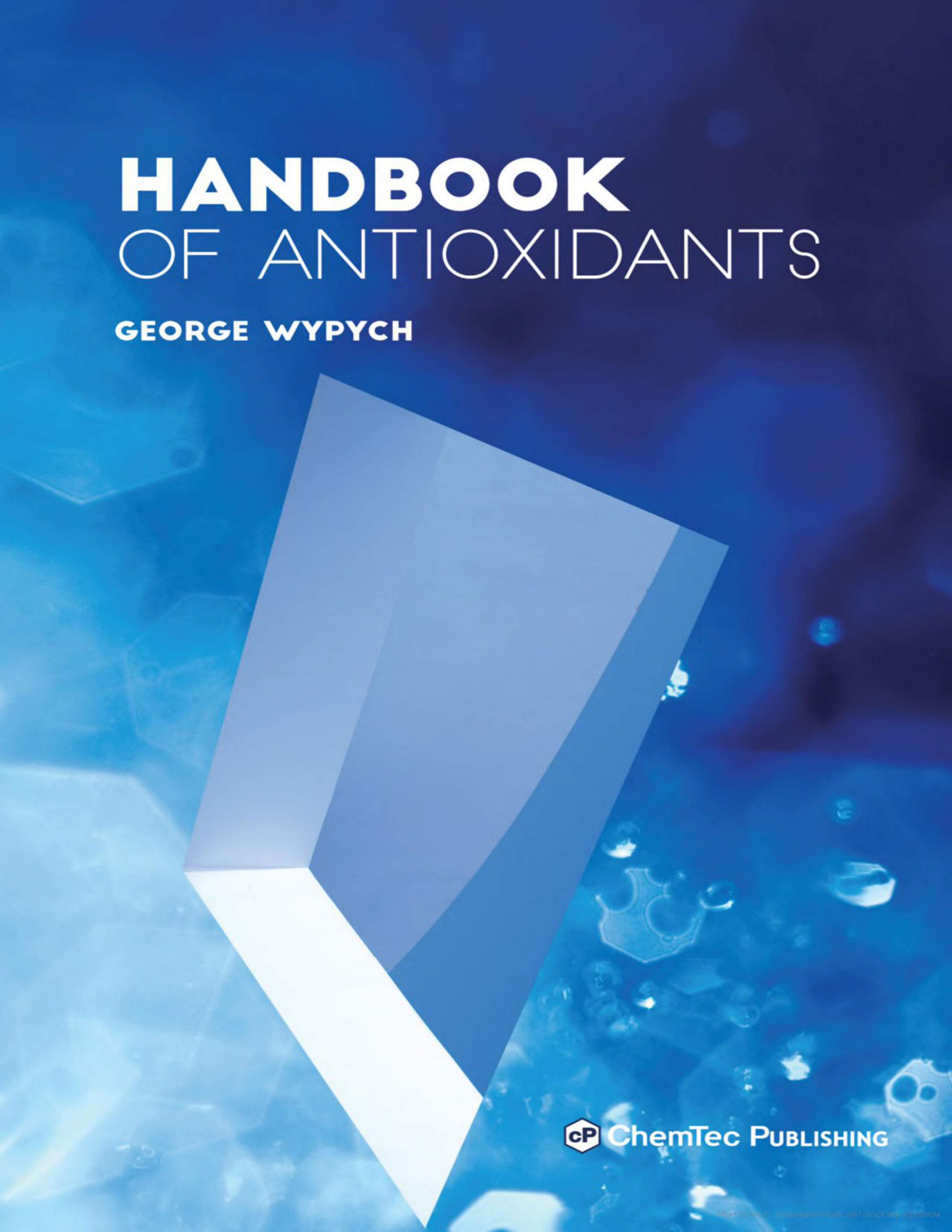


HANDBOOK OF ANTIOXIDANTS

GEORGE WYPYCH

ChemTec Publishing

Handbook of Antioxidants

George Wypych

ChemTec Publishing
Toronto 2020

Published by ChemTec Publishing
38 Earswick Drive, Toronto, Ontario M1E 1C6, Canada

ISBN 978-1-927885-59-8 (hard cover); 978-1-927885-60-4 (E-PUB)

Cover design: Anita Wypych

Library and Archives Canada Cataloguing in Publication
Title: Handbook of antioxidants / George Wypych.
Other titles: Antioxidants
Names: Wypych, George, author.
Description: Includes bibliographical references and index.
Identifiers: Canadiana (print) 20190145056 | Canadiana (ebook) 20190145064
ISBN 9781927885598 (hardcover) ISBN 9781927885604 (PDF)
Subjects: LCSH: Antioxidants-Handbooks, manuals, etc.

Classification: LCC TP159.A5 W976 2020 | DDC 660/.28443-dc23

Printed in Australia, United States, and United Kingdom

Table of Contents

1 1 Introduction 1

2 3 Typical Groups of Antioxidants 3
2.1 Acids and their esters 3
2.2 Algae 5
2.3 Amines 6
2.4 Anthocyanidins 7
2.5 Ascorbates 8
2.6 Benzofuranones 9
2.7 Benzimidazoles 10
2.8 Benzoquinones 11
2.9 Biopolyphenols 12
2.10 Curcumin 13
2.11 Coumarin derivative 14
2.12 Enzymes 15
2.13 Extracts 16
2.14 Flavonoids 17
2.15 Graphene 18
2.16 Hydrazide metal deactivators 19
2.17 Hydroquinidines 20
2.18 Hydroquinone 21
2.19 Hydroxylamines 22
2.20 Isoflavones 23
2.21 Lignanamide 24
2.22 Liposomes 25
2.23 Mitochondria-targeted antioxidants 26
2.24 Oil-derivatives 27
2.25 Peptides 28
2.26 Phenolics 29
2.27 Phosphites, diphosphites, and diphosphonites 31
2.28 Polyphenols 32
2.29 Stilbene derivatives 33
2.30 Sulfur-containing compounds 34
2.31 Terpenoids 35
2.32 Tocopherols 36

