protein isolates (WPIs) were used as the substitutes partially replacing the expensive SPI products, and purified β -lactoglobulin was taken as the positive control of WPI. The films prepared with SPI alternatives, approximately 50 mm thin, had homogeneous network structures, without any visible holes by direct observation with naked eye (Parris et al., 1995).

The effects of irradiation on mechanical properties of edible films of plant origin are summarized in Table 15.1.

15.2.5 Effect of Irradiation on Polysaccharides

Gamma radiation (0, 8, 16, and 32 kGy) induced an improvement of barrier properties and TS of films containing calcium caseinate, WPI, and glycerol (1:1:1) through creation of a cross-linked β -structure. Up to 32 kGy, the effect was accompanied with an increase in rigidity, and it

was larger with increasing radiation dose. The irradiation of protein solutions also caused improvement of puncture strength of films prepared with potato starch, soluble potato starch, or sodium alginate addition (at a level of 50 g/kg of total proteins). The WVP of the films decreased (from 18 to 13 g mm/m² day mmHg) with increasing irradiation dose (from 0 to 32 kGy) (Ciésła et al., 2003).

15.2.6 Effect of Irradiation on Peanut Protein

In a study by Liu et al. (2004), “the properties of peanut protein films were modified using physical and chemical treatments, and their effects on color, mechanical strength, water solubility, and barrier to water vapor and oxygen of the films were investigated. The physical treatments consisted of heat denaturation of film-forming solution for 30 min at 60, 70, 80, and 90°C; UV irradiation of films for up to 24 h; and three ultrasound processes of film-forming solution. The WVP and oxygen permeability (OP) of the films decreased after heat denaturation and aldehyde treatment. Formaldehyde-treated films had the lightest color, followed by the acetic anhydride-treated and heat cured films, with no significant differences between the two treatments. Heating the film-forming solution at 60°C decreased the WVP from 105.31 g cm/m² day mmHg (control, unheated film-forming solution) to 95.65 g cm/m² day mmHg. The TS of UV-treated films increased from 0.55 MPa (control) to 1.01 MPa for the high-dose treatment (24 h). Young’s modulus of the film increased from 1.79 to 3.38 MPa and the toughness increased from 13.54 to 28.90 J after 24 h of UV exposure. OP decreased significantly with UV exposure time (from 15.18 to 6.96 × 10⁶ g cm/m² day mmHg). The acylation of peanut protein film with acetic and succinic anhydride increased the water solubility of the films (to 52.15 and 57.24%, respectively).”

15.2.7 Effect of Irradiation on Gluten

To elucidate the effect of γ -irradiation on the physicochemical properties of gluten films, the molecular and mechanical properties of the films were examined after irradiation at 0, 4, 16, 32, and 50 kGy. The TS of the gluten films was affected by the γ -irradiation treatment, resulting in a 1.5-fold increase at 50 kGy. Thus, the TS of gluten films increased (from 2.7 to 3.9 MPa) with γ -irradiation treatment. The %E decreased (from 290 to 110%) with increase in irradiation dose (from 0 to 50 kGy). The WVP of gluten films decreased (from 7.8 to 5.9 ng/m² g Pa) significantly when irradiated (Lee et al., 2005b).

15.2.8 Effect of Irradiation on Corn Zein

Zein, a predominant corn protein, is an alcohol-soluble protein extracted from corn and is characterized by unique film-forming properties. The characteristic brittleness of zein diminishes its usefulness as a structural material. This goal was achieved by irradiating zein film-forming solutions with various doses of γ -rays (10, 20, 30, and 40 kGy) at a dose rate of

TABLE 15.1 Effect of Irradiation on Mechanical Properties of Edible Films of Plant Origin

| Film Type | Irradiation Type/Dose | %E | Tensile Strength (MPa) | Puncture Deformation | Puncture Strength (MPa) | Reference |
|---|--|--|---|-----------------------|------------------------------------|-------------------------|
| S SG1 SG2 | γ irradiation/0, 3, 6, 12, and 24 kGy | From 53.72 to 26 From 14.24 to 37.05 From 18.23 to 50.73 | From 10.04 to 9.41 From 12.84 to 11.74 From 11.62 to 13.59 | — | — | Nayak et al., 2008 |
| Starch/PVA | e beam irradiation/20, 30, and 40 kGy | From 780 to 310 | From 31 to 7 | — | — | Abd El Mohdy, 2006 |
| Starch/20% chitosan blend | e beam irradiation/0, 20, 40, 60, 80, 100, and 120 kGy | From 20 to 30 | From 31 to 44 | — | — | Zhai et al., 2003 |
| Chitosan powders | γ ray/0, 10, 25, 50, and 100 kGy | From 63.96 to 11.41 | From 15.33 to 7 | — | — | Zainol et al., 2009 |
| 30% collagen/70% chitosan | UV irradiation/ wavelength 254 nm | — | — | — | — | Sionkowska et al., 2005 |
| Cellulose | UV irradiation | From 110 to 20 | From 100 to 320 | — | — | Kumar and Gupta, 2008 |
| SPI | γ irradiation/0, 4, 16, 32, and 50 kGy | From 248.66 to 164.18 | From 1.6 to 3.2 | — | — | Lee et al., 2005a |
| Calcium caseinate, whey protein iso late, and glycerol (1:1:1) | γ irradiation/1, 8, 16, and 32 kGy | — | — | From 4.5 to 4.1 mm | From 53 to 75 Nmm ⁻¹ | Ciésla et al., 2003 |
| F G SA AA | UV irradiation | 115.69 117.25 88.23 74.88 | 1.85 1.98 0.48 0.42 | — | — | Liu et al., 2004 |
| Gluten | γ irradiation/0, 4, 16, 32, and 50 kGy | From 280 to 110 | From 2.6 to 3.8 | — | — | Lee et al., 2005b |
| Corn zein | γ irradiation/10, 20, 30, and 40 kGy | From 3.6 to 2.5 | From 11.22 to 5.60 | — | — | Soliman et al., 2009 |

10.5 kGy/h, employing a Co^{60} γ -irradiation source. The results indicated that γ -irradiation treatment of the film-forming solution can be used to improve the water barrier properties, as well as color and appearance, of the zein films (Soliman and Furuta, 2009).

Figure 15.5 displays the impact of irradiation treatment on TS and elongation of zein and gluten films.

The effects of irradiation on physical properties of edible films of plant origin are summarized in Table 15.2.

15.3 Edible Films of Animal Origin

Edible coatings can potentially extend the shelf life and improve the quality of food systems by controlling mass transfer, moisture and oil diffusion, gas permeability (O_2 and CO_2), and flavor and aroma losses. Coating formulations can be used to serve as adhesive for seasonings or to improve the appearance of foods. For example, edible coatings can be sprayed or dipped into the surface of snack foods and crackers to serve as a foundation or adhesive for flavorings. Candies are often coated with edible films to improve their texture by reducing stickiness (McHugh, 2000).

The ever-increasing interest of consumers in quality, convenience, and food safety has encouraged further research on edible films and coatings. The reinvention of “edible films” was due mainly to their numerous applications, such as coatings for sausages, fruits, and vegetables; chocolate coatings for nuts; and, occasionally, wax coatings. Although there are multiple objectives for the use of edible films, among the most important may be restriction of moisture loss, control of gas permeability, and control of microbial activity (Arvanitoyannis and Biliaderis, 1998).

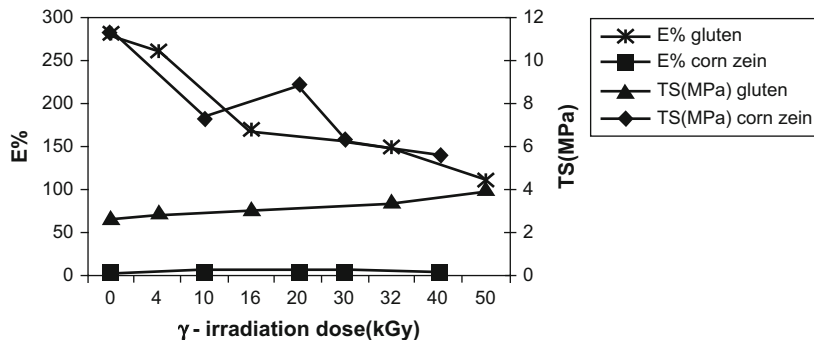


Figure 15.5: Influence of γ -irradiation treatment on tensile strength and elongation of zein (Soliman and Furuta, 2009) and gluten films (Lee et al., 2005b).

TABLE 15.2 Effect of Irradiation on Physical Properties of Edible Films of Plant Origin

| Film Type | Irradiation Type/Dose | Chromatometric Parameter | | | WVP | Reference |
|---|--|---|---|---|---|--------------------------|
| | | L^* | a^* | b^* | | |
| S SG1 SG2 | γ irradiation/0, 3, 6, 12, and 24 kGy | From 67.89 to 68.69 From 67.48 to 67.12 From 65.62 to 67.89 | From 0.33 to 0.28 From 0.39 to 0.35 From 0.39 to 0.43 | From 0.78 to 0.94 From 1.44 to 1.75 From 1.84 to 2.58 | From 6.87 to 4.70 ($\times 10^{-4}$ g/m ² s Pa) From 6.46 to 4.35 From 6.98 to 5.60 | Kim et al., 2008 |
| Starch/PVA | e beam irradiation/20, 30, and 40 kGy | — | — | — | — | Abd El Mohdy, 2006 |
| Starch/20% chitosan blend | e beam irradiation/0, 20, 40, 60, 80, 100, and 120 kGy | — | — | — | — | Zhai et al., 2003 |
| Chitosan powders | γ Ray/0, 10, 25, 50, and 100 kGy | — | — | — | — | Zainol et al., 2009 |
| 30% collagen/70%chitosan | UV irradiation/wavelength 254 nm | — | — | — | — | Sionkowska et al., 2006 |
| Cellulose | UV irradiation | — | — | — | — | Kumar et al., 2008 |
| SPI | γ irradiation/0, 4, 16, 32, and 50 kGy | From 87.918 to 87.378 | From 0.292 to 2.354 | From 4.004 to 10.614 | From 7 to 5.5 ($\times 10^{-2}$ g/m ² h Pa) | Lee et al., 2005a |
| Calcium caseinate, whey protein isolate, and glycerol (1:1:1) | γ irradiation/1, 8, 16, and 32 kGy | — | — | — | From 17 to 11.8 (g mm/m ² day mmHg) | Ciésła et al., 2003 |
| F G SA AA | UV irradiation | — | — | — | 92.65 (g cm/m ² day mmHg) 85.65 106.58 107.51 | Liu et al., 2004 |
| Gluten | γ irradiation/0, 4, 16, 32, and 50 kGy | — | — | — | From 7.2 to 5.4 (ng/m ² s Pa) | Lee et al., 2005b |
| Corn zein | γ irradiation/10, 20, 30, and 40 kGy | From 90.43 to 92.68 | From 6.46 to 5.45 | From 50.56 to 36.98 | From 1.62 to 1.14 (g mm/m ² h kPa) | Soliman and Furuta, 2009 |

Active compounds (antimicrobials, antioxidants, and nutrients) can be added to food coatings to extend shelf life, preserve the color, and improve the nutritional value of foods. Application of edible coatings to meat and fish products may be done by dipping, spraying, casting, rolling, brushing, and foaming. Coatings must have barrier properties with regard to water vapor, oxygen, carbon dioxide, and lipid transfer while maintaining good color, appearance, and mechanical and rheological characteristics (Guilbert, 1986).

Composite coatings improve the gas exchange, the adherence to coated products, and moisture vapor permeability properties. The addition of glycerol polyethylene glycol and also sorbitol can reduce film brittleness. A composite film containing antimicrobial or antioxidant compounds can prevent rancidity and improve shelf life by controlling bacterial proliferation. Sealing meat with a cross-linked sodium caseinate gel produced a juicier product by reducing drip loss; it also reduced the use of absorbent pads and protected the color of the meat (Kurth, 1997).

The benefits of edible film can be numerous, but some barriers to commercial implementation have not been overcome. The raw material for much of the edible films comes from underutilized sources, but the cost of purification can be financially impractical (Krochta et al., 1994).

According to Marques et al. (2002), “inert and nonbiodegradable plastic materials represent 30% of municipal solid waste. They note that although the idea of biodegradable films continues to be of research interest, such films are not practical under the current solid-waste handling conditions. Biodegradable films could work in a compost environment, but even biodegradable materials do not degrade well in landfills, where the majority of all packaging waste material is disposed.”

An edible film can be accepted only if it is generally recognized as safe (GRAS) and used within any limitations specified by the U.S. Food and Drug Administration. Many edible films can be produced from food-grade materials, but many require solvents to become soluble. Ultimately, any material that is used for direct food contact will face regulatory scrutiny, particularly biopolymers that act as carriers of additives intended to migrate to the food for preservative effects (Chen, 1995).

Milk proteins, such as whey and casein proteins, have been extensively studied due to their excellent nutritional value and their numerous functional properties, which are important for the formation of edible films (McHugh and Krochta, 1994a,b).

Caseinates can easily form films from aqueous solutions due to their random coil nature and their ability to form extensive intermolecular hydrogen, electrostatic, and hydrophobic bonds, resulting in an increase in the interchain cohesion. Moreover, edible films based on milk proteins were reported to be flavorless, tasteless, and flexible, and depending on the formulation, they varied from transparent to translucent (Brunner, 1977; Dalgleish, 1989).

15.3.1 Effect of Irradiation on Milk Protein

Ciésla et al. (2003) investigated the TS of films containing calcium caseinate, whey protein isolate, and glycerol (1:1:1) modified through creation of a cross-linked β -structure. Up to 32 kGy, the effect was accompanied by an increase in rigidity and was greater with increasing radiation dose. The irradiation of protein solutions also enhanced the puncture strength of films prepared with potato starch, soluble potato starch, or sodium alginate addition (at a level of 50 g/kg of total proteins). The WVP of the films decreased (from 17 to 12 g mm/m² day mmHg) with increase in irradiation dose.

The effect of γ -irradiation (0 and 32 kGy) on the physical properties of calcium caseinate, whey protein isolate, and glycerol (1:1:1) solutions and gels was investigated by Ciésla et al. (2003). Solutions irradiated with a 32-kGy dose and non-irradiated solutions were heated and considerable differences both in the structure of gels and in different temperature–viscosity curves were recorded for both samples during heating and cooling. The TS increased (from 53.9 to 77 Nmm⁻¹) with the 32-kGy irradiation dose. The WVP decreased (from 168.6 to 114.9 $\times 10$ g mm/m² day mmHg) with the 32-kGy irradiation (Ciésla et al., 2003).

Ouattara et al. (2002) employed γ -irradiation to produce freestanding cross-linked milk proteins. Film-forming solutions were prepared using calcium caseinate (CAS) with various proportions of WPI or whey protein concentrate (WPC). The following CAS:WP ratios were prepared: 100:0, 75:25, 50:50, 25:75, and 0:100. The WVP of the films was determined gravimetrically at 23.1°C using a modified ASTM procedure. The WVP was found to decrease from 2.07 to 1.38 g mm/m² day mmHg.

15.3.2 Effect of Irradiation on Whey Protein

Gamma irradiation (32 kGy) and thermal treatments have been used to produce sterilized cross-linked films. The physicochemical properties of formulations containing variable concentrations of calcium caseinate and whey proteins (WPI and commercial WPC) or a mixture of SPI with WPI were investigated by Lacroix et al. (1992). The obtained results revealed that the level of biodegradation of cross-linked films was 36% after 60 days of fermentation in the presence of *Pseudomonas aeruginosa*. The puncture strength of irradiated SPI film (gS) was 0.043 N/m, 37% higher than the unirradiated one (S) (0.032 N/m). The WVP decreased from 3.16 to 2.03 g mm/m² day mmHg, representing a decrease of 36%.

The impact of different irradiation doses on the WVP of calcium caseinate, whey protein isolate, and glycerol and SPI films is clearly shown in Figure 15.6.

15.3.3 Effect of Irradiation on Gelatin

Gelatin was irradiated at 0, 10, 20, and 30 kGy to investigate the irradiation effect on the mechanical properties of the film. The total organic carbon content produced from

Paenibacillus polymyxa and *Pseudomonas aeruginosa* also showed that the content of the 10-kGy irradiated film was lower than those of the 0-, 20-, and 30-kGy irradiated films. TS increased (from 106.7 to 116.7 kPa) by 10-kGy irradiation but decreased (100 kPa) by 30-kGy irradiation. The %E was higher in the 0- (20.35%) and 30-kGy (21.88%) irradiated film, and it had a negative correlation with the TS results. The Hunter color L^* and a^* values decreased with an increase in irradiation dose, whereas the Hunter color b^* value increased (Bigi et al., 1998).

The effect of irradiation on Hunter L^* , a^* , and b^* parameters of irradiated gelatin and SPI films is shown in Figure 15.7.

The real and imaginary parts of the dielectric constant were measured as a function of temperature at 10 kHz for a cobalt–gelatin film before and after exposure to different values of fast neutron fluences and γ -irradiation doses. The behavior of dielectric constant and AC conductivity seemed to be the same at higher and lower doses of both types of radiation. This behavior was also observed by comparing the calculated values of the activation energies for co-gelatin films before and after irradiation (Marianiva and Lapcik, 1993).

The UV and IR spectra of pure PVA and gelatin-doped PVA films with concentrations of 2, 5, 7, 10, and 15 wt% were studied before and after irradiation with neutron fluences in the range of 105–108 n/cm². The increase in dopant concentration above 5 wt% gelatin appeared to make the sample less resistant to degradation effects usually caused by neutron irradiation (Abd El-Kader et al., 1993).

The impact of irradiation treatment on WVP and %E of gelatin and gluten films is shown in Figure 15.8.

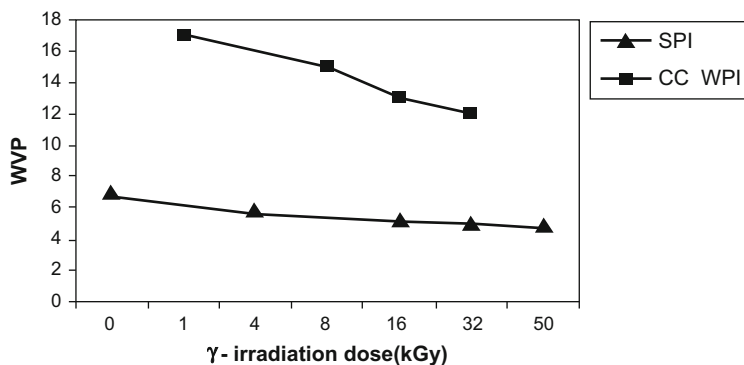


Figure 15.6: Effect of different irradiation doses on water vapor permeability (WVP) of films prepared using calcium caseinate, whey protein isolate, and glycerol (1:1:1) (CC-WPI) (Cíesla et al., 2003) and SPI films (Lee et al., 2005a).

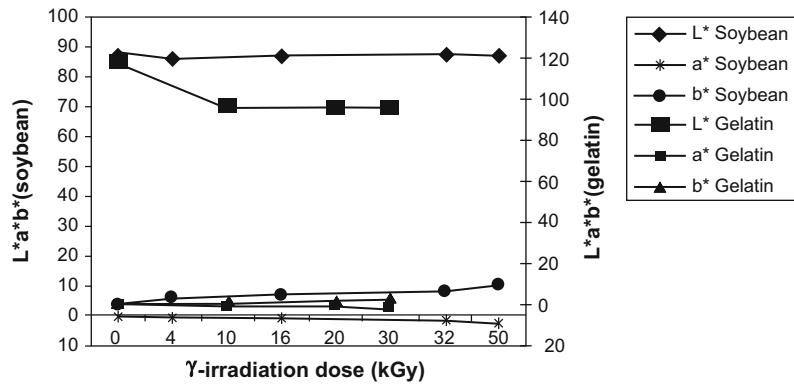


Figure 15.7: Effect of irradiation dose on Hunter L^* , a^* and b^* parameters of gelatin (Jo et al., 2005) and SPI films (Lee et al., 2005a).

15.3.4 Effect of Irradiation on Collagen

The photochemical stability of PVA in the presence of 1, 3, and 5% of collagen has been studied with FT-IR. PVA samples containing 1, 3, and 5% of collagen were irradiated with UV light wavelength $\lambda = 254$ nm in air. After UV irradiation of PVA, a small decrease of absorbance at 278 nm was observed, whereas in collagen an increase in absorbance in the region 250–320 nm was reported. The increase in the absorption of PVA in the region 250–300 nm after 2 h of UV irradiation was a result of the formation of conjugated double bonds. In the presence of 1, 3, and 5% of collagen in PVA, the amount of crystallinity decreased faster with UV irradiation time than that for pure PVA films (Sionkowska et al., 2004).

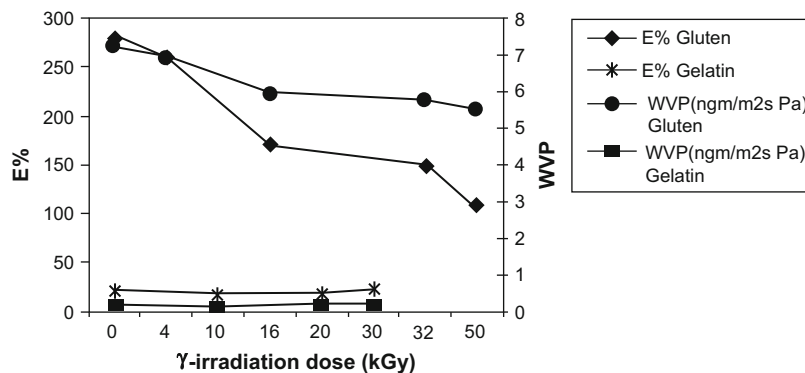


Figure 15.8: Effect of γ -irradiation treatment on water vapor permeability and elongation of gluten (Lee et al., 2005a) and gelatin films (Jo et al., 2005).

Bailey and Paul (1998) studied the surface properties of PVA films in the presence of 1, 3, and 5% of collagen before and after UV irradiation using atomic force microscopy (AFM) and contact angle measurements. After drying, the samples were irradiated with UV light wavelength $\lambda = 254$ nm in air. UV irradiation caused a decrease in surface roughness of collagen films and PVA films containing 1 and 5% of collagen. The roughness of PVA films and PVA containing 3% of collagen slightly increased after UV irradiation.

The thermal and mechanical properties of collagen/chitosan blends before and after UV irradiation were investigated using thermal analysis and mechanical (Instron) techniques. Air-dried collagen, chitosan, and collagen/chitosan films were exposed to UV irradiation (wavelength 254 nm) for different time intervals. The UTS of collagen film decreased after 2, 4, and 8 h of UV irradiation, whereas UTS of chitosan film increased after 2 h of UV irradiation. The %UE of the collagen film decreases after 2, 4, and 8 h of UV irradiation. Young's modulus was lower than for non-irradiated specimens for all of the blends (Sionkowska et al., 2004).

Modification of collagen films by UV irradiation (254 nm) was investigated using differential scanning calorimetry and SEM. It was found that the denaturation temperature of collagen decreased during irradiation, and the surface of the films was altered. The mechanical properties of irradiated collagen films were studied because after irradiation, these films crumbled and cracked (Sionkowska, 2000).

Table 15.3 presents the effect of irradiation on mechanical properties of edible films of animal origin.

15.3.5 Effect of Irradiation on Caseinate

Solutions of calcium caseinate (5%) combined with propylene glycol (PG) or triethylene glycol (0, 2.5, and 5%) and used for the development of edible films and coatings were irradiated at doses between 0 and 128 kGy. The puncture strength of films formed with caseinate increased significantly with the irradiation dose, followed by a plateau at doses of 16–32 kGy. At 16 kGy, in the presence of 5% PG, an increase in the puncture strength of 23% was observed compared to 12% for 2.5% PG and for films without plasticizers (Brault et al., 1997).

15.3.6 Effect of Irradiation on Albumin

Liu et al. (2006) investigated the effect of irradiation by power ultrasound on the adsorption of proteins on copper using bovine serum albumin (BSA) as a model protein in pH 7 phosphate buffer solution. The BSA molecules adsorbed on, and blocked, the copper surface, inhibiting the oxidation process and consequently decreasing the corresponding oxidation and reduction

TABLE 15.3 Effect of Irradiation on Mechanical Properties of Edible Films of Animal Origin

| Film Type | Irradiation Type/Dose | %E | Tensile Strength (MPa) | Puncture Deformation | Puncture Strength (MPa) | Reference |
|---|---|---------------------|-------------------------------------|----------------------|-------------------------|----------------------|
| Calcium caseinate, whey protein isolate, and glycerol (1:1:1) | γ irradiation/0 and 32 kGy | — | From 53.9 to 77.4 Nmm ⁻¹ | From 4.46 to 4.07 mm | — | Ciésla et al., 2003 |
| SPI:Gly (2:1) | γ irradiation/0 and 32 kGy | — | — | — | 43.30 | Lacroix et al., 2002 |
| SPI:Gly:CMC (20:10:1) | | | | | 52.20 | |
| SPI:Gly:CMC:PVA (20:10:1:2) | | | | | 59.00 | |
| SPI:WPI:Gly (1:1:1) | | | | | 40.32 | |
| SPI:WPI:Gly:CMC (10:10:10:1) | | | | | 41.27 | |
| SPI:WPI:Gly:CMC:PVA (10:10:10:1:2) | | | | | 46.07 | |
| Gelatin | γ irradiation/0, 10, 20, and 30 kGy | From 20.35 to 21.88 | From 106 to 100 kPa | — | — | Jo et al., 2005 |
| Gly 25%/Gly 45% | e beam irradiation/0, 50, 100, 150, and 200 kGy | From 20 to 68 | From 2 to 9.2 | — | — | Sabato et al., 2001 |

currents. Analysis of the spectra showed that the interfacial resistance was higher before than after irradiation, with a partial recovery of the BSA coverage, as would be expected if changes in adsorption occurred.

15.3.7 Effect of Irradiation on Fish Protein

When Cuq et al. (1995) applied γ -radiation to protein film-forming solution, an improvement in mechanical properties of whey protein films was recorded. The objective of this work was the characterization of mechanical and thermal properties of irradiated films based on muscle proteins from Nile tilapia (*Oreochromis niloticus*). The films were prepared according to a casting technique with two levels of plasticizer, 25 and 45% glycerol, and irradiated in a 0.550 MeV Radiation Dynamics electron accelerator at a dose range of 0–200 kGy. The TS value reached the major value for film with 45% glycerol at 100 kGy, followed by values at 50 and 150 kGy.

Edible films based on fish skin gelatin incorporated with chitosan and/or clove essential oil were elaborated and their antimicrobial activity was tested on *Lactobacillus acidophilus*, *Pseudomonas fluorescens*, *Listeria innocua*, and *Escherichia coli*. The gelatin/chitosan clove-added film showed good antimicrobial properties when applied to food, as did other films incorporated with chitosan and/or other essential oils on beef, bologna slices, or cold-smoked sliced sardine (Gómez-Estaca et al., 2007).

The effect of irradiation on the physical properties of edible films of animal origin is summarized in Table 15.4.

15.4 Conclusions

The effect of irradiation on edible films was found to depend greatly on the kind of substrate. Specifically, whenever there was a chance for cross-linking, the polymeric network became more resistant, resulting in higher tensile strength and puncture strength, but the percentage elongation decreased. On the other hand, cross-linking led to lower gas and water permeability values. In the case in which there was no cross-linking, the irradiated network loosened, and both mechanical and permeation properties decreased considerably.

TABLE 15.4 Effect of Irradiation on Physical Properties of Edible Films of Animal Origin

| Film Type | Irradiation Type/Dose | Effect on | | | WVP | Reference |
|--|---|----------------------|-------------------|-------------------|---|----------------------|
| | | L^* | a^* | b^* | | |
| Calcium caseinate, whey protein isolate, and glycerol (1:1:1) | γ irradiation/0 and 32 kGy | — | — | — | From 168.6 to 114.9 ($\times 10$ g mm/m ² day mmHg) | Ciésla et al., 2003 |
| SPI:Gly (2:1) SPI:Gly:CMC (20:10:1) SPI:Gly:CMC:PVA (20:10:1:2) SPI:WPI:Gly (1:1:1) SPI:WPI:Gly:CMC (10:10:10:1) SPI:WPI:Gly:CMC:PVA (10:10:10:1:2) | γ irradiation/0 and 32 kGy | — | — | — | — | Lacroix et al., 2002 |
| Gelatin | γ irradiation/0, 10, 20, and 30 kGy | From 118.09 to 95.37 | From 0.52 to 2.39 | From 1.29 to 3.64 | From 0.175 to 0.185 (ng/m ² s Pa) | Jo et al., 2005 |
| Gly 25%/Gly 45% | e beam irradiation/0, 50, 100, 150, and 200 kGy | — | — | — | — | Sabato et al., 2007 |

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Potential Uses of Irradiation

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16.1 Introduction

Food irradiation has been recognized as a reliable and safe method for the preservation of food and for improving the hygienic quality and nutritional value of food (Al-Kaisey et al., 2002; Diehl, 2002; Gampbell et al., 1983). In addition to the control of microorganisms of numerous food commodities, ionizing irradiation can be used to reduce several carcinogenic agents (Ahn et al., 2004b; Fan and Mastovska, 2006) and antinutritional factors, such as gossypol (Abu-Tarboush, 1998) and trypsin and tannin inhibitors (de Toledo et al., 2007). In addition, irradiation has also been used in the drying procedure of food commodities (Wang and Du, 2005) and in the development of traditional fermented foods (Byun et al., 2006).

This chapter presents a detailed review of data regarding the current and potential applications of ionizing irradiation on the reduction of carcinogenic agents and several antinutritional components, the production of fermented food, the process of drying food, food allergens reduction, and green tea extract improvement.

16.2 Production of Fermented Foods and the Use of Irradiation

According to Byun et al. (2006), inactivation of fermentative microorganisms, such as various lactic acid-producing bacteria and yeast strains, is essential for preservation and extending the shelf life of fermented food. Irradiation has proved to be an effective method for improving the quality of fermented foods (Kim et al., 2002; Park et al., 2008). Mojica et al. (2005) investigated the use of irradiation as a pretreatment in the production of fermented fish paste. Pretreatment of fish samples using irradiation for the production of fish paste from dilis and galunggong was performed. Pretreatment at 3 and 10 kGy resulted in lower microbial load of the fermented fish paste. Irradiation of dilis resulted in improved proteolytic degradation compared with that of galunggong. There was no significant change in pH for both species. Acceptability scores of treatment at 3 kGy showed general improvement in the quality of the fish paste for dilis but not

for galunggung. However, at 10 kGy, sample texture and overall acceptability were generally lower for dilis.

The radicidation of enteric bacteria in the fermentation process of kimchi was investigated by Kim et al. (2004a). According to Lee et al. (2002), γ -irradiation improved the quality of 15 and 20% salted shrimp jeotkal, whereas 30% salted shrimp jeotkal (control) was poor in sensory evaluation even though the shelf life was prolonged because of excess salt concentration. Results indicated that irradiation at 5 and 10 kGy with lower than usual (30%) salt content improved the sensory quality and microbial shelf stability during storage and can thus be applied in the industry. Viable cell numbers of enteric bacteria were 10^4 CFU/g at the initiation of the kimchi fermentation process, gradually reducing during the fermentation period and not detected after 10 days. The enteric bacteria in the early fermentation period of kimchi were eliminated by 2 or 3 kGy γ -irradiation, but *Lactobacillus* spp. survived and fermentation was maintained. It was considered that γ -irradiation was not only effective in sanitizing the early fermentation stage of kimchi but also effective in maintaining the fermentation process.

The effects of irradiation on low-salt fermented foods have been studied by several authors. Jo et al. (2004) developed the fermented and seasoned Alaska pollock (*Theragra chalcogramma*) intestine (Changran Jeotkal) with lower salt content (5% instead of 8% of commercial products). Gamma irradiation improved the microbial safety and chemical quality of the lower salt (5%) Changran Jeotkal, whereas the 8% salted control had lower sensorial quality compared to the sample with 5% salted and irradiated. Results indicated that 5% salt content and irradiation at 2.5 kGy improved the microbial shelf stability and chemical and sensory quality.

16.3 Irradiation as a Method for Drying Food Products

Drying is one of the oldest methods of food preservation. During drying, heat is transferred from the hot air to the product by convection, and evaporated water is transported to the air also by convection (Nowak and Lewicki, 2004). However, there are many problems with this kind of process, such as high energy consumption and lower quality of dried food commodities. Some studies have investigated ways to solve such problems by modifying the drying method. Wang and Chao (2002) dried bioproducts by hot air after they had been treated by γ -irradiation. They found that in comparison with non-irradiated apple, only a falling dehydration rate period was observed during the dehydration of irradiated apple (Fuji apple). In fact, an increase in dehydration rate resulted in greater temperature of sample during drying. In addition, they found that the greater the dosage (0, 2, 5, and 6 kGy), the higher the dehydration rate and the higher the temperature of the apple. The damages and changes in structure of apple caused by irradiation were the main reason for the higher dehydration rate. According to Wang and Chao (2003), the dehydration rate and rehydration ratio of apples (Fuji) were greatly affected by the

irradiation dose (0, 2, 5, and 6 kGy). The greater the dose, the higher the dehydration rate and the lower the rehydration ratio.

Wang and Du (2005) determined that compared with non-irradiated potato, γ -irradiation (0, 2, 4, 5, 6, 8, or 10 kGy) increased the dehydration rate and temperature of potato slices during hot-air drying; the greater the dose, the higher the dehydration rate and temperature. Similarly, as in the case of non-irradiated potatoes, the drying characteristics of irradiated potatoes were affected by air temperature and the thickness of the sample; the higher the air temperature and the thinner the slice, the higher the dehydration rate.

16.4 Effect of Irradiation on Chlorophyll

The presence of chlorophylls can cause color change and promotion of oxidation under certain conditions (Abraham and de Man, 1986). The breakdown of chlorophyll by irradiation was investigated by Byun et al. (2002a). Chlorophyll β standard (3 ppm) was added to a methanol solution containing 1% linoleic acid. Irradiation up to 20 kGy was performed with or without N_2 bubbling, and non-irradiated control was also prepared. The added chlorophyll β was decomposed by irradiation at 20 kGy with or without N_2 bubbling. With N_2 bubbling, the oil sample did not develop lipid oxidation during irradiation, and irradiated samples did not develop photo-oxidation during storage under light (3,300 lux). Without N_2 bubbling, irradiated oil samples had higher peroxide values than non-irradiated samples. Irradiation at 2.5 kGy or higher destroyed all added chlorophyll β . These results indicate that irradiation technology can be applied to reduce or eliminate the residual chlorophyll in oil processing without developing lipid oxidation during the irradiation process.

16.5 Ionizing Irradiation and the Reduction of Food Allergens

Allergic response is caused by mediation of IgE antibody production against allergen from sources such as house dust mite, foods, animals, grass pollen, etc. (Seo et al., 2007). Infants and toddlers show a relatively high prevalence of food allergies due to an immature gastrointestinal epithelial membrane barrier, which allows more proteins to move through the barrier and into the circulatory system (Metchlfe et al., 1997). Prevention of food allergy might be achieved by altering the dietary factors responsible for the sensitization and phenotypic expression of the disease (Taylor, 1980). The hydrolysis of allergens by proteolytic enzymes and development of recombinant foods with modified DNA were studied to eliminate protein allergens from allergenic foods (Nilsson et al., 1999). However, these approaches can be used only in a limited number of foods (Byun et al., 2002b). On the other hand, several researchers have reported that the antigenicity of proteins is modified by γ -rays (Byun et al., 2004b; Kume and Matsuda, 1995; Lee et al., 2001).

Lee et al. (2001) evaluated the application of food irradiation technology as a method for reducing milk allergies. Bovine α -casein and β -lactoglobulin (BLG) were used as milk proteins. Allergenicity and antigenicity of the irradiated proteins were changed with different slopes of the inhibition curves. The disappearance of the band on sodium dodecyl sulfate polyacrylamide gel electrophoresis (SDS-PAGE) and increase in the turbidity indicated that solubility of the proteins decreased with radiation, and this decrease might be caused by agglomeration of the proteins. Their results confirmed that epitopes on milk allergens were structurally altered by γ -irradiation.