3 Physics and Chemistry of Oxidation and Antioxidants 37
3.1 Acids 37
3.2 Amines 42
3.3 Anthocyanidins 44
3.4 Ascorbates 45
3.5 Benzofuranones 48
3.6 Benzimidazoles 50
3.7 Benzoquinones 51
3.8 Curcumin 54
3.9 Coumarin 57
3.10 Enzymes 58
3.11 Flavonoids 59
3.12 Graphene 62
3.13 Hydroquinones 64
3.14 Hydroxylamines 65
3.15 Isoflavones 66
3.16 Lignanamides 68
3.17 Oil components 69
3.18 Peptides 70
3.19 Phenolics 72
3.20 Phosphites 74
3.21 Polyphenols 76
3.22 Stilbene derivatives 77
3.23 Sulfur-containing compounds 79
3.24 Terpenoids 82
3.25 Tocopherols 84

4 Oxidation in Living Cells 89
4.1 Introduction 89
4.2 Microorganisms 90
4.3 Plants 93
4.4 Fish 96
4.5 Animals 98
4.6 Humans 100

5 Prevention of Oxidation of Selected Polymers and Rubbers 107
5.1 ABS (Acrylonitrile-butadiene-styrene) 107
5.2 AK (alkyd resin) 108
5.3 C (cellulose) 109
5.4 CA (cellulose acetate) 111
5.5 CAR (carrageenan) 112
5.6 CHI (chitosan) 113
5.7 CMC (carboxymethyl cellulose) 115

5.8 CN (cellulose nitrate) 117
5.9 COC (cyclic olefin copolymer) 118
5.10 CPE (chlorinated polyethylene) 120
5.11 CPVC (chlorinated poly(vinyl chloride)) 121
5.12 CR (polychloroprene) 122
5.13 CY (cyanoacrylate) 123
5.14 EC (ethyl cellulose) 124
5.15 ECTFE (poly(ethylene-co-chlorotrifluoroethylene)) 126
5.16 EP (epoxy resin) 127
5.17 EPDM (ethylene-propylene diene terpolymer) 128
5.18 EPR (ethylene-propylene rubber) 130
5.19 EVAc (ethylene-vinyl acetate copolymer) 131
5.20 EVOH (ethylene-vinyl alcohol copolymer) 132
5.21 GEL (gelatin) 134
5.22 HDPE (high-density polyethylene) 136
5.23 LDPE (low-density polyethylene) 139
5.24 LLDPE (linear low-density polyethylene) 143
5.25 NBR (acrylonitrile-butadiene elastomer) 145
5.26 PA (polyamide) 147
5.27 PANI (polyaniline) 150
5.28 PB (polybutylene) 151
5.29 PBD (polybutadiene) 153
5.30 PC (polycarbonate) 154
5.31 PCL (poly(ε-caprolactone)) 155
5.32 PDL (polylysine) 157
5.33 PDMS (polydimethylsiloxane) 159
5.34 PEEK (polyetheretherketone) 160
5.35 PET (poly(ethylene terephthalate)) 161
5.36 PEX (silane-crosslinkable polyethylene) 163
5.37 PFPE (perfluoropolyether) 165
5.38 PHB (poly(3-hydroxybutyrate)) 166
5.39 pHEMA (poly(2-hydroxyethyl methacrylate)) 168
5.40 PI (polyimide) 169
5.41 PIB (polyisobutylene) 170
5.42 PIP (polyisoprene) 171
5.43 PK (polyketone) 173
5.44 PLA (poly(lactic acid)) 174
5.45 PMMA (polymethylmethacrylate) 177
5.46 PP (polypropylene) 178
5.47 PPG (poly(propylene glycol)) 181
5.48 PPS (poly(p-phenylene sulfide)) 182
5.49 PPy (polypyrrole) 183
5.50 PR (proteins) 184

5.51 PS (polystyrene) 186
5.52 PSR (polysulfide) 187
5.53 PSU (polysulfone) 188
5.54 PU (polyurethane) 190
5.55 PVAl (poly(vinyl alcohol)) 194
5.56 PVB (poly(vinyl butyrate)) 197
5.57 PVC (poly(vinyl chloride)) 198
5.58 PVP (poly(N-vinyl pyrrolidone)) 200
5.59 SBC (styrene-butadiene block copolymer) 202
5.60 SBR (poly(styrene-co-butadiene)) 203
5.61 SBS (styrene-butadiene-styrene triblock copolymer) 206
5.62 SEBS (styrene-ethylene-butylene-styrene triblock copolymer) 207
5.63 SIS (styrene-isoprene-styrene block copolymer) 208
5.64 ST (starch) 209
5.65 UHMWPE (ultrahigh molecular weight polyethylene) 211
5.66 XG (xanthan gum) 213

Index **215**

1

INTRODUCTION

The two most popular definitions of oxidation processes are based on the description of chemical reaction which leads to the formation of oxidation product (a combination of the substance being oxidized and oxygen) or in broader terms a reaction in which one atom loses electron but increases its valence.

There are several terms that are almost synonymous with oxidation, such as combustion, rusting, nitrification, calcination, converting food to energy, or breathing. Oxidation has a negative connotation when materials or leaving cells are being damaged in the process and positive meaning when we produce new compounds, convert the energy of molecular bonds to heat, passivate the surface of metals, or simply breath air. From this subjective division comes prevention or its lack. For all these negative connotations, we develop systems preventing or delaying oxidation. The additives which take the impact of oxidation reaction are called antioxidants, and they are the primary subject of this book.

The action of antioxidants is more complicated than just a simple replacement of material targeted by oxygen. Oxidation is a chain reaction involving free radicals and hydroperoxide intermediates. Therefore, antioxidants must also act by reacting and decomposing free radicals and hydroperoxide intermediate species.