Byun et al. (2002b) studied the application of food irradiation technology as a method for reducing food allergy. Milk BLG, chicken egg albumin, and shrimp tropomyosin were used as model food allergens for experiments on allergenic and molecular properties by γ -irradiation. The amount of intact allergens in an irradiated solution was reduced by γ -irradiation depending on the dose. These results showed that epitopes on the allergens were structurally altered by radiation treatment and that the irradiation technology can be applied to reduce allergenicity of allergic foods.

The effect of different doses of irradiation on tropomyosin content of squid (*Todarodes sagittatus*), octopus (*Octopus vulgaris*), and shrimp is shown in Figure 16.1.

Seo et al. (2007) investigated the effect of γ -irradiation on the chemical and immunological properties of ovalbumin (OVA). Irradiation of more than 10 kGy resulted in alteration of the structure of OVA. Their results suggested that γ -ray irradiation of OVA suppressed humoral and cellular immune responses specific to the allergen OVA, and the modification method with γ -irradiation may possibly be used for the control of allergy.

Lee et al. (2007) compared the use of γ -ray and electron-beam irradiation for the inhibition and reduction of a food allergy. OVA (2 mg/ml) was irradiated at 3, 5, 7, and 10 kGy. Patterns

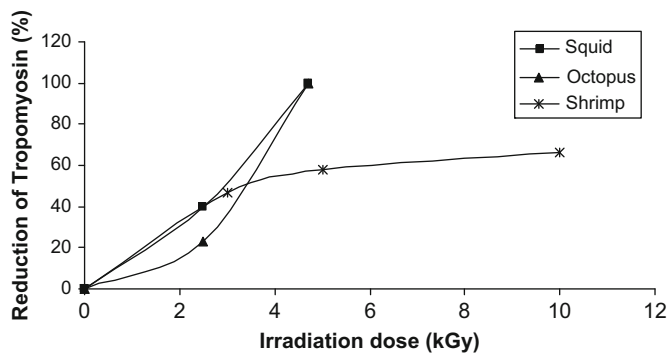


Figure 16.1: Effect of different doses of irradiation on tropomyosin content of squid (*Todarodes sagittatus*), octopus (*Octopus vulgaris*) (Sinanoglou et al., 2007), and shrimp (species not specified) (Byun et al., 2002b).

detected by SDS–PAGE and an immunoblot showed that the intact OVA band disappeared and that it was dependent on the radiation doses, regardless of the radiation type. Binding abilities of the irradiated OVA against the monoclonal IgG and the egg allergic patients' IgE decreased due to a conformational change of the epitope. However, differences between the two different radiation types were not observed. The results indicated that both radiation types can be used for inhibition and reduction of a food allergy.

Sinanoglou et al. (2007) found that the amount of tropomyosin, which is the major mollusk and crustacean allergen in the irradiated squid (*Todarodes sagittatus*), octopus (*Octopus vulgaris*), cuttlefish (*Sepia officinalis*), and shrimp (*Penaeus monodon*), was reduced by γ -radiation, depending on the dose applied. The initial concentration of allergen of the non-irradiated shrimp sample was 0.10 ppm (mg/kg). After treatment with 2.5 and 4.7 kGy, the allergen could no longer be detected (values were below the detection limit of 0.05 ppm).

16.6 Color Improvement of Green Tea Extracts

Green tea is consumed in more than 160 countries every day for drinking (An et al., 2004). Recently, tea has attracted attention for its health benefits, particularly with respect to its potential for preventing and treating cardiovascular diseases, because it is a very good source of polyphenols (10–30% dry leaf weight) including bioactive chemicals, flavonoids, and catechins and their derivatives (Higdon and Frei, 2003). Green tea is composed of approximately 30% polyphenols (dry basis), such as flavanols, flavandiols, flavonoids, and phenol acids. Polyphenols have various excellent biological activities, including the inhibition of tooth decay (Sakanaka et al., 1989), inhibition of allergies (Yeo et al., 1995), reduction of blood pressure (An, 1998), prevention of gout (An et al., 1996), and inhibition of oxidation. However, despite all the beneficial effects and after undergoing several trials in food and cosmetics, green tea leaves have been used mostly for drinking with boiling water. This is mainly because of its dark color and off-flavor, which make it very difficult to apply the proper amount in cosmetics, medicine, or foods (Jo et al., 2003a, b and c).

Gamma irradiation was tested as a new processing method for brighter colored green tea leaves extract (Jo et al., 2003b). Dried green tea leaves were purchased and extracted by 70% ethanol solution and irradiated at 0, 5, 10, and 20 kGy with γ -rays. The L^* value increased with an increase of irradiation dose at both storage temperatures. During storage at 4°C, the L^* value slowly decreased and the irradiation dose effect was partially reversed after 3 weeks. Thus, the sample with 5 or 10 kGy irradiation had higher L^* values than that with 20 kGy irradiation. This change was faster in the sample stored at 25°C than in the sample stored at 4°C. Results also indicated that the storage temperature is important for maintaining the proper color. The Hunter color a^* value did not change much in storage for 3 weeks at 4°C in a non-irradiated sample.

However, irradiation dramatically decreased the a^* value of the sample. The Hunter color a^* values of the 20-kGy irradiated samples stored at 25°C were increased after 1 week. Moreover, the authors found that there was no difference in the radical scavenging and tyrosinase inhibition effect by irradiation.

Jo et al. (2003c) examined the functional and sensory properties of raw and cooked pork patties with added irradiated freeze-dried green tea leaf extract powder. Components of green tea were extracted with 70% ethanol, and the extract was irradiated to obtain a bright color. The irradiated green tea extract was freeze-dried and the powdered sample (0.1%) was added to the pork patties. Their results revealed that addition of 0.1% extract to the patties decreased considerably the scavenging effect, thereby resulting in a reduction of the lipid oxidation in raw and cooked patties.

Lee et al. (2006) reported that the Hunter color L^* values of the green tea leaf and by-product extract solutions increased while the Hunter color a^* and b^* values of the samples decreased after exposure to 20 kGy γ -irradiation. The initial sample color of the by-product extract and its color change by irradiation were similar to those of the leaf extract. Moreover, their results suggested that although the biological activity of green tea by-product extracts was less than that of green tea leaf extract, it could be a potential source of a functional ingredient. Similarly, Son et al. (2001) reported that irradiation increased the L^* value of the green tea leaf extract without any adverse changes in physiological activities.

16.7 Reduction of Antinutrients with the Use of Irradiation

Cereals and other crops contain a substantial level of protein and significant levels of carbohydrates. However, in some of these commodities, the utilization of available protein and carbohydrates is much less than that calculated from the chemical composition because of the presence of various antinutritional substances, such as trypsin inhibitors, polyphenols, chymotrypsin inhibitors, α -amylase inhibitors, phytates, glucosinolates, cyanogenic glucosides, oligosaccharides, toxic non-protein amino acids, antivitamins, saponins, and alkaloids (Abu-Tarboush, 1998; D'Mello, 1995; Liener, 1994a,b; Makkar and Becker, 1998; Makkar *et al.*, 1998; Rattansi and Dikshit, 1997; Siddhuraju *et al.*, 2000).

16.7.1 Phytic Acid Reduction and Antioxidant Activity Increase with Irradiation

Phytic acid is historically considered to be an antinutrient. It binds to multivalent cations such as Zn^{2+} , Mg^{2+} , Ca^{2+} , and Fe^{2+} and decreases their bioavailability (Dvorakova, 1998; Wodzinski and Ullah, 1996; Zyla, 1992). It is widely found in cereals, nuts, legumes, oil seeds, pollen, and spores (Graf and Eaton, 1990). However, phytic acid is considered to be an antioxidant (Graf and Eaton, 1990), an anticarcinogenic (Shamsuddin *et al.*, 1997), and a hypoglycemic (Rickard and Thompson, 1997).

Several researchers have studied the effect of irradiation on various foodstuffs containing phytic acid. The effects of cooking followed by irradiation (10 kGy) on the antinutritional factors, phytic acid and nitrates, in a ready-to-eat meal of sorghum porridge and spinach-based relish were investigated. Irradiation of the cooked sorghum endosperm meal decreased phytic acid on both a dry and as-is basis. The phytic acid of the raw sorghum endosperm meal was 135 mg/100 g and for the cooked and irradiated sample was 80.5 mg/100 g (Duodu et al., 1999).

Ahn et al. (2004a) evaluated the antioxidant activities of irradiated phytic acid and other commonly used antioxidants. Degradation of phytic acid, dissolved in deionized distilled water at various concentrations (800, 400, 200, and 100 μM), was caused by γ -irradiation. The phytic acid solution at 100 μM was degraded more than 90% by irradiation at 10 kGy. However, degradation became more difficult as the concentration increased. Phytic acid was irradiated at 0, 10, and 20 kGy. Phytic acid irradiated at 20 kGy showed significantly higher 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging capacity than ascorbic acid at the 800 μM level, whereas non-irradiated phytic acid solution did not show DPPH radical scavenging activity regardless of its concentration. Furthermore, it was determined that ferric reducing antioxidant power (FRAP) of phytic acid was significantly increased by irradiation, which is in agreement with the results of Fan and Thayer (2002), who determined that in apple juice there was an irradiation-induced increase in FRAP.

Bhat et al. (2007) assessed the impact of γ -irradiation on the phytic acid content of seeds of *Mucuna pruriens* upon exposure to doses of 2.5, 5.0, 7.5, 10, 15, and 30 kGy. Excluding 2.5 kGy, the rest of the treatments showed significant decreases in phytic acid, and complete degradation was attained at 15 and 30 kGy. The impact of different doses of irradiation on phytic acid content of broad bean seeds (Al-Kaisey et al., 2003) and velvet bean seeds is displayed in Figure 16.2.

Microbial phytases can be used to reduce phytic acid content in commodities. Several microorganisms were tested for their ability to produce phytase, and some of them were used in

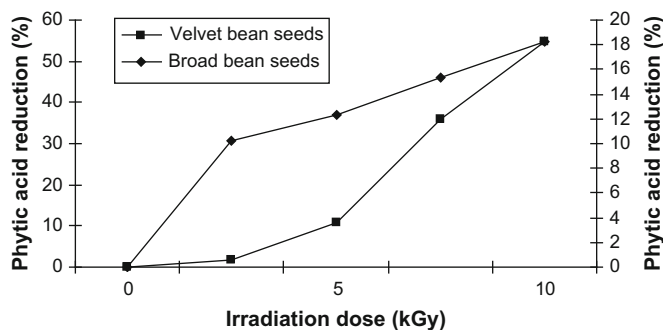


Figure 16.2: Impact of irradiation dose on phytic acid content of broad bean seeds (Al-Kaisey et al., 2003) and velvet bean seeds (Bhat et al., 2007).

reduction of phytic acid content in rapeseed meal and canola meal during solid-state fermentation (Ebune et al., 1995a,b). El-Batal and Karem (2001) investigated the effect of γ -irradiation (0.05, 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.25, 1.5, 1.75, and 2.0 kGy) on the production of phytase and hydrolysis of phytic acid in rapeseed meal during solid-state fermentation with *Aspergillus niger*. Phytic acid was completely hydrolyzed in rapeseed meal inoculated with γ -irradiated cultures at doses of 0.6–1.25 kGy, and results displayed a strong correlation between phytic acid hydrolysis and enzyme production.

El-Niely (2007) examined the effects of irradiation (dose levels of 5, 7.5, and 10 kGy) on nutritive characteristics of peas (*Pisum sativum*), cowpeas (*Vigna unguiculata*), lentils (*Lens culinaris*), kidney beans (*Phaseolus vulgaris*), and chickpeas (*Cicer arietinum*). Radiation treatment at dose levels of 5, 7.5, and 10 kGy significantly reduced the phytic acid content of peas by 8.9, 11.4, and 17.2%, of cowpeas by 8.6, 11.4, and 14.8%, of lentil by 15.1, 25.2, and 32.7%, of kidney beans by 7.5, 14.2, and 26.9%, and of chickpeas by 6.5, 11.5, and 20.2%, respectively, compared with respective raw seed materials. Radiation treatment resulted in a moderate significant reduction in tannins (TNs) in all legumes compared to controls. Approximately 13.6, 19.9, and 27.8% of the TN content of peas was reduced at irradiation dose levels of 5, 7.5, and 10 kGy, respectively. The reduction in TN content of cowpeas was 13.4, 21, and 22.9%, that of lentil was 7.6, 12, and 21.7%, that of kidney beans was 11.2, 16.7, and 25%, and that of chickpeas was 6.3, 16.4, and 28.1% as a result of being subjected to the previously mentioned irradiation doses, respectively.

Seeds of three different species of *Sesbania* (*S. aculeata*, *S. rostrata*, and *S. cannabina*) and one species of *Vigna* (*V. radiata*) were γ -irradiated at dose levels of 2, 4, and 6 kGy after aqueous soaking, and the effects of the irradiation on phytic acid level were investigated. When subjected to treatments such as soaking, and soaking followed by irradiation at dose levels of 2, 4, and 6 kGy, no significant differences were observed between the raw seeds and those subjected to the various treatments (Siddhuraju et al., 2002).

Al-Kaisey et al. (2003) studied the effect of γ -irradiation on the level of phytic acid of broad bean. Irradiation treatment reduced the phytic acid content. On irradiation, phytic acid decreased by 10.2, 12.3, 15.4, and 18.2% at 2.5, 5, 7.5, and 10 kGy, respectively. The results indicated that the maximum reduction in the value of the phytic acid was recorded at 10 kGy.

Ahn et al. (2003c) reported that the antioxidant activity of phytic acid was slightly increased by irradiation in a lipid model system, although at higher concentrations the antioxidant activity remained the same compared to that of non-irradiated phytic acid or was reduced. On the other hand, Park et al. (2004) employed a meat model system and concluded that irradiated phytic acid significantly inhibited lipid oxidation in meats compared to the control sample. Moreover, it was shown that irradiated phytic acid was capable of inhibiting the loss of heme iron as well as myoglobin formation during storage, which might improve antioxidant activity of phytic acid in meats.

The effect of irradiation on the phytic acid content of various food products is summarized in Table 16.1.

16.7.2 Effect of Irradiation on Gossypol

Gossypol, a polyphenolic compound, is a constituent of cottonseeds (Murti and Achaya, 1975). Furthermore, cottonseed meal is being utilized for human consumption in Latin America and, to a limited extent, in other areas of the world (Noyes, 1969). However, it has been shown to cause many deleterious effects to nonruminant animals, a characteristic that limits its use as a source of protein for animals and humans (Nomeir and Abou-Donia, 1985). According to the Protein Advisory Group of the United Nations, free gossypol content of edible-grade cottonseed flour should not exceed 0.06% (Abu-Tarboush, 1998). Rahma and Narasinga Rao (1984) reported 0.069% free gossypol after extraction of cottonseed with a 1:1 mixture of 85% 2-propanol and hexane. Moreover, Cherry and Gray (1981) obtained cottonseed flours with free gossypol content of 0.011–0.24% by using methylene chloride with other suitable solvents. Abu-Tarboush (1998) reported that irradiation with a dose of 10 kGy reduced both total and free gossypol in cottonseeds by 14.0 and 7.9%, respectively, but irradiation was not effective in reducing gossypol to the permissible level of 0.06%. Extraction with different solvents resulted in a reduction in gossypol content to varying extent. Jo et al. (2003d) studied gossypol dissolved in methanol (0.25 and 0.5 mg/ml) that was γ -irradiated at 0, 5, 10, and 20 kGy. Gossypol decreased by irradiation and the downward trend was generally in a dose-dependent manner, which resulted in a reduction of embryotoxicity in mice.

16.7.3 The Effect of Irradiation on Protease Inhibitors and Other Antinutrients

Protease inhibitors are well-known antinutrients responsible for reduced digestibility of plant food proteins (Rackis et al., 1986). Some of these compounds (e.g., trypsin inhibitors) may actually cause an increase in the secretion of digestive enzymes, including trypsin, chymotrypsin, and elastase, by inducing hypertrophy and hyperplasia of the pancreas. This led to the hypothesis that the growth depression caused by trypsin inhibitors is the consequence of an endogenous loss of amino acids in the form of enzymes being secreted by a hyperactive pancreas (Liener, 1994a,b). Soybean seeds (200 g) were irradiated at dose levels of 0, 1, 5, 10, 20, 40, 60, 80, and 100 kGy using cobalt-60 source. Inhibition of 25.4% trypsin inhibitor activities and 16.7% chymotrypsin inhibitor activities was found when the soybean seeds were irradiated at 100 kGy (Hafez et al., 1985). Joseph and Dikshit (1993) examined the trypsin and chymotrypsin inhibitor activities of safflower oil cake before and after irradiation. The various doses to which samples were exposed ranged from 0.07 to 0.1 kGy. The trypsin inhibitor was inactivated at 0.42 kGy, whereas the chymotrypsin inhibitor remained active, even at the much higher dose of 0.1 kGy. The *in vitro* digestibility values also showed significant improvement after irradiation. The overall results suggest that there is no harm in using irradiation for

TABLE 16.1 Effect of Irradiation on the Phytic Acid Content of Various Food Products

| Food Type | Gamma Irradiation Dose (kGy) | Other Technology | Irradiation Effect on Residual Nitrite | Reference |
|--|--|------------------|--|--------------------------|
| Ready to eat meal of sorghum porridge and spinach based relish | 10 | Cooking | The phytic acid of the raw sorghum endosperm meal was 135 mg/100 g and that for the cooked and irradiated sample was 80.5 mg/100 g. | Duodu et al., 1999 |
| Rapeseed meal | 0.05, 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.25, 1.5, 1.75, and 2.0 | — | Phytic acid was completely hydrolyzed in rapeseed meal inoculated with γ irradiated cultures at doses from 0.6 to 1.25 kGy, and results showed a strong correlation between phytic acid hydrolysis and enzyme production. | El Batal and Karem, 2001 |
| Broad bean | 0, 2.5, 5, 7.5, and 10 | — | On irradiation, the phytic acid of broad bean seeds decreased by 10.2, 12.3, 15.4, and 18.2% at 2.5, 5, 7.5, and 10 kGy, respectively. | Al Kaisey et al., 2003 |
| Seeds of three different species of <i>Sesbania</i> (<i>S. aculeata</i> , <i>S. rostrata</i> , and <i>S. cannabina</i>) and one species of <i>Vigna</i> (<i>V. radiata</i>) | 2, 4, and 6 | Soaking in water | No significant differences were observed between the raw seeds and those subjected to the treatments. | Siddhuraju et al., 2002 |
| Peas (<i>Pisum sativum</i>), cowpeas (<i>Vigna unguiculata</i>), lentils (<i>Lens culinaris</i>), kidney beans (<i>Phaseolus vulgaris</i>), and chickpeas (<i>Cicer arietinum</i>) | 5, 7.5, and 10 | — | Irradiation processing reduced the phytic acid content of the legume seeds in a dose dependent manner. | El Niely, 2007 |
| Seeds of <i>Mucuna pruriens</i> | 2.5, 5.0, 7.5, 10, 15, and 30 | — | Excluding 2.5 kGy, the rest of the treatments showed significant decreases in phytic acid, and complete degradation was attained at 15 and 30 kGy. | Bhat et al., 2007 |

detoxification of oil cake because a low dose of 42 Gy is well below the permissible dose of 10 kGy. It has the advantage over other methods in that fewer steps are involved than for solvent extraction.

The effect of γ -irradiation on the level of trypsin inhibitor (TI), phytic acid, and oligosaccharides of broad bean was investigated by [Al-Kaisey et al. \(2003\)](#). The seeds were subjected to γ -irradiation doses of 0, 2.5, 5, 7.5, and 10 kGy. Irradiation treatment reduced the trypsin inhibitor activity (TIA) of irradiated seeds. In subsequent doses of irradiation, the decrease in TIA was proportional to the irradiation dose. Irradiation did not cause significant changes in TIA during the first dose (2.5 kGy). The results indicate that the maximum reduction in TIA was observed at 10 kGy. During irradiation, there was a rapid decrease of the raffinose family oligosaccharides. Complete depletion or elimination of the raffinose family oligosaccharides was achieved at 10 kGy. Complete destruction of raffinose and stachyose was observed at 7.5 kGy.

[de Toledo et al. \(2007\)](#) studied the effects of γ -radiation on total phenolics, trypsin, and tannin inhibitors in soybean grains. “The cooking process decreased the content of phenolic compounds in all cultivars. The dose of 8 kGy promoted an increase in the content of total phenolic compounds in all raw samples and in cooked samples from some cultivars. All cultivars presented the same behavior in relation to radiation for inhibited trypsin units for both raw and cooked samples, with significant differences between all doses used. Controls presented the highest values, followed by doses of 2 and 4 kGy, and a dose of 8 kGy presented the lowest value. It is possible that increases in the radiation dose used promoted decreases in the trypsin content of the samples. Radiation with a dose of 2 kGy promoted a reduction of 11.19% on average in TIA, a dose of 4 kGy reduced TIA 28.59%, and a dose of 8 kGy reduced TIA 37.60%. Furthermore, the tannin contents underwent reduction with increases in the radiation doses for both raw and cooked samples. The cooking process also promoted reduction in the antinutritional factors mentioned in this study.”

[Sattar and Neelofar \(1990\)](#) investigated the irradiation and germination effects on phytate of soybean. Irradiation independently decreased the original phytate (212.0 mg/100 g) to 190.0–205.0 mg/100 g depending on dose level. Germination of non-irradiated seeds for 120 h in distilled and tap water lowered the phytate to 55.0 and 94.9 mg/100 g (74.1 and 55.2% reduction), respectively. Maximum destruction of phytate to levels of 20.5 and 50.9 mg/100 g (90.3 and 76.0% reduction) occurred during germination of 0.20-kGy samples for 120 h in distilled and tap water, respectively.

In a study by [Rattansi and Dikshit \(1997\)](#), TIA and chymotrypsin inhibitor activity (CIA) were assayed before and after processing of karanja oil seed residue. The samples were exposed to different doses (1, 5, 10, and 50 kGy) of γ -radiation. The degradation of protease inhibitors on exposure to γ -radiation was directly proportional to the radiation dose. CIA and TIA retained in the cake on exposure to the 50-kGy dose were 22 and 16%, respectively.

The effect of irradiation on protease inhibitors in various products is given in Table 16.2.

16.8 Carcinogens and Their Relation to Irradiation

16.8.1 Reduction of Volatile N-Nitrosamine and Nitrite Content with Irradiation

Human exposure to carcinogen *N*-nitrosamines occurs through endogenous and exogenous sources such as foods and beverages (Chung, 1996, 2000). The major *N*-nitrosamines found in food systems are nitrosodimethylamine (NDMA) and nitrosopyrrolidine (NPYR) (Lijinsky, 1999). Low levels of biogenic amines in food are not considered a serious risk. However, if the amount consumed is high enough, or normal pathways of amine catabolism are inhibited, various physiological effects may occur, such as hypotension or hypertension, nausea, headache, rash, dizziness, cardiac palpitation and emesis, and even death (Rawles et al., 1996). The formation of *N*-nitrosamines in foods occurs due to an addition of nitrite, smoking, drying with combustion gas, salting, pickling, fungal contamination, or food contact materials (Thicker, 2000). Nitrite is an essential additive for developing typical cured meat color, flavor, and texture

TABLE 16.2 Effect of Irradiation on Protease Inhibitors in Various Products

| Food Type | Gamma Irradiation Dose (kGy) | Irradiation Effect | Reference |
|--------------------------|--------------------------------------|---|----------------------------|
| Soybean seeds | 0, 1, 5, 10, 20, 40, 60, 80, and 100 | Inhibition of 25.4% trypsin inhibitor activities and 16.7% chymotrypsin inhibitor activities were found when the soybean seeds were irradiated at 100 kGy. | Hafez et al., 1985 |
| Safflower oilcake | 0.07 0.1 | The trypsin inhibitor was inactivated at 0.42 kGy, whereas the chymotrypsin inhibitor remained active, even at the much higher dose of 0.1 kGy. The <i>in vitro</i> digestibility values also showed a significant improvement after irradiation. | Joseph and Dikshit, 1993 |
| Karanja oil seed residue | 1, 5, 10, and 50 | Trypsin and chymotrypsin inhibitor activities retained in the cake on exposure to 50 kGy dose were 22 and 16%, respectively. | Rattansi and Dikshit, 1997 |
| Broad bean | 0, 2.5, 5, 7.5, and 10 | Irradiation treatment reduced the trypsin inhibitor of irradiated seeds. In subsequent dose of irradiation, the decrease in trypsin inhibitor was proportional to the irradiation dose. | Al Kaisey et al., 2003 |
| Soybean grains | 2, 4, and 8 | Radiation with dose of 2 kGy promoted reduction of 11.19% on average in trypsin inhibitory activity, and a dose of 4 kGy reduced 28.59% and that of 8 kGy reduced 37.60%. | de Toledo et al., 2007 |

and for protecting against oxidative rancidity and pathogenic microorganisms, especially *Clostridium botulinum*, in meat products. According to Cassens (1997), the residual nitrite content of cured meats at the retail level is approximately 10 ppm. That is why the nitrite in meat products is a primary problem in the formation of carcinogenic volatile *N*-nitrosamines under high-temperature conditions (Ahn et al., 2002a and b).

Several methods have been developed to inhibit nitrosamine formation with the use of green tea (Yang and Wang, 1993), ascorbic acid (Vermeer et al., 1999), and phenol compounds (Bartsch et al., 1988). Fiddler et al. (1981) found that irradiation sterilization (30 kGy) reduced residual nitrite in bacon prior to frying, thereby reducing volatile nitrosamines after frying, and destroyed preformed volatile nitrosamines in the bacon before irradiation. Hu and Song (1988) reported that γ -irradiation could reduce nitrite from 41.2 to 21.0 ppm in eel at 5 kGy of irradiation.

Jo et al. (2003a) studied the packaging and irradiation effect on pork sausage. Emulsion-type cooked pork sausage was made with (156 ppm) or without NaNO₂ and packaged at 4°C in aerobic, vacuum, and CO₂ (100%) conditions. The samples were irradiated at 0 and 5 kGy. Residual nitrite content was the lowest in the sausage with CO₂ packaging, but no irradiation effect was found at 5 kGy. The 5-kGy irradiation eliminated the nitrosopyrrolidine (NPYR) in the sausage with vacuum or CO₂ packaging at 0 weeks. At 4 weeks, the NPYR increased significantly in the sausage with NaNO₂ and the irradiation also helped to reduce the NPYR content in the sausage regardless of packaging. Moreover, irradiation at 5 kGy significantly reduced the NDMA content regardless of packaging method.

The characteristics of nitrite radiolysis with γ -rays were investigated by Ahn et al. (2003a). Sodium nitrite in deionized distilled water was irradiated at 0, 5, 10, 15, 20, 25, 30, and 40 kGy. The sodium nitrite was reduced approximately 50% by 10-kGy irradiation, and complete degradation was shown over 40 kGy. When nitrite was nitrosated at different pH ranges (2, 3, 4, and 6) after irradiation, the irradiated nitrite could not form the carcinogenic *N*-nitrosodimethylamine. The authors concluded that γ -irradiation could be effectively used for reducing nitrite, and radiolytically destroyed nitrite could not form carcinogenic *N*-nitrosamine, even in a model human stomach condition.

Ahn et al. (2002a) studied the reduction of carcinogenic *N*-nitrosamines and residual nitrite in model system sausage with irradiation. Sausages were packed under air and under vacuum and irradiated at 0, 5, 10, 20, and 30 kGy. The residual nitrite levels were significantly reduced with γ -irradiation, and in vacuum packaging the reduction was dose dependent. Vacuum packaging proved to be more effective than aerobic packaging for lowering the nitrite levels. In aerobic-packaged sausage, NPYR levels were not affected by irradiation. However, after 4 weeks of 20 and 30 kGy of irradiation, NPYR levels were reduced 47.7–51.0% in VP compared to non-irradiated sausage. NDMA levels in non-irradiated aerobic and VP samples were significantly higher than those in 20-kGy irradiated samples. A significant difference was found between

non-irradiated samples and samples irradiated with a 10-kGy or higher dose in aerobic packaging. In conclusion, for reduction of NDMA and NPYR in sausage, 20 kGy of irradiation or higher was needed.

Gamma irradiation was applied for the breakdown of the volatile *N*-nitrosamines, NDMA and NPYR. NDMA and NPYR were dissolved in distilled water, dichloromethane, or ethanol and irradiated at 2.5, 5, 7.5, 10, 15, 20, and 25 kGy. The NDMA in dichloromethane was broken down to the level of 448 ppb (mg/l) at 2.5 kGy, and NPYR was completely broken at the same dose. The NDMA required a dose of 10 kGy or higher of γ -irradiation to achieve 99% breakdown. NDMA and NPYR dissolved in ethanol were comparatively stable to γ -irradiation. At the dose of 20 kGy, NDMA and NPYR showed 95 and 100% breakdown, respectively. NDMA and NPYR dissolved in distilled water were easily broken down with γ -irradiation, and all of the volatile *N*-nitrosamines were undetectable at 5 kGy or higher. NDMA and NPYR displayed 65–84% breakdown at 2.5 kGy, and NPYR was the most sensitive to γ -irradiation. The results indicated that volatile *N*-nitrosamines in distilled water were easily decomposed with γ -irradiation at doses of 5 kGy or higher (Ahn et al., 2002b).

Ahn et al. (2003b) studied salted and fermented anchovy sauce spiked with or without NDMA and NPYR. Samples were irradiated at 0, 5, 10, 15, and 20 kGy. NDMA and NPYR reduction with irradiation was not observed in nonspiked samples at 0 weeks, whereas a significant reduction was observed after 4 weeks of storage at 15°C. NDMA and NPYR levels decreased with irradiation at 5 kGy or higher after storage at 15°C. After storage, the degraded nitrosamines with irradiation were not recombined.

The impact of different doses of irradiation on NDMA content of pepperoni sausage, packaged under air, and fermented anchovy sauce at Week 0 is shown in Figure 16.3.

Byun et al. (2004a) studied volatile NDMA and NPYR in irradiated pepperoni and salami sausages. These fermented sausages were packed under vacuum, air, 100% CO₂, 100% N₂, or

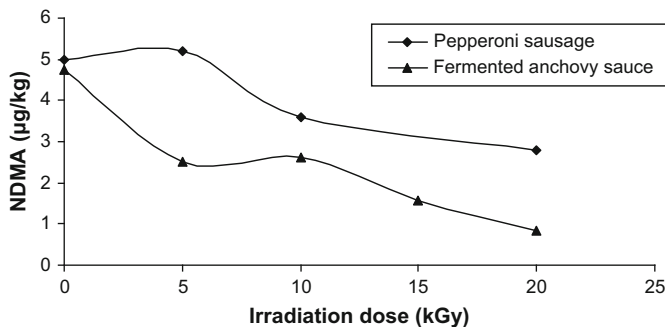


Figure 16.3: Effect of different doses of irradiation on *N*-nitrosodimethylamine (NDMA) content of pepperoni sausage, packaged under air (Byun et al., 2004a), and fermented anchovy sauce at Week 0 (Ahn et al., 2003b).

25% CO₂/75% N₂, and they were irradiated at 0, 5, 10, and 20 kGy and then stored for 4 weeks at 4°C. Irradiation significantly reduced the NDMA in the salami sausage at 0 weeks, whereas the NPYR was not detected in the sausage irradiated over 5 or 10 kGy. Regarding the pepperoni sausage, the VP showed lower nitrosamine content than that of the air packed. After storage for 4 weeks, the irradiated salami showed low NDMA and NPYR contents compared to non-irradiated ones. Results indicated that a high dose of irradiation (>10 kGy) was required to reduce the carcinogenic *N*-nitrosamines in the fermented sausages.

The effect of different doses of irradiation on NPYR content of pepperoni sausage, packaged under air, and fermented anchovy sauce is displayed in Figure 16.4.

Ahn et al. (2004c) investigated the combined effects of irradiation and modified atmospheric packaging (MAP) on residual nitrite and NDMA in sausage during storage. Sausages were packed under air, vacuum, CO₂, N₂, or CO₂/N₂ packaging and irradiated at 5 kGy. Residual nitrite was reduced by irradiation, and the contents were lower under vacuum or MAP than aerobic ones. Furthermore, NDMA was significantly reduced with a 5-kGy dose.

Ahn et al. (2004b) investigated the irradiation effects on cooked pork sausage during storage at 4°C. Sausage with aerobic or vacuum packaging was irradiated at 0, 5, 10, or 20 kGy. “It was found that irradiation treatment reduced the nitrite contents of sausage, and especially under vacuum, nitrite contents decreased with γ -ray dose in a dose-dependent manner. Irradiation at 20 kGy reduced the residual nitrite contents to 31 and 17% under aerobic and vacuum packaging, respectively. After 4 weeks of storage, a decrease in residual nitrite content was reported in all samples, and the irradiation effect was still found. Residual nitrite contents of sausage irradiated at 5 kGy or higher were lower than those of non-irradiated control for both packaging conditions. NDMA contents in sausage with VP were decreased by irradiation at 10 and 20 kGy, whereas no difference was found

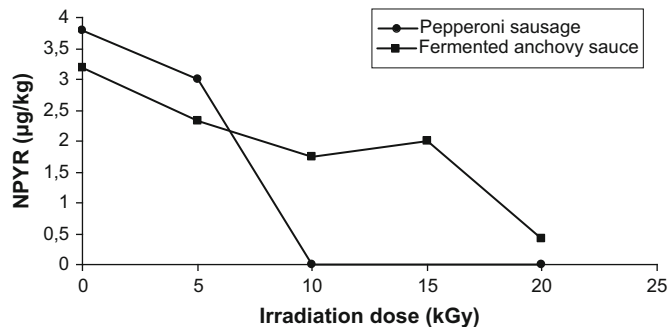


Figure 16.4: Effect of different doses of irradiation on *N*-nitrosopyrrolidine (NPYR) content of pepperoni sausage, packaged under air (Byun et al. 2004a), and fermented anchovy sauce at Week 0 (Ahn et al., 2003b).

in aerobic packaging at 0 weeks. Irradiation reduced NPYR contents in sausage with aerobic packaging, and NPYR was not detected by irradiation at 5 kGy or higher. After 4 weeks of storage, irradiation decreased NPYR contents in sausage with VP, whereas the packaging effect was not found during storage.”

The impact of various doses of irradiation on residual nitrite content of food products, a model system sausage and cooked pork sausage, packaged under air is shown in Figure 16.5.

Table 16.3 summarizes the effect of irradiation on the reduction of *N*-nitrosamines and residual nitrite in various food products.

16.8.2 Reduction of Acrylamide with Irradiation

Acrylamide was found to be carcinogenic in rodents and is classified as a probable human carcinogen by the International Agency for Research on Cancer (Tereke et al., 2003). Acrylamide is formed by Maillard reaction from asparagine and reducing sugars (Becalski et al., 2004; Stadler et al., 2002; Yaylayan and Stadler, 2005; Yaylayan et al., 2003; Zyzak et al., 2003). Due to the presence of acrylamide in many foods and its potential hazards to human health, means to reduce levels or to minimize its formation, such as addition of amino acids and glycine, have been investigated by many researchers (Brathen et al., 2005; Grabda et al., 2004; Kim et al., 2005a).