Because of widespread applications, various groups of chemicals (in total 32 groups of additives) are involved in antioxidation, including acids and their esters, algae, amines, anthocyanidines, ascorbates, benzofuranones, benzoimidazoles, benzoquinones, biopolyphenols, curcumin, coumarin, enzymes, extracts, flavonoids, graphene, hydrazide metal deactivators, hydroquinidines, hydroquinones, hydroxylamines, isoflavones, lignanamides, liposomes, mitochondria-targeted antioxidants, oil derivatives, peptides, phenolics, phosphites, phospholipides, polyphenols, stilbene derivatives, sulfur-containing compounds, terpenoids, and tocopherols. Chapter 2 contains a brief discussion of the general properties of these groups of antioxidants with emphasis on chemical composition, physical-chemical properties, UV absorption, forms, application to polymers and final products, and concentrations used. This chapter contains only a summary of the properties of groups of antioxidants involved. The details on different representatives of the groups are included in the companion book – **Databook of Antioxidants**, which brings information on individual products. The selection of antioxidants is critical because, in modern applications, synthetic antioxidants are gradually being replaced by the products obtained from renewable resources, mostly of plant origin. This conversion in the area of cosmetics, medicine, pharmacy, food additives, and food protection is very advanced. In polymer processing, the application of natural antioxidants is still on the developmental stage but essential to know for future replacement options and performance.

Chapter 3 contains information on the physics and chemistry of oxidation and antioxidation, including the influence of UV radiation. In this chapter, peculiarities of oxidation and its prevention by antioxidants are discussed for different groups of antioxidants. In total, 25 groups of antioxidants are discussed in separate sections of this chapter. The focus of the evaluation of research findings is on the mechanism of action of antioxidants, their stability, and eventual methods of its improvement.

A separate discussion of the effects of oxidation and photooxidation on living cells is included in Chapter 4. In the introduction, the differences and similarities between the behavior of polymers and livings things and their use of antioxidants are briefly outlined. The opening is followed by separate sections discussing oxidation phenomena in microorganisms, plants, fish, animals, and humans.

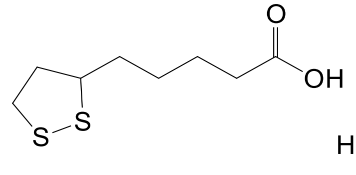
Chapter 5 constitutes the technological part of the book, which includes the analysis of progress and applications of antioxidants in different polymers and rubbers. In total, 66 polymers are discussed in separate sections of this chapter. The main subjects of this discussion include mechanisms of degradation and its prevention by antioxidants. Selection of the most suitable antioxidants and methods of their use constitutes one of the main subjects of discussion. This part of the book heavily relies on patent literature in addition to the scientific findings. The emphasis is given to the most recent applications rather than a historical review of applications.

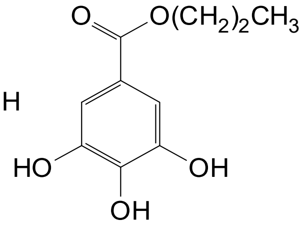
2

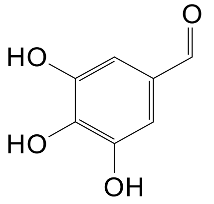
TYPICAL GROUPS OF ANTIOXIDANTS

In this chapter, the information on typical groups of antioxidants is presented in the form of tables containing information on the range of properties (general, physical, chemical, health, ecological, and uses). The presented data are based on information obtained from manufacturers of several hundred commercial additives and data found in research papers.

2.1 ACIDS AND THEIR ESTERS







GENERAL		
Names: coumaric acid, ellagic acid, ferulic acid, gallic acid, isochlorogenic acid, kojic acid, lipoic acid, nordihydroguaiaretic acid, propyl galate, salvianolic acid, sulfonic acid		
CAS #: 62-46-4, 121-79-9, 149-91-7, 476-66-4, 500-38-9, 501-30-4, 501-98-4, 1135-24-6, 2450-53-5, 30931-67-0, 121521-90-2		
Molecular weight: 142-718	**Biobased**: Y/N	**Mixture**: N
PHYSICAL		
Color: white, off-white, beige, brown, cream, yellow		**pK$_a$**: 3.52-9.56
Boiling point, °C: 312	**Freezing point**, °C: 45-260	**State**: solid
Odor: odorless, balsamic, faint	**Specific gravity**: 1.29-1.69	
Solubility: acetone, DMF, DMSO, ethanol, ethyl acetate, chloroform, glycerol, glycol, methanol, pyridine		
Max. UV absorbance, nm: 256-365		
HEALTH		
Flash point, °C: 153-177		

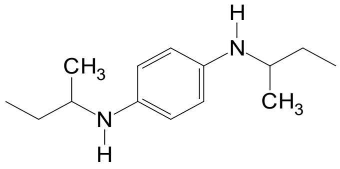
(Continued)

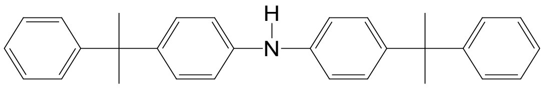
USE
Manufacturers: Cayman Chemical, ENZO, Foodchem International Co., Santa Cruz Biotechnology, Inc., Sigma Aldrich, Thermo Fisher (Kandel) GmbH
Recommended for products: anti-aging products, anti-aging products, cosmetics, dietary supplements, ethers, emulsions, foods, fats, herbal antioxidant formula, oils, pharmaceuticals, skin whitening products, sunscreen products, transformer oil to prevent autoxidation and microbial growth, vitamin and herbal health supplements, waxes, whitening facial cleanser
Concentrations used, %: <0.02-0.1

2.2 ALGAE

GENERAL		
Names: brown algae, macroalgae, microalgae, multicellular algae, red algae		
Major components of extracts: carotenoids, combination of acids (see section 2.1), epicatechin, flavonoids, phenolics, phloretin, quercetin, rutin, sulfated polysaccharide		
Extract yield, mg/g: 54-56	**Biobased**: Y	**Mixture**: Y
PHYSICAL		
Solubility: ethanol, methanol, supercritical fluid, water		
USE		
Recommended for products: cosmeceutical products, food industry (hydrocolloids, nutraceuticals), functional foods, radical scavenging, UV absorption		

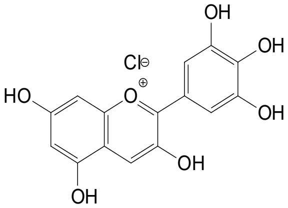
2.3 AMINES





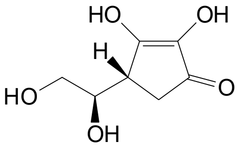
GENERAL		
Names: acetone diphenylamine, alkylated diphenylamine, diarylamine, hydrogenated rape oil based, hydrogenated tallow alkyl amine, phenylenediamine, polymeric amine		
CAS #: 101-96-2, 10081-67-1, 26780-96-1, 68411-46-1, 68412-48-6, 143925-92-2, 204933-93-7		
Molecular weight: 220-613	**Biobased**: N	**Mixture**: N/Y
PHYSICAL		
Ash, %: <0.3-<0.5	**Color**: amber, cream, brown, red, white, yellow	
Boiling point, °C: >300->400	**Freezing point**, °C: 18-135	**State**: liquid/solid
Odor: odorless	**Specific gravity**: 0.94-1.33	**pH**: 5.1-7
Solubility: acetone, 1,1-dichloromethane, benzene, carbon disulfide, chloroform, ethyl acetate, n-hexane, MEK, methanol, toluene		
Thermogravimetric analysis, %/°C: 10/305; 50/346		**Viscosity**, mPas: 565-1320
HEALTH		
Autoignition temp., °C: 250-490		**Flash point**, °C: 91-277
Carcinogenicity: N	**Mutagenicity**: N	**Teratogenicity**: N
LD50 oral rat, mg/kg: >2000->5000		**UN #**: 1673, 3077
ECOLOGICAL		
Aquatic toxicity, LC50, mg/l: *Bluegill sunfish* >100; *Daphnia magna* 41		
Bioaccumulative and toxic (PBT) assessment: product contains components with potential for bioaccumulation		
Partition coefficient: 3.5-8.8		
USE		
Manufacturers: Addivant, BASF, Crompton/Uniroyal Chemical, TDS Hunan Chemical BV		
Recommended for polymers: CR, elastomers, EVA, IR, NR, polyols, PA, PE, PP, PU, SBR, SR, styrenics, TPE		
Recommended for products: adhesives, appliance, automotive, belts, fibers, foams, footwear, gloves, hose, hot melts, hydraulic fluids, latex, lubricants, metal working fluids, tires, wire &cable		
Concentrations used: 0.01-0.6%		

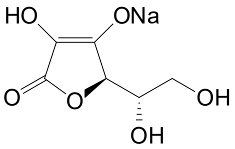
2.4 ANTHOCYANIDINS

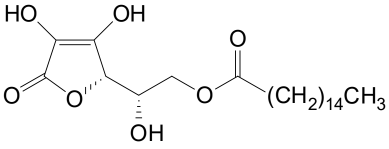


GENERAL		
Names: anthocyanidin, ephdine		**CAS #**: 528-53-0, 88082-60-4
Molecular weight: 339-865	**Biobased**: Y	**Mixture**: N
PHYSICAL		
Color: , brown, red	**State**: solid	**pK$_a$**: 5.99-11.97
Dipole moment: 391-402		**Freezing point**, °C: 350
Maximum absorption: 280, 450, 498, 550		**Refractive index**: 1.84
Solubility: DMSO, ethanol, methanol		**Specific gravity**: 1.8
HEALTH		
Carcinogenicity: N	**Mutagenicity**: N	**Teratogenicity**: N
USE		
Manufacturers: ENZO, Santa Cruz Biotechnology, Inc.		
Sources: black beans, bilberries, blackcurrants, blueberries, cowpeas, red grapes, red wine		
Recommended for products: antiradical capability		

2.5 ASCORBATES

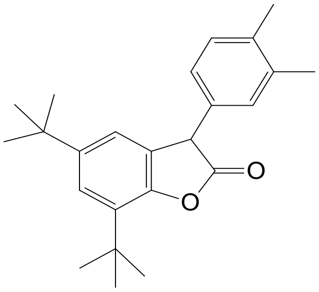






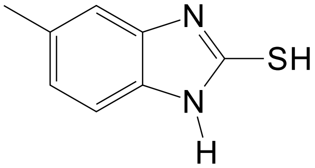
GENERAL		
Names: ascorbic acid, ascorbyl linoleate, ascorbyl dipamitate, ascorbyl palmitate, ascorbyl stearate, ascorbyl tetraisopalmitate, calcium ascorbate, erythorbic acid, palmitate ascorbate, potassium ascorbate, sodium ascorbate, sodium erythorbate		
CAS #: 50-81-7, 89-65-6, 134-03-2, 137-66-6, 25395-66-8, 28474-90-0, 5743-27-1, 6381-77-7, 15421-15-5, 121869-32-7, 183476-82-6		
Molecular weight: 176-1130	**Biobased**: Y/N	**Mixture**: Y/N
PHYSICAL		
Ash, %: <0.1	**Color**: colorless, white, yellow	**pK_a**: 4.10-11.6
Odor: citrus-like, faint, mild, odorless		**Boiling point**, °C: 164-415
Freezing point, °C: 60-192	**State**: liquid/solid	**Specific gravity**: 0.93-1.65
pH: 2.1-8.0	**Specific optical rotation**: +20.5 to +24°	
Solubility: alcohol, animal oil, ethanol, vegetable oil, water		
HEALTH		
Flash point, °C: >100-180		**LD50 oral rat**, mg/kg: >25000
ECOLOGICAL		
Bioaccumulative and toxic (PBT) assessment: no components considered to be either persistent, bioaccumulative and toxic (PBT), or very persistent and very bioaccumulative (vPvB) at levels of 0.1% or higher		
Biological oxygen demand: 71% of the ThOD (28 d)		**Partition coefficient**: -1.85 to 7.13
USE		
Manufacturers: Acme-Hardesty Co., BASF, Boc Sciences, Foodchem International Co.. GC Chemicals Co., Ixom Operations Pty Ltd(Australia), MakingCosmetics Inc, Natural Spices B.V., Sigma-Aldrich, Inc., Spectrum Chemical Manufacturing Co., TCI America		
Recommended for products: agriculture/animal feed, antioxidants in food and beverage industries, breakfast cereals, condensed milk, cosmetics industry, dairy based drinks, egg-based desserts, food industry as a natural preservative for oils, makeup products, margarine, meat industry, mustard, pharmaceuticals, pre-cooked pasta, processed cheese, skin care, vinegar, vitamins and colors		
Concentrations used: <0.02-7%		