Fan and Mastovska (2006) reported that as the irradiation dose increased from 0 to 1.5 kGy, acrylamide in water decreased from 1000 ng/ml to approximately 20 ng/ml (98% reduction). Similar as for furan, lower initial acrylamide concentrations in the irradiated solutions resulted in even faster degradation rates. In oil, however, irradiation had very little effect on acrylamide reduction. Even at 10 kGy, only approximately 5% of acrylamide was decomposed. Moreover, to test whether irradiation reduces acrylamide in real foods, potato chips were irradiated. Fan

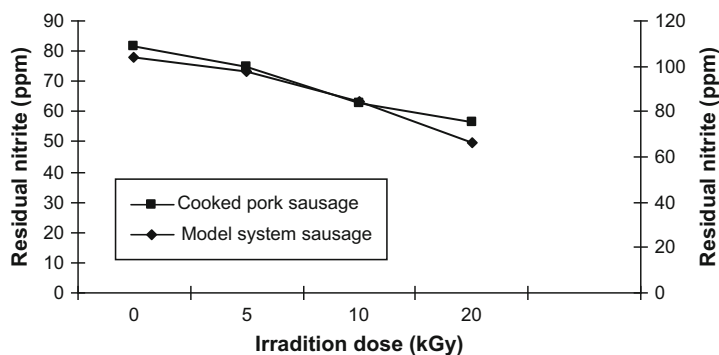


Figure 16.5: Impact of irradiation dose on residual nitrite content of food products a model system sausage (Ahn et al., 2002a) and cooked pork sausage, packaged under air (Ahn et al. 2004b).

TABLE 16.3 Effect of Irradiation on the Reduction of *N*-Nitrosamines and Residual Nitrite in Various Food Products

| Food Type | Gama Irradiation Dose (kGy) | Other Technology | Storage | Irradiation Effect on Residual Nitrite | Irradiation Effect on <i>N</i> Nitrosamines | Reference |
|--|-----------------------------------|--|-----------------|--|--|------------------------|
| Model system sausage | 5, 10, 20, and 30 | Packaged under air or vacuum | 4 weeks at 4°C | The residual nitrite levels were significantly reduced by γ irradiation, and in VP, the reduction was dose dependent. | The NDMA of the sausage irradiated at 10 kGy or higher reduced in aerobic packaging, whereas a dose of 20 kGy was required in VP. The NPYR reduction was found at 20 and 30 kGy irradiation. | Ahn et al., 2002a |
| NDMA and NPYR dissolved in distilled water, dichloro methane, or ethanol | 2.5, 5.0, 7.5, 10, 15, 20, and 25 | — | — | — | NDMA and NPYR in distilled water and dichloromethane were easily broken at 5 kGy or higher. NDMA and NPYR dissolved in ethanol were the most resistant to irradiation and the breakdown was 90% or more at 20 kGy. | Ahn et al., 2002b |
| Cooked pork sausage made with (156 ppm) or without NaNO ₂ | 5 | Packaged under CO ₂ (100%), air, and vacuum | 4°C for 4 weeks | Residual nitrite content in the cooked pork sausage packaged by CO ₂ (100%) was lower than that by aerobic or vacuum. | Irradiation at 5 kGy significantly decreased volatile <i>N</i> nitrosamines in cooked pork sausage. | Jo, Yook, et al., 2003 |
| Sodium nitrite in deionized distilled water | 5, 10, 15, 20, 25, 30, and 40 | — | — | The sodium nitrite was significantly reduced by irradiation in a dose dependent manner. | When nitrite was nitrosated in different pH ranges (2, 3, 4, or 6) after irradiation, the irradiated nitrite could not form the carcinogenic NDMA. | Ahn, et al., 2003a |

(Continued)

Table 16.3 Effect of Irradiation on the Reduction of *N*-Nitrosamines and Residual Nitrite in Various Food Products—cont'd

| Food Type | Gama Irradiation Dose (kGy) | Other Technology | Storage | Irradiation Effect on Residual Nitrite | Irradiation Effect on <i>N</i> Nitrosamines | Reference |
|------------------------------------|-----------------------------|------------------------------|------------------|--|---|--------------------|
| Salted and fermented anchovy sauce | 5, 10, 15, and 20 | — | 15°C for 4 weeks | — | NDMA and NPYR reduction by irradiation was not observed in nonspiked samples at Week 0, whereas a significant reduction was observed after 4 weeks of storage. NDMA and NPYR levels were decreased by irradiation at 5 kGy or higher after storage. After storage, the decomposed nitrosamines by irradiation are not recombined. | Ahn et al., 2003b |
| Pepperoni and salami sausages | 5, 10, and 20 | Packaged under aerobic or VP | 4 weeks at 4°C | — | Both NDMA and NPYR were significantly reduced by irradiation. The VP showed significantly lower <i>N</i> nitrosamine levels than those of the aerobic ones. After storage, the contents of NDMA and NPYR in the irradiated sausages were lower than those of the non irradiated control. Results indicated that a high dose of irradiation (>10 kGy) was needed to reduce the carcinogenic <i>N</i> nitrosamines in the fermented sausage during storage. | Byun et al., 2004a |

| | | | | | | |
|---------------------|---------------|---|----------------|---|--|-----------------------------------|
| Sausage | 5, 10, and 20 | Packaged under vacuum, air, 100% CO ₂ , 100% N ₂ , or 25% CO ₂ /75% N ₂ | 4 weeks at 4°C | Residual nitrite was reduced by irradiation, and the contents were lower under vacuum or MAP than those of aerobic ones. | Irradiation significantly reduced NDMA in the salami sausage at Week 0, whereas NPYR was not detected in the sausage irradiated over 5 or 10 kGy. After storage for 4 weeks, the irradiated salami showed low NDMA and NPYR contents compared to those of non irradiated ones. | Ahn et al., 2004b |
| Cooked pork sausage | 5, 10, or 20 | Packaged under air or vacuum | 4 weeks at 4°C | Irradiation treatment reduced the nitrite contents; especially under vacuum, nitrite contents were decreased by γ ray in a dose dependent manner. Irradiation at 20 kGy reduced the residual nitrite contents to 31 and 17% under aerobic or VP, respectively. | NDMA contents in sausage with VP decreased by irradiation at 10 and 20 kGy, whereas no difference was found in aerobic packaging at Week 0. Irradiation reduced NPYR contents in sausage with aerobic packaging, and the NPYR was not detected by irradiation at 5 kGy or higher. After 4 weeks of storage, irradiation decreased NPYR contents in sausage with VP, where as no packaging effect was observed over storage | Ahn et al., 2004c |

and Mastovska (2006) found that irradiation even at 10 kGy did not significantly reduce acrylamide in the dry chips. When water was added to the chips, irradiation at 10 kGy destroyed acrylamide by only approximately 15%. The previous results show that irradiation is effective in destroying acrylamide only in foods containing mostly water. Moreover, in foods with limited water content, irradiation at low doses that cause no significant changes in flavor and nutrition will have little effect on acrylamide levels.

Gokmen et al. (2007) investigated the effects of various controlled atmosphere conditions and low-dose irradiation on tuber components (sugars and free asparagine) of two cultivars (Agria and Russet Burbank) during 6 months of storage at $9 \pm 1^\circ\text{C}$. It was determined that postharvest irradiation (0.05 and 0.2 kGy) reduced the risk of acrylamide formation to a certain extent during storage under normal atmosphere conditions. Furthermore, it was found that the sum of glucose and fructose concentrations displayed a good correlation with the potential of acrylamide formation for both cultivars.

16.8.3 Relation of Furan and Irradiation in Food Products

Furan is a volatile compound that is considered as “possibly carcinogenic to humans” by the International Agency for Research on Cancer (1995). A survey by the U.S. Food and Drug Administration (2004) reported that furan was present in many canned foods, such as infant foods, soups, and meat products, that underwent retort process. Furan is induced by thermal treatments from simple carbohydrates, ascorbic acid, amino acids, fatty acids, or a combination of these compounds (Becalski and Seaman, 2005; Fan, 2005a,b; Locas and Yaylayan, 2004; Maga, 1979).

Fan (2005a) studied the formation of furan in freshly prepared apple and orange juices as affected by ionizing radiation and thermal treatments. Results showed that furan levels increased linearly as radiation dose increased from 0 to 5 kGy. Irradiation induced more furan in apple juice than in orange juice. During post-irradiation storage at 4°C , furan levels increased in both apple and orange juice. On the other hand, irradiation decomposed deuterated furan (d_4 -furan) spiked in water and fruit juices. The rate of degradation as a function of radiation dose was the highest in water and lowest in orange juice. The results showed that ionizing radiation induces furan formation in fruit juices.

The formation of furan from sugars, ascorbic acid, and organic acids as affected by ionizing radiation was investigated by Fan (2005b). The results revealed that irradiation induced formation of furan from ascorbic acid, fructose, sucrose, or glucose. Little furan was produced from malic acid or citric acid. The pH and concentration of sugars and ascorbic acid solutions had profound influences on furan formation due to irradiation. The rate of irradiation-induced furan formation increased with decreasing pH from 8 to 3. Approximately 1600 times less furan was formed at pH 8 than at pH 3. At the same pHs, the amounts of furan formed from irradiation of ascorbic acid, fructose, and sucrose were always higher than that of glucose. Furthermore,

the levels of sugars commonly found in fruits and fruit juices, upon irradiation, would be high enough to potentially produce parts per billion levels of furan. The concentration of ascorbic acid at which a maximum of furan was produced upon irradiation was approximately 0.5 mg/ml—a level commonly found in some foods.

According to [Fan and Mastovska \(2006\)](#), ready-to-eat (RTE) meat and poultry products, in addition to having meat as the major component, often contain ingredients such as Na ascorbate, Na erythorbate, glucose, honey, corn syrup, and Na nitrite. They investigated the generation of irradiation-induced furan in aqueous solutions of these ingredients and in nine RTE food products (eight meat- and poultry-based and one vegetable burger). Irradiation at doses up to 4.5 kGy induced formation of furan in aqueous solutions of Na ascorbate, Na erythorbate, glucose, honey, and corn syrup. Addition of Na nitrite into these solutions prior to irradiation completely eliminated, or significantly reduced, furan formation. Exposure of RTE food products to 4.5 kGy radiation in the nonfrozen state (5°C) or to 10-kGy radiation in the frozen state (−18°C) did not significantly increase furan levels in most of the samples. Furthermore, the irradiation treatments reduced furan levels in samples (frankfurters) that contained more than 3 ng/g of furan. The results from this research showed that irradiation induces furan formation in solutions of many RTE food ingredients but not in RTE meat and poultry products.

[Fan and Mastovska \(2006\)](#) investigated the possibility of using ionizing radiation to reduce the levels of thermally induced furan in water and selected foods. Aqueous furan solutions and foods (frankfurters, sausages, and infant sweet potatoes) that contained furan were irradiated with various doses of γ -rays. Results showed that irradiation at 1 kGy destroyed almost all furan in water. The rate of irradiation-induced destruction of furan was much lower in frankfurters, sausages, and infant sweet potatoes than the rate in water, although significant reductions in furan levels were observed in all foods. Irradiation at 2.5–3.5 kGy—doses that can inactivate 5 log of most common pathogens—reduced furan levels in the food samples by 25–40%. The results revealed that a low dose of irradiation easily decomposed furan in water but the reduction of furan is less effective on real foods.

[Fan and Sokorai \(2008\)](#) studied the possible formation of furan from fresh-cut fruits and vegetables due to irradiation treatment. Nineteen fresh-cut fruits and vegetables were irradiated by 5-kGy γ -rays at 4°C. The results showed that upon irradiation, almost all tested fruits and vegetables produced nondetectable levels or less than 1 ng/g of furan. Irradiation induced low levels of furan only in grape and pineapple. Dipping apple slices into calcium ascorbate before irradiation did not increase furan formation. Low levels of furan were induced by irradiation only in those fruits that had a high amount of simple sugars and low pH.

16.8.4 The Reduction of Biogenic Amines with Irradiation

Biogenic amines (BAs) are toxic substances that cause illness in humans and animals following ingestion of foods containing them (Shalaby, 1996). The ingestion of BAs can cause headache, hypertension, pyrexia, or heart disease (Min et al., 2007a,b). According to Nout (1994), an intake of more than 40 mg BAs per meal is considered potentially toxic. BAs are produced by microbial decarboxylation of amino acids in food products. The most significant BAs occurring in foods are histamine, putrescine, cadaverine, tyramine, tryptamine, 2-phenylethylamine, spermine, spermidine, and agmatine (Ozogul et al., 2008). BAs are also possible precursors of carcinogens, such as *N*-nitrosamines (Ayala et al., 1994). They are frequently found in high concentrations in food and not reduced by a high-temperature treatment (Shalaby, 1996; Silla Santos, 1996). The initial microbial population is an important factor influencing the formation of BAs (Bover-Cid et al., 2000). Thus, irradiation is expected to reduce BAs by decreasing the levels of microorganisms (Kim et al., 2003).

The effects of irradiation on BAs of Korean fermented soybean paste were investigated by Kim et al. (2003). Soybean paste was prepared and irradiated with doses of 5, 10, and 15 kGy and then fermented at 25°C for 12 weeks. BAs detected were putrescine, cadaverine, β -phenylethylamine, spermidine, spermine, tryptamine, histamine, tyramine, and agmatine. Among the BAs detected, agmatine was the predominant one. No significant difference was observed in BA content between control and irradiated samples immediately after γ -irradiation. However, four BAs—putrescine, tryptamine, spermidine, and histamine—showed significant reduction by irradiation during fermentation.

According to Mendes et al. (2005), the positive effect of irradiation (1 and 3 kGy) in decreasing BA contents in fresh Atlantic horse mackerel (*Trachurus trachurus*) stored at $0 \pm 1^\circ\text{C}$ was especially clear in the case of histamine. Histamine in the irradiated lots was undetectable when the fish was spoiled after 23 days, whereas in the control lot the concentration did not exceed the maximum allowed in fresh fish (100 mg/kg).

Kim et al. (2005b) studied the irradiation effects on BAs of low-salt fermented soybean paste during fermentation at 25°C for 12 weeks. Low-salt fermented soybean paste was prepared with 6 and 8% salt, and a 12% salted paste was used as a control. The prepared fermented soybean pastes were irradiated with doses of 5, 10, and 15 kGy. Non-irradiated samples (6 and 8% salt) showed optimum pH to produce BAs during fermentation. The BAs detected were putrescine, cadaverine, β -phenylethylamine, spermidine, spermine, tryptamine, histamine, tyramine, and agmatine. Most BAs, except β -phenylethylamine and tyramine, were significantly reduced by irradiation treatment during fermentation. These results indicated that lower salt conditions (6 and 8% salt) could produce more BAs than the control (12% salt). However, the reduction of BA levels in low-salt fermented soybean paste to similar or lower levels than those of the control (12% salt) can be achieved with irradiation.

The impact of irradiation (5 kGy) on the putrescine content of products during the fermentation period (fermentation at 25°C) of low-salt (6%) fermented soybean paste is displayed in Figure 16.6.

Kim et al. (2005a) investigated the combined effects of γ -irradiation and packaging on BA formation in pepperoni sausage during storage. Pepperoni (fermented sausage) was made and packaged with air, vacuum, and CO_2/N_2 (25%/75%) gas and then γ -irradiated at 0, 5, 10, and 20 kGy. A total of six different BAs—putrescine, cadaverine, β -phenylethylamine, spermidine, spermine, and tyramine—were found in the pepperoni sausage. Detected BAs were statistically low under the irradiation or packaging conditions, except for cadaverine and β -phenylethylamine. Gamma irradiation was effective in reducing putrescine, spermidine, spermine, and tyramine. Irradiation effects were not observed with regard to the level of β -phenylethylamine, whereas the CO_2/N_2 packaging caused an increase in the level of β -phenylethylamine. Most BAs detected were reduced by γ -irradiation of the pepperoni sausage during storage. Modified atmospheric packaging, such as CO_2/N_2 packaging, was not effective in reducing the BA levels of the pepperoni after irradiation.

Min et al. (2007a) studied the effect of irradiation in controlling the formation of BAs in ground beef and pork. *Bacillus cereus*, *Enterobacter cloacae*, and *Alcaligenes faecalis* were inoculated into the ground beef and pork with approximately 10^7 CFU/g. Gamma irradiation was used, with absorbed doses of 0, 0.5, 1, and 2 kGy. The levels of putrescine, tyramine, spermine, and total amount of BAs were significantly reduced by irradiation of ground beef and pork inoculated with different microorganisms tested. Moreover, the authors concluded that irradiation was a more effective method than organic acid treatment for controlling the production of BAs in ground beef and pork.

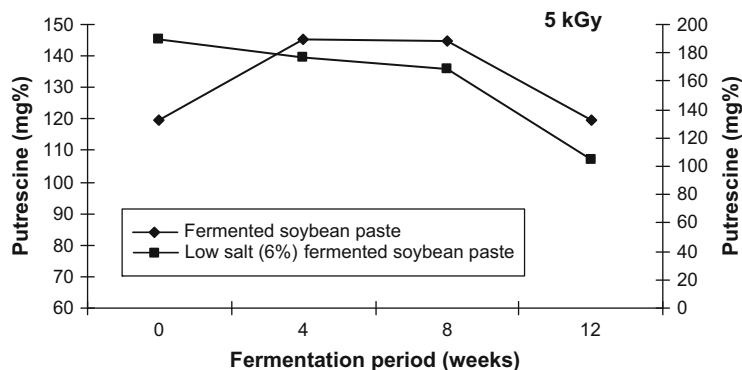


Figure 16.6: Effect of irradiation (5 kGy) on the putrescine content of products during the fermentation period (fermentation at 25°C) of low-salt (6%) fermented soybean paste (Kim et al., 2005b) and fermented soybean paste (Kim et al., 2003).

The effects of irradiation on nine BAs (putrescine, cadaverine, β -phenylethylamine, spermidine, spermine, tryptamine, histamine, tyramine, and agmatine) were investigated by Kim et al. (2004b). The BAs were dissolved in distilled water with a concentration of 10 mg% and γ -irradiated at 2.5, 5, 10, 20, or 25 kGy. The BA reduction was dose dependent. Putrescine and spermine were completely broken down by irradiation at 5 kGy, and the complete breakdown was observed in spermidine with 10 kGy. Complete breakdown was observed for β -phenylethylamine and histamine with 15 kGy irradiation. Cadaverine, tryptamine, and agmatine showed 95–98% of breakdown by irradiation at 20 kGy.