2.6 BENZOFURANONES



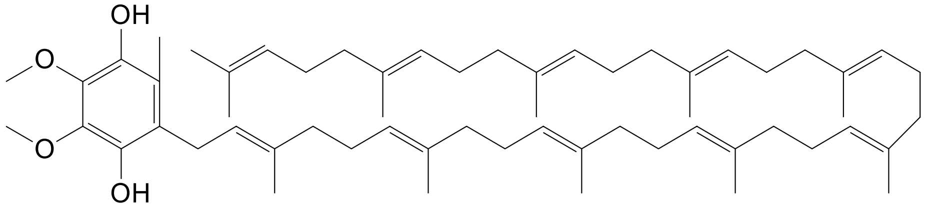
GENERAL		
Names: benzofuranone	**CAS #**: 164391-52-0, 1261240-30-5	
Molecular weight: 350-1178	**Biobased**: N	**Mixture**: Y/N
PHYSICAL		
Color: white	**State**: solid	**Specific gravity**: 0.93
USE		
Manufacturers: BASF, Chitec		
Recommended for polymers: ABS, engineering plastic including aliphatic polyketone, HDPE, HIPS, PE, PEEK, PEKK, PEK, PP, PU, SEBS, synthetic rubber, styrene homo- and copolymers, TPE		
Recommended for products: pharmaceutical industry, polymer processing		
Concentrations used: 0.05-0.15%		

2.7 BENZIMIDAZOLES



GENERAL		
Names: mercaptotolumimidazole, mercaptomethybenzimidazole		
CAS #: 27231-36-3, 53988-10-6, 61617-00-3		
Molecular weight: 164-391	**Biobased**: N	**Mixture**: Y/N
PHYSICAL		
Ash, %: <0.5	**Color**: beige, tan, white	**State**: liquid/solid
Freezing point, °C: 270-300	**Odor**: odorless	**Specific gravity**: 1.2-1.54
pH: 7-9	**Solubility**: diesters, polyglycols	
Viscosity, mPas: 175		
HEALTH		
Autoignition temp., °C: 287	**LD50 oral rat**, mg/kg: 800	**UN #**: 3077
ECOLOGICAL		
Aquatic toxicity, LC50, mg/l: *Daphnia magna* 346		**Bioconcentration factor**: 1017
Biodegradation probability: 0% (28 d) not readily biodegradable		
Partition coefficient: 3.07		
USE		
Manufacturers: Akrochem, Lanxess, Vanderbilt Chemical Co. Ltd.		
Recommended for polymers: BR, CR, EPDM, IR, NR, Neoprene, NBR, polyolefins, PS, SBR, synthetic rubber		
Recommended for products: natural and synthetic latexes, glove and thread industries, latex application: coagulated goods, foams, shoes, automotive		
Concentrations used: 0.5-2 phr		

2.8 BENZOQUINONES

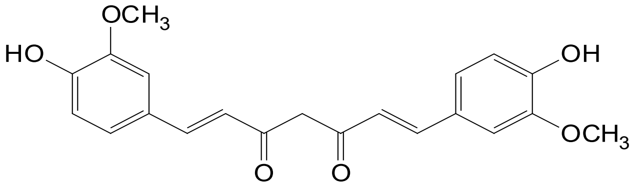


GENERAL		
Names: coenzyme Q10, benzoquinone, ubiquinone		**CAS #**: 303-98-0, 65085-29-2
Molecular weight: 863	**Biobased**: Y	**Mixture**: Y
PHYSICAL		
Color: orange, reddish, yellow	**Odor**: odorless, characteristic	**State**: solid/liquid
Freezing point, °C: 48-52	**Specific gravity**: 1.12-1.16	**pH**: 4-6 (5% solution in water)
Solubility: cosmetic oil, ethanol,		
HEALTH		
Flash point, °C: >100		**Carcinogenicity**: N
LD50 oral rat, mg/kg: >4000 to 5000		
ECOLOGICAL		
Biodegradation probability: 17% in 28 days		
USE		
Manufacturers: Cayman Chemical, DSM Natural Products Ltd., Lotioncrafter, MakingCosmetics Inc.		
Recommended for products: cosmetic ingredient for skin conditioning and personal care products		

2.9 BIOPOLYPHENOLS

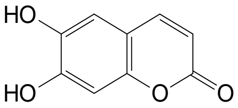
GENERAL		
Names: Argania spinoza extract, barley extract, biopolyphenol, black garlic extract, gardenia flower extract, grape seed polyphenols, tea extract		
CAS #: 85251-64-5, 91082-91-6, 92457-01-7, 999999-99-4		
Molecular weight: 180-599	**Biobased**: Y	**Mixture**: Y/N
PHYSICAL		
Ash, %: <2.0 to ≤5.0	**Color**: amber, brown, off-white, pink, purple red, yellow	
Freezing point, °C: 218	**State**: liquid/solid	**Odor**: characteristic, weak
Specific gravity: 0.99-1.05	**pH**: 4-7	**Refractive index**: 1.35-1.4
Solubility: DMSO, ethanol		
HEALTH		
Flash point, °C: 199-320		**Mutagenicity**: N
USE		
Manufacturers: BASF, Beauty Care Solutions France SAS, Bio-Extracts, Dermalab, Foodchem International Co., IMPAG AG, MakingCosmetics Inc., Shaanxi Haokang Bio-technology Co., Ltd.		
Recommended for products: cosmetic ingredient for skin conditioning, dietary supplements, food, health products, multi-functional cosmetic active ingredient for personal care products, ointments, pharmaceuticals		
Concentrations used: 0.07-4%		

2.10 CURCUMIN



GENERAL		
Names: curcumin, hydroxycinnamic acid, turmeric extract		**CAS #**: 458-37-7
Molecular weight: 368	**Biobased**: Y	**Mixture**: N
PHYSICAL		
State: solid	**Odor**: characteristic	**Color**: orange, yellow
Freezing point, ^{o}C: 170-188	**Refractive index**: 1.42	**Specific gravity**: 0.93
Solubility: ethanol		
Maximum absorption, nm: 427		**Vapor density**: 12.72
HEALTH		
RTECS #: MI5230000	**LD50 oral rat**, mg/kg: >2000->5000	
ECOLOGICAL		
OH rate constant, cm^3/mol-sec: 1.58E-10		**Partition coefficient**: 3.29
USE		
Manufacturers: Cayman Chemical Co., Tokyo Chemical Industry Co., Ltd.		
Recommended for products: anticancer protection, pharmaceuticals, UV protection		

2.11 COUMARIN DERIVATIVES



GENERAL		
Names: dihydroxycoumarin, esculetin		**CAS #**: 305-01-1
Molecular weight: 178	**Biobased**: Y	**Mixture**: N
PHYSICAL		
Color: white, yellow	**pK$_a$**: 7.74	**Boiling point**, °C: 470
Freezing point, °C: 271-273	**State**: solid	**Odor**: characteristic
Specific gravity: 1.55	**Solubility**: DMSO, DMF	
Maximum absorption, nm: 344		
HEALTH		
Flash point, °C: 201.5	**LD50 oral rat**, mg/kg: 1500	**Carcinogenicity**: N
RTECS #: GN6382500		
USE		
Manufacturers: Santa Cruz Biotechnology, Inc., Tokyo Chemical Industry Co., Ltd.		
Recommended for products: cosmetics, skin conditioning		

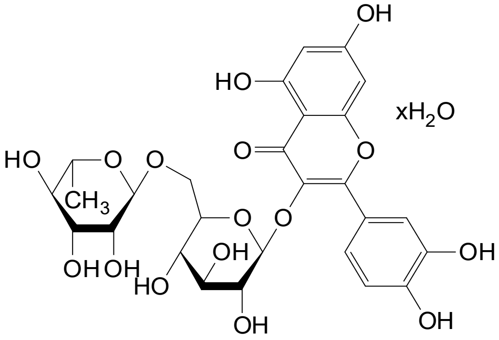
2.12 ENZYMES

GENERAL		
Names: biocell, melatonin (hormone), superoxide dismutase		**CAS #**: 73-31-4, 9054-89-1
Molecular weight: 232	**Biobased**: Y/N	**Mixture**: Y/N
Additional information: Enzyme functions as a catalyst to quench the superoxide radical, converting it to hydrogen peroxide and molecular oxygen. Biocell SOD remains intact to continue on in its defense of the body, unlike non-enzymatic antioxidants which are consumed during the neutralization process. SOD is commercially obtained from marine phytoplankton, bovine liver, horseradish, cantaloupe, and certain bacteria. H_2O^2 accumulated from 0.04 to 2.09 mmol kg^{-1} in mung beans during germination for 6 d.		
PHYSICAL		
State: solid	**Color**: blue, gray, off-white, white	
Freezing point, ^{o}C: 115-121	**Specific gravity**: 1.272	
HEALTH		
RTECS #: AC595500		**LD50 oral rat**, mg/kg: 3200
USE		
Manufacturers: Cayman Chemical Co., Lonza, TCI Chemical		
Recommended for products: cosmetics, medicine, food, health care products, pharmaceuticals, skin conditioning cosmetics-prevent drying and aging of the skin without causing irritation.		
Costabilizers enhancing light stability: combination of superoxide dismutase and gliadin (type of protein sourced from wheat) may help increase antioxidant activity.		
Concentrations used: 0.1-5		

2.13 EXTRACTS

GENERAL		
Names: aloe vera extract, creanatural wasabi extract, danshensu powder, eden fruit extract, ginkgo biloba extract, goji berry extract, green coffee extract, rosemary extract, sage extract, wild jujube extract		
CAS #: 1415-73-2, 76822-21-4, 84604-14-8, 84775-62-2 , 85085-46-7, 85085-68-3, 90045-36-6, 1232681-33-2		
Biobased: Y/N		**Mixture**: Y
Additional information: phytochemical and pharmacological results have revealed that flavonoid, polysaccharide, phenolic, vitamin C, and triterpenic acid are the main active ingredients of wild jujube extract. Oxidoreductases, isocyanates, and glucosinolates are three general species of Wasabia japonica.		
PHYSICAL		
Ash, %: ≤2.0%	**Color**: amber, brown, green, yellow	
Boiling point, °C: 100-481	**Freezing point**, °C: 0-148	**Solubility**: ethanol
State: liquid/solid		**Odor**: characteristic, slight
Specific gravity: 1.03-1.55	**pH**: 4-7	**Refractive index**: 1.39-1.50
HEALTH		
Flash point, °C: 61-259		**RTECS #**: LZ6520000
ECOLOGICAL		
Aquatic toxicity, LC50, mg/l: *Fathead minnow* 7417		
USE		
Manufacturers: Flavex Naturextrakte GmbH, Formulator Sample Shop, Givaudan, Induchem AG, MakingCosmetics Inc., Maruzen Pharmaceutical Co., Ltd., Shaanxi Haokang Bio-technology Co., Ltd., Sinoway Industrial Co., Ltd., The Innovation Company		
Recommended for products: cosmetic ingredient for skin conditioning, food industry (dressings, sausages, snacks, etc.), food supplements, functional drinks, medicine, multi-functional cosmetic active ingredient for personal care products, ointments, pharmaceuticals, sun care applications		
Concentrations used: 0.05-5%		