Min et al. (2007b) investigated the effect of irradiation on the production of BAs of raw chicken breast and thigh meat. *Bacillus cereus*, *E. cloacae*, and *A. faecalis* were selected and inoculated into raw ground chicken breast and thigh meat at approximately 10⁷ CFU/g. The samples were irradiated at 0, 0.5, 1, and 2 kGy. Viable cell counts and BA contents were determined. Irradiation was effective in reducing the inoculated bacteria: 0.5 kGy achieved approximately a 2-log reduction, and no viable cells were detected at a dose of 2 kGy. Irradiation of raw chicken breast and thigh reduced the BA content, but the rate of BA reduction differed by inoculated organism.

The impact of irradiation on the BA content in various food products is presented in Table 16.4.

16.9 Conclusions

The applications and potential uses of irradiation (γ -, e-beam, and microwave) continue to expand. Recent applications include the following:

- Production of fermented foods
- Drying food products
- Reduction of food allergens
- Color improvement of green tea extracts
- Reduction of antinutrients (phytic acid, gossypol, and protease inhibitors)
- Antioxidant activity increase
- Reduction of carcinogens (volatile *N*-nitrosamine and nitrite content, acrylamide, and biogenic amines)

In the case of furans, the situation is different. Furans can be formed when certain foods (i.e., juices of pH \approx 3) are subjected to irradiation. However, furans can be decomposed by irradiation as well. Of course, the latter occurs more effectively in model compounds and in foods of neutral pH. In general, there is great potential for additional irradiation applications both for

TABLE 16.4 Effect of Irradiation on the Biogenic Amine Content of Various Food Products

| Food Type | Gamma Irradiation Dose (kGy) | Other Technology | Storage | Irradiation Effect | Observations | Reference |
|---|------------------------------|---|--------------------------------|--|---|-------------------|
| Korean fermented soybean paste | 5, 10, and 15 | — | Fermented at 25°C for 12 weeks | Biogenic amines (BAs) detected were putrescine, cadaverine, β phenylethylamine, spermidine, spermine, tryptamine, histamine, tyramine, and agmatine. However, only putrescine, tryptamine, spermidine, and histamine showed significant reduction by irradiation during fermentation. | No significant difference was observed in BA content between control and irradiated samples after γ irradiation. | Kim et al., 2003 |
| Pepperoni (fermented sausage) | 0, 5, 10, and 20 | Packaging under air, vacuum, and MAP (25% CO ₂ /75% N ₂) | 4°C for 4 weeks | Gamma irradiation was effective in reducing putrescine, spermidine, spermine, and tyramine. Irradiation effects were not observed for β phenylethylamine. | The CO ₂ /N ₂ packaging caused an increase in the level of β phenylethylamine. | Kim et al., 2005a |
| BAs dissolved in distilled water with a concentration of 10 mg% | 2.5, 5, 10, 20, or 25 | — | — | Putrescine and spermine were completely broken down by irradiation at 5 kGy. Complete breakdown was observed in spermidine with 10 kGy and in β phenylethylamine and histamine with 15 kGy irradiation. Cadaverine, tryptamine, tyramine, and agmatine showed 95–98% breakdown by irradiation at 20 kGy. | Putrescine, spermidine, and spermine had higher degradation rates than the other BAs. | Kim et al., 2004b |

(Continued)

Table 16.4 Effect of Irradiation on the Biogenic Amine Content of Various Food Products—cont'd

| Food Type | Gamma Irradiation Dose (kGy) | Other Technology | Storage | Irradiation Effect | Observations | Reference |
|--|------------------------------|----------------------|--------------------------------|---|--|---------------------|
| Fresh Atlantic horse mackerel (<i>Trachurus trachurus</i>) | 1 and 3 | — | 0 ± 1°C for 23 days | During ice storage, the levels of histamine, cadaverine, putrescine, tyramine, agmatine, and spermidine increased, in general, as deterioration progressed, but they remained very low until the eighth day. After that period, the production rate of BAs increased considerably, yet histamine always remained low. | Irradiation treatment was more effective in the case of histamine. | Mendes et al., 2005 |
| Beef and pork | 0.5, 1, and 2 | — | 4°C for 20 h | The BAs tested were β phenylethylamine, putrescine, cadaverine, histamine, tyramine, spermidine, spermine, and serotonin. The levels of putrescine, tyramine, spermine, and total amount of BAs were significantly reduced by irradiation. The reduction of tyramine was the greatest. | Irradiation treatment had an impact on the production of BAs, even at the initial stage of storage. | Min et al., 2007a |
| Low salt fermented soybean paste | — | 12% salted (control) | Fermented at 25°C for 12 weeks | — | Lower salt conditions produced more BAs than higher ones. | Kim et al., 2005b |
| Low salt fermented soybean paste | 5, 10, and 15 | 6 and 8% salt | Fermented at 25°C for 12 weeks | The BAs detected were putrescine, cadaverine, β phenylethylamine, spermidine, spermine, tryptamine, histamine, tyramine, and agmatine. Most BAs, except β phenylethylamine and tyramine, were significantly reduced by irradiation treatment during fermentation. | However, γ irradiation of low salt fermented soybean paste could reduce the BA contents during fermentation. | |

reducing the concentration of carcinogenic or hazardous substances and for increasing and/or improving certain food processes beneficial for human activities.

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Consumer Behavior toward Irradiated Food

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17.1 Introduction

17.1.1 Definitions

Food irradiation is defined by the International Atomic Energy Agency as a process involving the exposure of food, either prepackaged or in bulk, to γ -rays, X-rays, or electrons in a special room and for a specific duration. It is a method of food preservation essentially comparable to processing by heating (e.g., pasteurization or canning) and freezing (Henson, 1995).

Food irradiation is the process of treating food with approved levels of energy to eliminate harmful bacteria such as *Escherichia coli* in meat and poultry or to keep vegetables fresher longer (Schmidt, 2004). Food irradiation is the processing of food with a specific type of energy—ionizing radiation. Irradiated food is a processed food; irradiation is carried out to change the food in order to achieve a desired benefit (which is often safer or longer lasting food) (Roberts, 2004).

Food irradiation is processing technology aimed at the improvement of food safety, which has gained the interest of researchers in the fields of food science and consumer research worldwide during the past few decades (Behrens et al., 2009).

17.1.2 Process of Food Irradiation

Irradiation is carried out in specially contained areas where the food is exposed to a defined dose of radiation in a continuous or batch process. The level of exposure is designed to take into account interdependent parameters such as the type of operation (batch or continuous), the optimum energy requirement to successfully safeguard the food, and the source of irradiation (γ -rays, X-rays, or electron beam). For example, electron beam irradiation in a continuous process is sufficient to treat most prepackaged food items, whereas treatment of large bulk

quantities of food would require a batch system either with X-rays or γ -rays from a radioactive source (Food Safety Authority of Ireland [FSAI], 2005).

17.1.3 Beneficial Effects

The major benefit of food irradiation is that, at the permitted doses, it reduces virtually all common foodborne pathogens, such as *Salmonella* (various species), *Campylobacter jejuni*, *E. coli* O157:H7, *Listeria monocytogenes*, and *Staphylococcus aureus* associated with meat, poultry, and fresh produce. Because pathogens in raw poultry or meat can be substantially reduced by low-dose irradiation, the effects of cross-contamination in foods are lessened. Irradiation also ensures that the food is safe even if it is not fully cooked. Some microbiological contaminants are resistant to irradiation, including viruses, bacterial spores, some molds and yeasts, and prions (the agents thought to be responsible for bovine spongiform encephalopathy or “mad cow” disease) (DeRuiter and Dwyer, 2002).

17.1.4 Advantages of Irradiation

All food processes have advantages and disadvantages. Food irradiation has the following advantages: (1) It is a cold process (food more natural); (2) it treats solid, raw foods, hence the concept of cold pasteurization; (3) it has broad-spectrum effectiveness for dealing with foodborne pathogens (not viruses or prions) and insects; (4) it is penetrating (especially γ - and X-rays); (5) treatment can be performed on food in its final packaging; and (6) there are no chemical residues (Roberts, 2004).

A unique advantage of the process is its strong penetrative power. Materials can be treated in their final packaging, avoiding the possibility of recontamination. The method is not, however, a substitute for a good manufacturing process. The irradiation process causes only a slight increase in temperature and consequently raw food products, such as poultry meat, are still raw after treatment (Henson, 1995).

Food irradiation is a useful process that can help protect the public from foodborne illnesses (Hoefler et al., 2006). Food irradiation has been shown to be an effective tool to eliminate certain foodborne pathogens from food (Gunes and Tekin, 2006). Research has shown that food irradiation can decrease the incidence of foodborne illness and disease. Proponents of irradiation claim that it improves food safety by reducing harmful bacteria (Nayga et al., 2004).

Irradiation may also reduce chemical contaminants because it eliminates the need for chemical treatments such as with ethylene oxide (a chemical used to fumigate spices and herbs) or other fumigants to protect rice and grain from insect infestation. It extends shelf life by retarding the ripening or spoilage of fruits and vegetables, and it is an approved phytosanitary treatment for some tropical and semitropical fruits and vegetables. It can be used on ripe fruit and fruits that do not tolerate heat treatment. Moreover, irradiation neither causes hard spots

nor increases susceptibility to mold. It can also prevent the spread of harmful insects (e.g., the Mediterranean fruit fly). Finally, irradiation cuts wastage and extends shelf life and therefore may decrease some costs of wastage that offset the added costs of irradiation (DeRuiter and Dwyer, 2002; U.S. General Accounting Office, 2000).

17.1.5 Disadvantages of Irradiation

Negative public perception has discouraged widespread use by the food industry (Roberts, 2004). Irradiation cannot improve poor-quality food products because it does not reverse the physiological and chemical processes involved in decay (Henson, 1995).

Irradiation can often have an unpleasant effect on flavor, odor, and texture of food. For example, pork can turn red, beef can smell like a wet dog, fruit and vegetables can become mushy, and eggs can lose their color and become runny (Huang et al., 1997; Wong et al., 1996).

Irradiation disrupts the chemical composition of everything in food—not just harmful bacteria, which the food industry often asserts. Scores of new chemicals called “radiolytic products” are formed by irradiation; these chemicals do not naturally occur in food and there has never been an in-depth study of their safety. One such chemical, 2-DCB, was found to promote the cancer-development process in rats, cause genetic damage in rats, and cause genetic and cellular damage in human and rat cells (Delincée and Pool-Zobel, 1998; Delincée et al., 1999, 2002).

17.1.6 Physical Effects of Irradiation on Food

According to the FSAI (2005), irradiation, even at low doses, is not suitable for all food because it can produce undesirable odors and flavors in certain foods and even tissue damage in some fruit. During exposure to irradiation, food and water absorb energy, most of which is used in the generation of molecules that are unstable and reactive and are collectively referred to as radiolytic products. However, radiolytic products are not unique to irradiated food, with identical products found in food that has been cooked, frozen, or pasteurized and even in unprocessed food. In addition, irradiation disrupts some of the bonds in DNA of food as well as that of contaminating microorganisms or pests. Although this disruption is inconsequential to the food, it reduces the chances of survival and proliferation of the contaminating pests or microorganisms.

17.1.7 Effects of Irradiation on the Nutritional Content of Food

The effect of irradiation on the nutritional quality of food is similar to, and in some cases less than, that for some other preservation methods. Only minor changes in some vitamins (B₁, C, A, and E) occur, whereas carbohydrates, fats, and proteins remain largely unaffected by low or medium doses. However, nutritional changes in food due to irradiation are dependent on factors such as temperature, radiation dose, packaging environment, and storage. For example,

irradiation of frozen food or food in an oxygen-free environment actually minimizes any nutrient loss (FSAI, 2005).

17.1.8 Labeling of Irradiated Foods

Irradiated foods are required to be labeled with the radura symbol and the phrase “treated by irradiation.” Given the negative connotations associated with the words “radiation: and “irradiation,” the labeling requirement is viewed as an obstacle to consumer acceptance. Many in the food industry believe that an alternative wording, such as the phrase “electronically pasteurized,” would be helpful (Fox, 2002).

In the European Union (EU), any irradiated food or food containing an irradiated ingredient must carry the word “irradiated” in a prominent position either as part of the main label or next to the ingredient that has been irradiated. It may also (optionally) show the international icon for irradiated food called the radura symbol, which is shown in Figure 17.1 (FSAI, 2005).



Figure 17.1: Radura symbol indicating irradiated food.

17.2 Consumer Concerns

The concerns of those opposed to food irradiation regard safety, radioactivity, and chemical breakdown products; the argument that “good food should not need irradiating”; it benefits big business rather than consumers; and it allows a lower standard of food hygiene. Food irradiation appears to be gaining consumer acceptance in the United States, whereas it has been slow to gain support within many areas of Europe, including the United Kingdom (Olsen, 1999).

Government and industry approval of irradiation does not result in automatic acceptance of irradiation by consumers. In general, consumers suspect new technologies applied to food. In the past, consumer groups have threatened to boycott and pursue legal action against food companies for marketing irradiated food products due to questions concerning the long-term safety of eating these products (Anantheswaran, 2003).

U.S. consumers are less concerned about irradiation than about other food processing technologies. When asked, 29% considered irradiation a potentially serious health hazard compared to 77% who identified bacteria as a serious hazard and 66% who classified pesticides as serious. The percentage classifying irradiation as serious is comparable to the percentage of those who view nitrites as serious. When consumers are given the opportunity to express food

safety concerns, microbiological hazards and spoilage are mentioned most frequently (Abt Associates, 1996). Less than 1% of consumers volunteer food irradiation. It is noteworthy that irradiation addresses the food safety area when concern is greatest (Bruhn, 1998).

17.2.1 Safety

Several organizations and committees have reviewed the safety of irradiated food. Some of the most important reports are the following:

1. 1981 report of the United Nations World Health Organization (WHO), International Atomic Energy Agency (IAEA), and Food and Agriculture Organization (FAO) Joint Expert Committee on the Wholesomeness of Irradiated Foods.
2. 1986, 1992, 1998, and 2003 reports from the European Scientific Committee on Food (SCF).
3. 1986 report on the safety and wholesomeness of irradiated foods by the UK Advisory Committee on Irradiated and Novel Foods.

There is general scientific consensus that irradiated food is safe to consume and irradiation of food up to an overall average dose of 10 kGy does not introduce any special nutritional and microbiological problems. However, the safety of building and maintaining irradiation facilities is sometimes questioned. Irradiation facilities do not discharge radioactive waste, and operations at irradiation facilities do not contaminate the environment or people in their vicinity.

Currently, approximately 15 commercial irradiation facilities are operating in the United Kingdom, irradiating a range of nonfood products including cosmetics, packaging, medical devices, and medical products. Two-thirds of these are γ -irradiation facilities and one-third are electron beam facilities.

17.2.2 Radioactivity

Radioactivity is present naturally in the environment, including the food we consume. Irradiation does not add to the natural radioactivity in food. However, many consumers associate food irradiation with radioactivity and, because of their fear of radioactivity, are suspicious of the irradiation process. Many people mistakenly fear, for instance, that the process may induce radioactivity in the food product and that irradiation will result in the formation of toxic by-products in food (International Consultative Group on Food Irradiation [ICGFI], 1999b).

Consumers often associate the term irradiation with radioactivity and have expressed concern about the safety of irradiated foods (Osterholm and Norgan, 2004). Taste is also cited as a deterrent to purchasing irradiated meat. For example, changes in the odor and flavor have been cited when comparing irradiated and non-irradiated chicken (Mahrouf et al., 2003). A similar evaluation of ground beef found that consumers had no difference in preference between irradiated and non-irradiated cooked ground beef (Hamilton-Zienkewicz and Penner, 2004).

17.2.3 Chemical Breakdown Products

Irradiation induces some chemical changes in food, as do other food processes. The majority of chemical substances formed are not unique to irradiation but either occur naturally in some foods or occur as a result of conventional methods of food processing such as cooking. Similar to heat processing of food, irradiation may be conducted at various intensities to optimize the process (e.g., the irradiation dose should be sufficient to reduce the number of microorganisms without causing chemical changes that might adversely affect the food's physical and sensory properties) (Food Standards Australia New Zealand, 2002).

One class of chemical substances characteristically produced in food by irradiation is 2-alkylcyclobutanones (ACBs). These ACBs are produced from fatty material and have not been identified in non-irradiated foods. Their identification is the basis of a detection test for fat-containing irradiated foods (Crone et al., 1992, 1993).

The SCF assessed a report of the toxicological properties of ACBs in July 2002. The SCF noted that adverse effects of ACBs refer almost entirely to *in vitro* studies, and it is not appropriate to make a risk assessment for human health on the basis of these results. The SCF accepts that food irradiation is a safe process, and the safety of irradiated fat-containing foods is demonstrated by the results of the large number of feeding studies that the SCF considered in its 1986 report. These feeding studies also formed the basis for the wholesomeness assessments published by WHO/FAO/IAEA in 1981, in which it was concluded that irradiated food is safe to eat (Revised Codex General Standard for Irradiated Foods, ALINORM 03/12A, Para 78, Appendix V).

17.3 Factors Affecting Consumer Behavior toward Irradiated Food

Nowadays, the consumer is often asked to make decisions about purchasing various products (genetically modified, irradiated, organic, etc.) without having the required background for such decisions. On the other hand, heavy advertising creates a rather fictitious and unrealistic picture of the food items in question.

Conjoint analytic surveys were administered to 225 potential consumers of foods processed by innovative and emerging food technologies in order to assess the factors contributing to their interest in using such products. Respondents rated their interest in 49 different food product concepts that varied in food type, processing or production technology, costs, benefits, risks, endorsing agencies, and product information. Results showed that the relative importance of factors did not vary greatly among the consumer groups (Cardello et al., 2007).

Food irradiation is being promoted as a simple process that can be used to effectively and significantly reduce foodborne illnesses throughout the world. However, a thorough search of the literature reveals a paucity of adequate research conducted to specifically address health concerns that may directly result from the consumption of irradiated food. Consumers are

entitled to their right of choice in the consumption of irradiated versus nonirradiated food. Different countries should further evaluate their local and global risks and benefits prior to developing and recommending national and international food irradiation policies (Ashley et al., 2004).