2.14 FLAVONOIDS

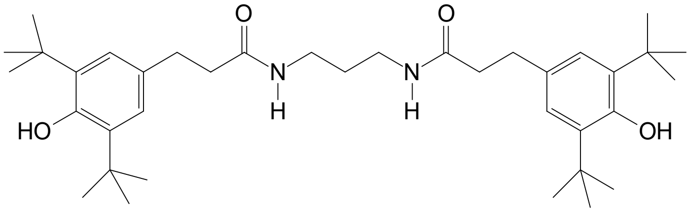


GENERAL		
Names: apigenin, dihydroquercetin, luteolin, rutin, pelargonidin chloride, rutin trihydrate, taxifolin		
CAS #: 134-04-3, 153-18-4, 491-70-3, 520-36-5, 24198-97-8, 250249-75-3		
Molecular weight: 270-664	**Biobased**: Y/N	**Mixture**: N
PHYSICAL		
Color: amber, brown, green, off-white, red, white, yellow		**State**: solid
Freezing point, °C: 195->350	**Specific gravity**: 1.5-1.7	**Refractive index**: 1.73
Solubility: acetone, ethanol, diluted potassium hydroxide, DMSO, methanol, pyridine		
HEALTH		
Flash point, °C: 217-239	**RTECS #**: DK1295000, LK9275210, LK9276000, VM2975000	
USE		
Manufacturers: Coompo Research Chemicals, ENZO, Santa Cruz Biotechnology, Inc.		
Recommended for products: cosmetics: hair and skin conditioning		

2.15 GRAPHENE

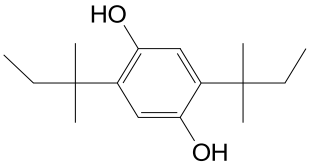
GENERAL		
Names: graphene, graphene oxide, reduced graphene oxide		**2D dimensions**, µm: 0.4-1000
CAS #: 7440-44-0, 7782-42-5, 1034343-98-0		**Thickness**, nm: 0.8-100
Surface properties: polar, hydrophobic, hydrophilic		**Number of layers**: 1-10+
Functional groups: amine, carbonyl, carboxyl, ether, fluoro, hydroxyl		
PHYSICAL		
Ash, %: 1-6	**Carbon content**, %: 46-97	**Oxygen content**, %: 1-49
Hydrogen content, %: 1-2	**Nitrogen content**, %: 0-2.5	**Melting point**, °C: 3,652-3,697
Color: gray to brown to black	**State**: solid	**Odor**: odorless
Specific gravity: 1.0-2.3	**Specific surface area**, m^2/g: 5-1,000	
Peak decomposition temperature, °C: 750		
HEALTH		
UN #: not classified as dangerous goods		
ECOLOGICAL		
Biodegradation probability: readily absorbed into soil		
USE		
Manufacturers: ACS Material LLC, Advanced Graphene Products, Graphenea, SigmaAldrich		
Outstanding properties: Antioxidant (3,5-di-tert-butyl-4-hydroxyphenylpropionic acid or 4-amino-2,2,6,6-tetramethylpiperidine) grafted graphene oxide improved both of the thermal and mechanical properties of polyketone composite. The thermo-oxidative aging resistance of natural rubber was improved using functionalized graphene which was prepared by grafting 2-tert-butyl-6-(3-tertbutyl-2-hydroxy-5-methylphenyl) methyl-4-methylp-henyl acrylate onto graphene oxide using (3-mercaptopropyl) trimethoxysilane as a bridging agent. One-atom-thick two-dimensional nanosheet of graphene composed of sp^2 hybridized carbon is capable of both scavenging free-radicals and serving as gas barriers, improving the thermal stability of elastomer/graphene nanocomposites. The presence of graphene nanoplatelets improved the photo-oxidation stability of polypropylene. The radical scavenging ability of graphene oxide was enhanced by grafting with Irganox 245, which was used to protect polyamide against degradation.		
Recommended for polymers: natural rubber, PA, polyketone, PP, SBR		
Recommended for products: composites, nanocomposites, water disinfection		
Concentrations used: 0.1-5 wt%		

2.16 HYDRAZIDE METAL DEACTIVATORS



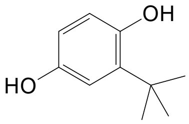
GENERAL		
Names: hydrazide metal deactivator		
CAS #: 32687-78-8, 36411-52-6, 69851-61-2		
Molecular weight: 214-594	**Biobased**: N	**Mixture**: N
PHYSICAL		
Acid #, mg KOH/g: <1	**Color**: cream, white, yellow	**State**: solid
Odor: odorless	**Freezing point**, °C: 170-320	**Boiling point**, °C: 653
Specific gravity: 0.88-1.55	**pH**: 6	**Refractive index**: 1.53-1.54
Solubility: acetone, methanol, THF		
Transmittance, %/nm: 96/425, 97/500		
HEALTH		
Autoignition temp., °C: 380-390		**Carcinogenicity**: N
Flash point, °C: >180 to >200		**Mutagenicity**: N
LD50 oral rat, mg/kg: >2000 to >7000		**Teratogenicity**: N
ECOLOGICAL		
Aquatic toxicity, LC50, mg/l: *Daphnia magna* >100		
Biodegradation probability: not readily biodegradable 6%/28 days		
Bioconcentration factor: 3.1-10 (60/days)		**Partition coefficient**: >7.79
USE		
Manufacturers: Addivant, BASF, Chitec, Santa Cruz Biotechnology, Inc.		
Outstanding properties: efficient metal deactivator which forms stable complexes with metals, particularly with copper ions. Improves the stability of the polymer in contact with copper		
Recommended for polymers: engineering plastics, NBR, PE, PO, PP, SBR, styrene homo-and copolymers, TPE, TPU, X-SBR		
Recommended for products: electric parts including plugs, outlets and switches, fuel hoses, telecommunications wire and cable, wire & cable		
Concentrations used: 0.1-0.2%		