Producing, processing, or manufacturing foods that meet consumers' and society's expectations is a very complex undertaking. On the one hand, we live in a world in which the socioeconomic situation and infrastructure, the environment, cultural values, and regulatory requirements are different; on the other hand, the movement of people, trade of goods and services, as well as communication have made food safety a global concern. Therefore, ensuring food safety in today's complex world is a daunting task and is possible only with a concerted effort of all sectors, including government, consumer organizations, and industry (Motarjemi and Mortimore, 2005).

Determinants of consumer adoption of innovations were studied from different angles and from the perspectives of various disciplines. The framework distinguishes "distal" and "proximal" determinants of acceptance. Distal factors (characteristics of the innovation, the consumer, and the social system) influence consumers' intention to accept an innovation through proximal factors (perceived cost/benefit considerations, perceptions of risk and uncertainty, social norms, and perceived behavioral control) (Ronteltap et al., 2007).

17.3.1 Awareness/Education

Consumer awareness and acceptance of irradiated foods were investigated in Turkey; consumer awareness was very low (29%) compared to that in the United States (72%) (Gunes and Tekin, 2006). Given the statement, "Irradiation can eliminate these pathogens from raw red meat and poultry products," would you buy irradiated foods? The majority of consumers (62%) indicated they would buy them, whereas 13% expressed that they would not buy irradiated foods. However, 25% of consumers were hesitant about buying irradiated foods. Another surprising finding was that consumer acceptance increased to 66% if highly trusted companies produced irradiated foods.

The awareness and acceptance of the irradiation process by Turkish consumers are relatively low (29%) compared to those of developed countries such as the United States. This is associated with a lack of knowledge about the process. Listening to benefit statements substantially increased the acceptance of irradiated foods. The latter would be even greater if their price was the same as that of non-irradiated foods and trusted companies produced irradiated foods (Gunes and Tekin, 2006).

According to Flores and Hough (2008), in a consumer search carried out in Argentina,

when respondents were asked whether irradiated foods could be hazardous or had lesser nutrient or sensory properties, the majority of answers fell in the category of "I do not know/I

am not sure,” thereby expressing doubts about this methodology. Only 14% said they would definitely buy irradiated foods. Moreover, insect control and/or shelf life extension were not considered important irradiation benefits; therefore, promoting irradiation based on these benefits is anticipated to have very minor impact. Only 15% of respondents had read or heard about food irradiation in Argentina. The problem is there have been no campaigns explaining the process, and its application is limited to foods containing less than 10% of irradiated components, which are not labeled as “irradiated.”

Studies involving qualitative and quantitative research to assess beliefs, knowledge, and attitude about irradiated foods should be carried out with Brazilian consumers to understand the local market behavior and to develop appropriate strategies for the promotion and commercialization of irradiated foods in Brazil. The minimally processed fruits submitted to the irradiation process with doses of 1 and 2.5 kGy obtained good acceptance by the consumers without causing changes in the sweetness of watermelon and in the sourness of pineapple. Although no significant differences ($P > 0.05$) were observed between the purchase intentions of irradiated and non-irradiated watermelon, the results suggested the consumers still expressed a certain reluctance to purchase irradiated food. This seemed to be due to the lack of information about the irradiation process and its safety (Martins et al., 2008).

Consumer knowledge and concern about hazards associated with food is high. Communicating about risk and hazard is an interactive exchange of information about risk and non-risk factors pertaining to risk management. Communication is a two-way process that involves listening, identifying, and responding to consumer questions. Consumer research provides information essential for designing and evaluating communication efforts. An effective communication strategy moves people toward a more accurate perception of the likelihood of ill effects and empowers people to make informed decisions relative to potential benefits (Bruhn, 2005).

Qualitative research was carried out with 47 people divided into six focus groups located in three markets (Dallas, New York City, and Los Angeles) in January and February 1998. The results of this research revealed consumers' acceptance of food knowledge about the process. Therefore, the more informed the consumers were about food irradiation, the more favorably inclined they were toward the process. It was surprising that this finding was applicable even to consumers skeptical of food irradiation. The consumers whose educational level was high were able to describe the process and knew that herbs and medical supplies were currently irradiated. Most consumers were willing to pay a slightly higher price for irradiated foods, at least for the trial period. Consumers were more prone to buy irradiated meat than irradiated vegetables because the latter are supposed to be consumed fresh (see www.ific.org/research/irradiationres.cfm).

For years, most consumers have expressed less concern about food irradiation than other food processing technologies. Attitude studies have demonstrated that when given science-based information; 60–90% of consumers prefer the advantages that irradiation processing provides.

When information is accompanied by samples, acceptance may increase to 99%. Information on irradiation should include product benefits, safety, and wholesomeness; address environmental safety issues; and include endorsements by recognized health authorities. It has been shown that after exposure to educational and marketing programs, consumers will buy high-quality, safety-enhanced irradiated food (Bruhn, 1998).

Consumers' acceptance of irradiated foods is greatly affected by factors such as their education level, gender, attitude toward and familiarity with food irradiation, ethnicity, and household status, although the impact of these was mixed (Nayga et al., 2004).

According to Weaver and Marcotte (1988), "the role of food and health professionals (food scientists, dietitians, home economists, nurses, and nutritionists) could be a crucial component to the acceptance of irradiated food products. While the benefits, uses, and safety of food irradiation have been scientifically documented, public awareness of such information has been limited."

Consumer acceptance/rejection of innovative food technologies is the result of a complex decision-making process that involves an assessment of the perceived risks and benefits associated with the new technology and existing alternatives. The acceptance of a new food technology is not simply related to the characteristics of the process but also to the needs, beliefs, and attitudes of individual food consumers and the nature of the economic, political, and social environment in which food choices take place (Henson, 1995).

The importance of consumers' education was demonstrated in South Africa, where an extensive marketing and educational program was conducted before the introduction of irradiated foods in the market. With regard to irradiated meat products, a marketing survey found that initially 15% of people surveyed indicated they were likely to purchase the irradiated food. After having received visual information and tasting the food, the percentage of people who would purchase the irradiated product increased to 76%, whereas only 5% stated they would probably not buy it (see www.ers.usda.gov/publications).

17.3.2 Health Implications

Consumers in the United States are resistant to food irradiation despite scientific evidence and professional attestation to its benefits and safety. Young, senior, and female respondents are more likely to oppose irradiated beef because of the perceptions that irradiation is harmful and consumption of irradiated beef may lead to health complications and that irradiation poses serious environmental hazards.

Protection of workers and consumers from skin toxicities (irritation and allergy) associated with exposure to products, and the ingredients they contain, requires toxicological skin testing prior to manufacture, transport, or marketing. Testing for skin corrosion or irritation has traditionally been conducted in animals, particularly in rabbits via the long-established Draize test method.

However, this procedure, among others, was subject to criticism both for its limited predictive capacity for human toxicity and for its use of animals (Robinson et al., 2002).

Several factors influence peoples' decisions about food irradiation, a technology perceived as risky. Responses to questions about three aspects of acceptability of food irradiation provide the dependent variables. Risk message characteristics, respondent background characteristics, knowledge, and attitudes comprise the independent variables. Multiple regression is used to assess relative effects. The only message manipulation that had a significant impact was information about irradiated food users (e.g., astronauts) and prestigious national and international organizations that endorse food irradiation (Bord and O'Connor, 1990).

Angulo and Gil (2007) noted that,

food scares increased consumer food safety concern, particularly for beef. Traceability and food quality labels were applied to communicate to consumers the safety characteristics of the specially labeled beef in hopes of recovering confidence and consumption. As a consequence, production costs increased considerably and thus consumer prices as well. Results indicated that income, level of beef consumption, the average price consumers pay for beef and the perception of beef safety were the main determinants of Spanish consumers' willingness to pay for certified beef. Perception of food safety risk is one such psychological interpretation.

17.3.3 Cost of Irradiated versus Non-irradiated Food

The price of a food item is a decisive factor for the consumer who has to make a choice based both on his or her budget and on his or her awareness and educational level (Table 17.1). He et al. (2005) stated that,

consumers are unwilling to pay a higher price for irradiated beef. The reasons considered are "the current price is all I am willing to pay," "irradiation will not actually make the beef safer than it already is," "the government should pay for the cost of irradiation," and "other reasons given by the respondents," which is used to normalize the set of equations. Gender is the only variable found to have a significant impact on the model, with females being more likely to think the government should pay for the cost of beef irradiation.

Respondents were asked whether they would buy irradiated food at the current market price for non-irradiated food. For irradiated beef, approximately 51% of the sample responded positively, whereas more than 31% said "no"; the rest were unsure whether they would buy it or not. In contrast, Frenzen et al. (2000) found that for irradiated ground beef, 52.8% were not willing to buy, whereas 24.5% said "yes." Similar behavior was reported for irradiated chicken: 51.9% were not willing to buy, whereas 23.7% agreed to pay the same price for non-irradiated food. Those who would buy irradiated beef were then asked whether they were willing to pay a higher price for it. Approximately 60% of them indicated that they were willing, 32% were unwilling, and approximately 8% were not sure about their attitude (He et al., 2005). Percentages of respondents willing to pay a higher price for irradiated

TABLE 17.1 Consumer Opinion about Irradiated Meat

| Product | Country | Consumers Opinion (Questionnaire) | Scale (%) | Reference |
|---------------------------|---------------|---|-----------|------------------------|
| Beef | United States | Telephone survey with dichotomous choice questions (740 respondents) | | He et al., 2005 |
| | | Consumption of irradiated beef may lead to health complications. | 23 | |
| | | Irradiation poses serious environmental hazards. | 3 | |
| | | Food irradiation poses occupational hazards. | 4 | |
| | | Food safety regulations either inadequate or not effectively enforced | 66 | |
| | | Unwilling to pay a higher price for irradiated beef | 40 | |
| | | Irradiation will not actually make the beef safer than it already is. | 10 | |
| | | The government should pay for the cost of irradiation. | 19 | |
| Other reasons. | 13 | | | |
| Ground beef and chicken | United States | Telephone survey, USDA Inspection Service (10,780 adults) | | Frenzen et al., 2000 |
| | | Consumer awareness | 72 | |
| | | Insufficient information about risks and/or benefits | 35 | |
| | | Concerned about safety of eating irradiated food | 22.7 | |
| | | Irradiation doesn't make food safer | 4.2 | |
| | | Doesn't eat meat or poultry (vegetarians) | 4 | |
| | | Concerned about environment impact of irradiation | 3.9 | |
| | | Doesn't need irradiation to make food safe | 3.5 | |
| | | Doesn't like trying new food/products | 3.3 | |
| | | Price of irradiated food | 2.5 | |
| | | Taste/appearance of irradiated food | 1.4 | |
| | | Other, unspecified reasons | 10.2 | |
| Doesn't know/not sure | 7.9 | | | |
| Refused to answer | 1.4 | | | |
| Meat and poultry products | Turkey | Consumer awareness on food irradiation | 29 | Gunes and Tekin, 2006 |
| | | Uncertain about the safety of irradiated foods | 80 | |
| | | Not safe, radioactive, or can have harmful Compounds | 9 | |
| | Argentina | Consumer awareness on food irradiation | 15 | Flores and Hough, 2008 |
| | | Feel insecure eating irradiated foods | 63 | |
| | | Doubtful about food safety regulations (high percentage of irradiated components) | 92 | |

ground beef and irradiated chicken were 22.7 and 24.5%, respectively; 7 and 7.2%, respectively, would not pay more; and 17.5 and 16.5%, respectively, were uncertain about paying more.

Gunes and Tekin (2006) reported that the purchase intent for irradiated food was the greatest (44%) provided the price was the same as non-irradiated foods. Twenty-three percent of respondents indicated that they would pay a 5% premium price for irradiated foods. The percentage of consumers who would pay a premium for irradiated foods was lower in our study compared to the percentages reported in other studies conducted with consumers in the United States (Bruhn, 1998; Fox and Olson, 1998). This may be due to the fact that the purchasing power of consumers in Turkey is still considerably lower than that in the United States.

Earlier studies on irradiation cost conducted by Kaye and Turman (1999) and Bogart and Tolstun (1999) estimated that the cost of irradiating meat or poultry varied from 0.5 to 1.5 cents per pound for meat and from 0.8 to 2.0 cents per pound for poultry depending on the annual volume of the plant (100 million pounds for a plant equipped with an e-beam source and 220 pounds for a plant equipped with a γ - or X-ray source, respectively). If transportation was involved, an additional minimal cost of 0.2 cents per pound had to be added, based on calculations by the U.S. Department of Agriculture (USDA, 1999).

Surveys carried out between 1995 and 2000 showed that the final price of the irradiated food remained a key factor for consumer purchase. According to a survey conducted by FoodNet, 49.5% of consumers were willing to buy irradiated meat or poultry versus 32% who were unwilling. It is interesting to note, however, the most important reasons given by those who were unwilling to buy irradiated foods: insufficient information (35%), concern about safety of consuming irradiated food (22.7%), concern about environmental impact of irradiation (3.9%), no need for irradiation usage (3.5%), and the price of irradiated products (2.5%).

Consumers are questioning the ability of the modern food system to provide safe food. Whereas governments and industry generally support the adoption of new technologies, consumer organizations question the underlying need, which results in less willingness to accept the risks, even when they are small (Macfarlane, 2002).

In a nonhypothetical laboratory experiment, participants were willing to pay an average of \$0.71 for the right to exchange a typical meat sandwich for a sandwich irradiated to eliminate the potential risk of foodborne bacteria. Forty-one of sixty participants (68.3%) were willing to pay some positive amount. Tobit analysis was used to allow for the fact that willingness to pay (WTP) was censored at zero. WTP was interpreted as the demand for irradiation to control foodborne disease. A positive WTP was interpreted as acceptance of irradiation (Giamalva et al., 1997).

17.3.4 Labeling

The labeling of irradiated items has been one of the crucial issues because it has been very controversial. Several early surveys indicated that many consumers remained concerned about the safety of irradiated food despite their reported willingness to buy such products. For example, a national survey conducted by the Gallup Organization in 1993 reported that more than 60% of consumers were extremely concerned that irradiated food might be radioactive or capable of causing cancer or birth defects (American Meat Institute Foundation, 1993). Many consumers also opposed the USDA's initial proposal in 1997 to allow certain irradiated food to be labeled as "organic." The subsequent revision of the organic food standards to exclude irradiated products was based in part on 275,000 public comments provided to the USDA, nearly all of which opposed the use of irradiation technology in organic production systems (USDA, 2000).

Most respondents (92%) answered that irradiated foods should be labeled as such. In Argentina, food regulations state that if a food contains more than 10% of irradiated components, it should be labeled "food treated with ionizing energy" (Código Alimentario Argentino, 2005). Considering the respondents' doubts and insecurities, it is probable that if these respondents came across a food labeled as "treated with ionizing energy," they would not choose to buy it (Flores and Hough, 2008).

Derr et al. (1995) claimed that,

someday, shoppers entering a major supermarket may encounter a broad display of produce over which hangs a sign with the radura logo and a statement "Treated with irradiation." Shoppers who are concerned about the environment may select irradiated, imported cherries or grapes instead of those treated with methyl bromide, because methyl bromide has been implicated in damaging the stratospheric ozone layer. For other imported items, such as guavas or lychee fruit having no alternative quarantine treatment, there is no non-irradiated choice.

17.4 Irradiation in the United States and Europe

17.4.1 Irradiation in the United States

The United States has been the pioneering country in terms of irradiating foods. Irradiation in the United States dates back to 1963 when wheat and wheat flour were irradiated to control insects. Since then, many foods of both plant (potatoes, herbs, spices, vegetable seasonings, enzyme preparations, fresh fruits, vegetables, and grains) and animal origin (pork, fresh and frozen poultry, poultry feed, frozen uncooked red meat, ground beef, and eggs) have been determined to be acceptable for irradiation. [Table 17.2](#) shows the progress of food irradiation in the United States, and [Table 17.3](#) presents foods approved for irradiation in the United States.

TABLE 17.2 Progress in Food Irradiation in the United States

| Year | Consumed Irradiated Food | Occasion/Comments |
|-----------|---|--|
| 1972 | Ham, beefsteak, turkey, and corned beef (high irradiation doses) | U.S. astronauts consumed them on Apollo 17 mission |
| 1986 | Mangoes | Sold well |
| 1987 | Hawaiian papayas | Outsold their identically priced non irradiated counterparts by more than 10 to 1 |
| 1987 | Apples | Favorably received (Missouri) |
| 1992 | Strawberries, grapefruit, and orange juice | Outsold the non irradiated by 10 to 1 |
| 1993 1994 | Tomatoes, mushrooms, and onions | Marketed with high success. In second year, the irradiated outsold the non irradiated by 20 to 1 |
| 1995 | Tropical fruits (papaya, litchi, and starfruit) from Hawaii | Determination of the potential of irradiation for quarantine treatment |
| 1995 | Poultry | 60% of market share when priced 10% lower than store brand. 39% when priced equally. 30% when priced 10% higher |
| 1996 | Poultry | 63% of market share when priced 10% lower than store brand. 47% when priced equally. 18% when priced 10% higher |
| 2000 | Frozen ground beef patties, packaged hamburgers, and jerky snacks | Huisken Meats subsidiary of Sara Lee Company |
| 2001 | Beef patties (frozen and fresh), poultry, and pork | SureBeam contracted to irradiate products for Cargill Foods, Tyson Foods, Iowa Beef Packers/Omaha Steaks, and Schwan's |
| 2002 | Chicken, turkey, beef, and egg products | Food Technology Service launched the I Care Foods brand |
| 2002 | Hamburgers | Restaurants serve irradiated products |

Data from the International Food Information Council Foundation (www.ific.org/research/irradiationres.cfm).

Sales of irradiated foods clearly indicate that U.S. consumers appreciate the value of irradiated foods. All irradiated foods offered for sale have sold well. The results of U.S. consumer attitude surveys can be used to predict the acceptance of quality irradiated foods, especially when improved food safety is the perceived benefit. Consumers perceive the most benefit when irradiation is used to improve food safety or to reduce the chemicals used on foods. Consumer activists continue to attempt to prevent the sale of labeled irradiated foods, but to date they have not been successful (Marcotte and Kunstadt, 1993).

TABLE 17.3 Foods Approved for Irradiation in the United States

| Approval Year | Food | Target/Goal |
|---------------|--|---|
| 1963 | Wheat and wheat flour | To control insects |
| 1964 | White potatoes | To inhibit sprout development |
| 1983 1986 | Herbs, spices, and enzyme preparations | To kill insects and control microorganisms |
| 1985 | Dry or dehydrated enzyme preparations | To kill insects and control microorganisms |
| 1986 | Pork | To control the parasite <i>Trichinella spiralis</i> , which causes trichinosis |
| 1986 | Fresh fruits, vegetables, and grains | To control insects and inhibit growth, ripening, and sprouting |
| 1990, 1992 | Fresh or frozen packaged poultry | To control <i>Salmonella</i> , <i>Campylobacter</i> , and other bacteria |
| 1995 | Poultry feed | To eliminate <i>Salmonella</i> |
| 1999 | Frozen uncooked red meat, ground beef | To eliminate <i>Escherichia coli</i> O157:H7 and <i>Salmonella</i> to extend shelf life |
| 2007 | Liquid egg | To eliminate <i>Salmonella</i> |

17.4.2 Legislation in Europe

For many years, all Member States of the EU have had their own rules regarding which foods for sale within their borders they permit to be irradiated and at what doses. Some Member States have authorized several food categories for irradiation, whereas others have authorized none. In March 1999, the European Commission (EC) introduced two directives on the irradiation of foods. Directive 1999/2/EU established a framework for controlling irradiated foods—their labeling and importation—and Directive 1999/3 established an initial positive list of foods that may be irradiated and traded freely between Member States.

Currently, most EU Member States do not permit irradiation of any foods other than those on the EU list. Only five—Belgium, France, Italy, The Netherlands, and the United Kingdom—permit the irradiation of additional foods. Even in these countries, only a few of the foods permitted are irradiated in practice, and in most cases the percentage of those foods that are irradiated is small. In 2000, the EC put forward a draft proposal for extension of the community positive list. The current list contains only one food category—dried aromatic herbs, spices, and vegetable seasonings. The EC suggested the addition of the following foods to the list, all of which were granted a favorable opinion from the EU SCF: deep frozen aromatic herbs, dried fruit, flakes and germs of cereals, mechanically recovered chicken meat, offal of chicken, egg white, gum arabic, frog legs, and peeled shrimps. Several other foods that also received a favorable opinion from the SCF were suggested for exclusion from the EC list. These were fresh fruits and vegetables,

cereals, starchy tubers (potatoes), fish, camembert from raw milk, casein, rice flour, blood products, fresh red meats, and poultry meat (see [www.foodmagazine.org.uk/campaigns/europe and the uk](http://www.foodmagazine.org.uk/campaigns/europe_and_the_uk)).

The EC proposal was opened for discussion via a consultation with consumer organizations, industry, and other interested parties. An EC communication issued in August 2001 stated that due to the diversity of the views expressed and the complexity of the issue, a broader debate is needed (see [http://www.foodmagazine.org.uk/campaigns/europe and the uk](http://www.foodmagazine.org.uk/campaigns/europe_and_the_uk)).

Consumer organizations [BEUC—European Consumers Organization, Swedish Consumer Coalition, the British Medical Association, Die Verbraucher e. V. (Germany), Kuluttajahäälä-Konsumentit (Finland), Consumers in Europe Group, Movimento dei Consumatori (Italy), and others] believe that the technology does not offer real benefits to consumers and that it will eventually lead to consumers being misled regarding the freshness and quality of the food they purchase.

17.4.3 Opposition of European Union Food Industry to Irradiation

It is noteworthy that several EU industries, such as the Liaison Centre for the Meat Processing Industry, the Brussels Association of Dried Fruits and Vegetables Industries, the Dutch Fish Product Board, and the German Milk Industry Association, were not favorably inclined toward the introduction of ionizing irradiation.

The British Medical Association commented that “the proposed strategy would encourage food producers to lower food safety standards because any degree of contamination could be compensated by irradiation,” and so “food irradiation should be restricted to dried aromatic herbs, spices, and vegetable seasonings.”

The European Community of Consumer Cooperatives (Euro Coop) argued that “the commission discusses safety and hygiene at the wrong point of the chain,” “it is possible to raise chicken in a salmonella-free environment,” and “priority should focus on improving production at primary level, storage, manufacturing processes, etc. rather than on killing off contamination at the last stage.” It stated that food irradiation may make the problem of food poisoning worse if it is being used to legitimate bad hygiene (see [www.foodmagazine.org.uk/campaigns/europe and the uk](http://www.foodmagazine.org.uk/campaigns/europe_and_the_uk)).

17.5 Health Risks Due to Consumption of Irradiated Food

Food irradiation (depending on dosage and irradiation time) can destroy essential vitamins in food. This damage can increase with long storage times of irradiated foods and cooking. This is not in the interest of consumers, and it could be particularly harmful for impoverished nations

or segments of society already struggling to obtain adequate nutrition, such as the elderly, the young, the sick, and the poor.

Irradiation results in radiolytic by-products in food (e.g., cyclobutanone irradiation is a by-product of certain fatty acids), some of which have known or suspected carcinogenic and mutagenic properties. Considerable controversy remains regarding the health impacts of consuming these chemicals and also about the amount and quality of research undertaken to study them.

The Italian Consumer Movement stated that there are good grounds for asserting precaution, until medium- and long-term tests on superior mammals are made compulsory, before putting products on the market.

Food irradiation does not inactivate hazardous toxins that have already been produced by bacteria prior to irradiation. In some cases, such as *Clostridium botulinum*, it is the toxin produced by the bacteria, rather than the bacteria, that causes sickness. Moreover, bacterial spores, viruses, and the BSE prion survive the doses used to irradiate food. Therefore, simply destroying the bacteria does not necessarily guarantee that food is safe (Food Irradiation Campaign [FIC], 2002).

17.5.1 Prolonged Shelf Life: Is It a Benefit for Consumers?

Euro Coop commented, “extended shelf life of food products is not in the interest of the consumer, but always in the producer’s interest” (see [www.foodmagazine.org.uk/campaigns/europe and the uk](http://www.foodmagazine.org.uk/campaigns/europe_and_the_uk)). There are similar concerns regarding the appropriateness of using irradiation to delay sprouting and ripening. The Association of German Food Traders noted that “sprouting and ripening are natural processes that allow the consumer to judge the age and freshness of products. Through irradiation consumers might be misled.”

This approach holds true for U.S. consumers as well, who can accept the application of irradiation for meat and poultry but not for agricultural products. Similarly, the Dutch are against the irradiation of fish because it will undergo a thermal treatment (cooking, frying, or baking) prior to its consumption.

17.5.2 Worker and Environmental Hazards

Use of radioactive materials for irradiating foodstuffs involves serious risks. Workers can suffer accidental exposure, and radioactive spills and leaks from plants and during transportation of radioactive materials put the environment and human populations at risk through contamination of groundwater and food chains. Although fatal incidents are few, some accidents involving worker fatalities have occurred in recent years in the United States, Italy, Norway, Mexico, Brazil, El Salvador, and Australia.

Increased shelf life with γ -irradiation has been closely linked with ecosystem disruption. In fact, prolonged shelf life allows the transportation of foods over greater distances, thereby contributing to increased fuel consumption and air pollution, socioeconomic decline among small-scale local farmers, and loss of wildlife habitats to industrial farming and road construction (FIC, 2002).

17.5.3 Safety Risks

It has been reported that approximately 200 losses and thefts of radioactive materials occur each year. Recent events in the United States have raised concerns regarding the potential for terrorists to obtain such materials for use in “dirty bombs”—conventional bombs containing radioactive materials. Building more plants that hold radioactive materials means more security risks for everyone. There are currently five approved facilities outside the EU: three in South Africa, one in Switzerland, and one in Turkey (see [www.foodmagazine.com/Science Nutrition/FSA finds irradiate ingredients in samples](http://www.foodmagazine.com/Science/Nutrition/FSA_finds_irradiate_ingredients_in_samples)).

Improvements to security are essential. However, this entails an increase in maintenance costs of irradiation facilities, resulting in higher prices for irradiated foods, which is not a benefit to consumers (FIC, 2002).

17.5.4 Illegal Irradiation in Europe

The EC directives require all foods, or listed ingredients of foods, that have been irradiated to be labeled with the words “irradiated” or “treated with ionizing radiation” or with the radura symbol. Irradiated foods traded within the EU must have been treated only at EC-authorized irradiation facilities, and so far no facilities outside the EU have received this EC authorization. All of these measures within the directives aim to ensure that consumers are protected.

In June 2002, a Food Standards Agency survey revealed that illegally irradiated, unlabeled herbal supplements, seafoods, and spices were being sold to UK consumers. This indicates that despite the availability of tests for detecting irradiated foods, illegally irradiated foods are sold and consumers are exposed to potential health risks. Furthermore, consumers are misled and lose their legitimate right to know how their food has been processed. The survey findings shocked the public, especially because food manufacturers and retailers in the United Kingdom claim they do not sell irradiated foods or food ingredients. The major UK supermarkets control approximately 60–70% of the UK grocery market. The Food Commission’s surveys of 1993, 1995, and 2002 revealed that none of the major UK supermarkets had any plans to stock irradiated foods because consumers do not want to buy them. UK supermarkets are also taking steps to avoid unknowingly stocking irradiated foods (see [www.foodmagazine.org.uk/campaigns/europe and the uk](http://www.foodmagazine.org.uk/campaigns/europe_and_the_uk)).

Some of the products identified in the UK survey were soon after found on sale in Denmark, but the Danish government stated that it had no plans to conduct an irradiation survey.

Further confirming the validity of the survey findings, both UK and Irish governments reported finding illegally irradiated food products in 2006. The UK reported that half (24 of 48) of the food supplements tested were either wholly irradiated (11) or contained an irradiated ingredient (13). None of the irradiated products were labeled. In Ireland, 14 samples of noodles tested positive for irradiated ingredients. None of them were labeled. All irradiated products were removed from sale (see www.foodandwaterwatch.org/food/foodirradiation/int/foodirradiation/europe 1).

Parties that lobby against the use of food irradiation claim that food irradiation deteriorates the structure, promoting the increase of free radicals and depleting vitamin and mineral contents. However, representatives of the food irradiation industry argue that scientific evidence proves that the depletion of irradiated foods is absolutely minimal and may be even lower compared to that of other processing methods (Andress et al., 1998).

The following associations and institutes support irradiating many foods: ICGFI, Association Internationale d'Irradiation Industrielle, Panel on Gamma and Electron Irradiation, Gammaster Provence SA (an irradiation company), Croatian Association for Consumer Protection, Institute of Food Research (Norwich, UK), and Société Civile d'Études et de Recherches dans la Domaine des Technologies d'Innovation.

Despite opposition to irradiated food, a study by ICGFI revealed that in most European countries, the consumption of irradiated food is increasing and it can be even more enhanced by implementing educational programs and occasional media coverage and providing accurate scientific information about the advantages of food irradiation. Economic analysis indicated that price greatly influences willingness to buy. Whereas lower income groups were sensitive to price, higher income groups were likely to purchase irradiated food at lower, identical, or even higher prices. Attitude studies demonstrate that more than half of consumers expect and are willing to pay more for irradiated foods (ICGFI, 1999a).

17.6 Cases of Some European Countries

Irradiated strawberries were test marketed in May and June 1987 in Lyon, France. Two tons of product packed in covered plastic trays, labeled "Protected by ionization," and priced 30% higher than the non-irradiated product sold well. However, in the long-term, irradiated strawberries were priced too high to compete economically. Labeled irradiated frog legs sold well. Other irradiated products appear regularly on the market (ICGFI, 1999a).

A questionnaire distributed to a panel of 1158 people showed that in The Netherlands the percentages of people concerned about getting ill due to improperly processed foods and those

concerned about the use of irradiation were comparable, with slightly fewer concerned about the safety of pesticides and preservatives. Twenty-six percent were very concerned about irradiation, and 24% were somewhat concerned. Women were more concerned about these issues than were men.

Both concerned and less concerned consumers were most receptive to information that supported their point of view. More “in-depth” information about irradiation not only did not lessen concern about the process but also increased sensitivity to the potential hazards of other food handling methods. All the consumers were given mushrooms (half irradiated and half non-irradiated) that they were told were irradiated. The mushrooms that were actually irradiated were judged significantly better by both the very concerned and the not concerned consumers (see www.iaea.org/nafa/d5/puplic/foodirradiation.pdf).

An early 1990s study of consumer attitudes found that 25% of consumers interpreted irradiation as excellent and positive, and a further 14% described irradiation positively. One-third would probably or definitely buy labeled irradiated products, one-third definitely would not buy irradiated products, and the other third were undecided.

Consumers in the United Kingdom appear to be lacking in knowledge about irradiation, and few are interested in purchasing irradiated foods. Interviews with 198 shoppers in Manchester and Salford soon after the Chernobyl nuclear power accident found that 12% of consumers were prepared to buy irradiated foods, whereas 70% said they would not buy them. People younger than 25 years and women were most negative about the technology. Concern about health risks, including cancer, was the most prevalent reason for unwillingness to purchase irradiated food. Concern about nutrient value and general lack of information about the process was also expressed. Although educational attainment was related to knowledge about irradiation, there was no clear relationship between more knowledge and greater or lesser willingness to buy irradiated foods.

A total of 107 consumers assessed the sensory quality of a chilled irradiated (2 kGy) meal 4 days after treatment and a non-irradiated ready meal consisting of beef and gravy, Yorkshire pudding, carrots, broccoli, and roast potatoes. The irradiated meal was moderately to very acceptable and was not significantly different from the non-irradiated meal. The beef and gravy component of the meal was most liked by consumers. Appearance and aroma appeared to be more important than flavor or texture in the overall assessment of the meals (Stevenson et al., 1995).

In 1989, a survey conducted for the Association for Consumer Research found that half the people interviewed had not heard of food irradiation. Fewer than one in five agreed that food irradiation prevents food poisoning, and more than half of the people thought irradiation should not be permitted in the United Kingdom. Consumers wanted irradiated food labeled and indicated they preferred conventional food preservation methods.

Within the frame of a rather old quantitative and qualitative work, it was found that the general public was concerned about the safety and effectiveness of food irradiation. Research found that if given the opportunity to purchase irradiated food, a large proportion of consumers in Britain would not do so. Further exploration of this response revealed that consumers were confused about what food irradiation is. Moreover, there was strong concern regarding the detection of irradiated food (Thomas, 1990).

In Brazil, food regulation authorities first approved irradiation in 1973, and in 2001 the regulation was revised and extended. The Brazilian regulation states that the absorbed radiation dose must be sufficient for the purpose of disinfestation, microorganism load reduction, or sterilization, without causing nutritional losses and functional or sensory changes to the food. As in other countries, irradiated foods must be labeled with the inscription “treated by irradiation process” (Anvisa, 2001). Despite all these benefits, this technology remains underutilized not only in Brazil but also in other countries. The main reason appears to be consumer concerns and doubts about the use of radiation in food processing (Cardello, 2003; Gunes and Tekin, 2006; Resurreccion et al., 1995).

Behrens et al. (2009) studied three focus groups in São Paulo, Brazil, consisting of 30 consumers responsible for food choices and purchases. They reported that,

reactions were similar among the groups and differences between the irradiated and the non-irradiated samples were hardly perceived. When provided with positive information about irradiation and its benefits to foods and human health, many people still remained suspicious about the safety of the technology. Participants asked for more transparency in communication about risks and benefits of irradiated foods to human health, especially with respect to the continued consumption. Therefore, an education program directed to Brazilian consumers is needed, in order to explain the principles, aims, and benefits of irradiation to food products and to address the actual consumer risk perceptions and concerns.

Attitude tests carried out from 1994 to 1996 in the Republic of Korea indicated a potential-positive response from consumers. In a sample of radiation workers and the general public, 94% of the workers ($n = 324$) and 72% of the public ($n = 376$) had heard of food irradiation; however, only 58 and 32%, respectively, knew the process had been approved by the Republic of Korea’s government and international organizations. In addition, 10% of radiation workers and 40% of the public either did not know or were uncertain whether irradiated foods were the same as foods contaminated by radionuclides. Despite a lack of information about irradiation, 67% of the workers and 55% of the public were willing to buy irradiated food when the process was used to improve microbiological safety.

The ICGFI (1999a) reported that consumers preferred irradiated to chemically preserved food. It was concluded that if the benefits and safety of food irradiation were explained, the public would accept the process. Women and people with less formal education were more concerned about irradiation.

17.7 Conclusions

Marketing studies clearly demonstrate that consumers are receptive to irradiated food and will select it in preference to a non-irradiated equivalent when they perceive benefits. The public's knowledge of food processing methods in general and food irradiation in particular is very limited.

Increasing the dissemination of information may be key to the promotion of food irradiation. The majority of respondents in studies have resisted irradiated meat because of safety concerns that are unfounded according to scientific evidence and professional attestation. This implies that dispelling the unfounded concerns through effective information dissemination to consumers may enhance acceptance of irradiated beef.

Although in the United States, due to government-funded educational programs and occasional media coverage, accurate scientific information about food irradiation is reaching a small number of consumers, most people are not well informed about the advantages of this technology. In other countries, the level of public knowledge is extremely low as well. When irradiated foods are introduced into an area, public recognition of the process will increase.

Attitude studies in the United States and elsewhere indicate that consumer information should explain the benefits of the irradiation process and the effect of irradiation on food flavor and wholesomeness; should review worker and environmental safety; and should feature endorsement by recognized health experts. The relative credibility of health experts may differ between countries. In the United States, these are taken to include the American Medical Association, the American Dietitians Association, the Food and Drug Administration, the Department of Agriculture, and the World Health Organization. These and other scientific and health organizations have endorsed the safety of irradiated foods.

Increased understanding by consumers and utilization of irradiation by the food industry will result in increased consumer welfare by enhancing food safety through a reduction of foodborne pathogens; increasing the availability of a wide variety of nutritious, flavorful, high-quality fruits and vegetables; and reducing food spoilage. The majority of consumers respond positively to these benefits.

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