2.17 HYDROQUINIDINES



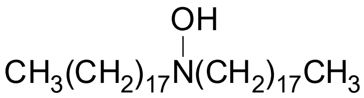
GENERAL		
Names: hydroquinidine, polymerized trimethylquinoline		**CAS #**: 79-74-3, 26780-96-1
Molecular weight: 250	**Biobased**: N	**Mixture**: Y/N
PHYSICAL		
Ash, %: 0.1-0.25	**State**: solid	**Color**: amber, beige, brown
Odor: slight	**Solubility**: acetone, benzene, chloroform, and carbon disulfide	
Freezing point, °C: 82-185	**Specific gravity**: 1.03-1.1	
HEALTH		
Flash point, °C: 204	**RTECS #**: MX6300000	**Carcinogenicity**: N
LD50 oral rat, mg/kg: 2000-3190		
ECOLOGICAL		
Aquatic toxicity, LC50, mg/l: *Daphnia magna* 56; *Zebra fish* >100		
Biodegradation probability: 28% (28 d), not readily biodegradable		
Bioconcentration factor: 477-1160		**Partition coefficient**: 5.177
USE		
Manufacturers: Songwon Industrial Co. Ltd., Vanderbilt Chemical Co. Ltd.		
Outstanding properties: inhibits oxygen attack and flex cracking, improves heat aging		
Recommended for polymers: CR, IR, NR, SR, SBR, use in latex/waterborne dispersions		
Recommended for products: adhesives, automotive, belts, films, footwear, hose, hot melts, latex, tapes, tires, unvulcanized rubber adhesives, wire & cable		
Concentrations used: 2 phr		

2.18 HYDROQUINONES



GENERAL		
Names: tertiary butyl hydroquinone		**CAS #**: 1948-33-0
Molecular weight: 166	**Biobased**: N	**Mixture**: Y/N
PHYSICAL		
Color: amber, brown, tan, white		**Odor**: very slight aromatic
State: solid/liquid	**pK$_a$**: 10.7	**Boiling point**, °C: 300
Freezing point, °C: 126.5-128.5		**Specific gravity**: 0.99
Viscosity, mPas: 284		
Max. UV absorbance, nm: 206, 227, 292		**Vapor density**: 5.73
HEALTH		
Flash point, °C: 171	**LD50 oral rat**, mg/kg: 951	**UN #**: 3082
ECOLOGICAL		
Aquatic toxicity, LC50, mg/l: *Fathead minnow* 0.6		
Biodegradation probability: 19% (28 tert-butyl hydroquinone), 81.7 (28 d, ready biodegradability/propylene glycol), 97% (28 d, biodegradability ready/citric acid)		
Partition coefficient: -0.92 to 2.94		
USE		
Manufacturers: Eastman Chemicals		
Recommended for products: cosmetics, food industry, polymers		
Concentrations used: 0.02% singly or in combination, by weight, in fat or oil portion of food		

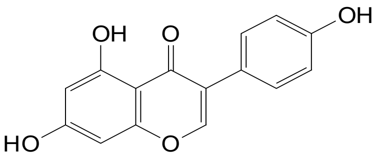
2.19 HYDROXYLAMINES



$$CH_3(CH_2)_{17}\overset{\overset{\displaystyle OH}{|}}{N}(CH_2)_{17}CH_3$$

GENERAL		
Names: hydroxylamines	**CAS #**: 143925-92-2, 1374859-51-4	
Molecular weight: 538	**Biobased**: N/Y	**Mixture**: Y/N
PHYSICAL		
Ash, %: <0.1	**State**: solid	**Color**: cream, off-white, white
Odor: faint, odorless	**Freezing point**, °C: >55-98	**Specific gravity**: 0.95
pH: 7-10		
Solubility: slight in acetone, ethyl acetate, dichloromethane, toluene		
HEALTH		
LD50 oral rat, mg/kg: >2000	**UN #**: 3077	**Carcinogenicity**: N
Mutagenicity: N	**Teratogenicity**: N	
USE		
Manufacturers: BASF, Chitec		
Outstanding properties: resistance to extraction, low volatility, offers long-term thermal stability, hydroxylamine based antioxidant is not as effective as hindered phenolic antioxidant which is always recommended for use in conjunction with phosphite stabilizers		
Recommended for polymers: PE, PP, TPE, TPO		
Recommended for products: automotive, fibers		
Concentrations used: 0.05-0.15%		

2.20 ISOFLAVONES



GENERAL		
Names: genistein, isoflavone, soy, phytoestrogen, soybean isoflavone, trihydroxyisoflavone		**CAS #**: 446-72-0, 574-12-9
Molecular weight: 222-270	**Biobased**: Y	**Mixture**: Y/N
Additional information: nano-active isoflavone is the inclusion of soy isoflavones in the polar lipid layer and lipophilic nuclei of sodium found in several plants including lupin, fava beans, soybeans, kudzu		
PHYSICAL		
Color: yellow	**State**: solid/liquid	**Odor**: odorless, characteristic
Freezing point, °C: >280	**Boiling point**, °C: 361	**Specific gravity**: 1.0-1.1
Solubility: DMSO, oil		**pH**: 5-8
HEALTH		
Flash point, °C: 171		**RTECS #**: NR2392000
ECOLOGICAL		
Partition coefficient: 2.84-2.91		
USE		
Manufacturers: Sinoway Industrial Co., Ltd.		
Outstanding properties: exhibit antioxidant, anticancer, antimicrobial, and anti-inflammatory properties. Genistein influences multiple biochemical functions in living cells like direct antioxidation with some prooxidative, activation of Nrf2 antioxidative response feature		
Recommended for products: cosmetics: anti-wrinkle and anti-aging cream, whitening, removing spots, removing wrinkles, nourishing hair, hair growth, hair removal cream, food, pharmaceutical		
Concentrations used: 1-3%, equal to 0.04-0.12% of soy isoflavones		

2.21 LIGNANAMIDES

GENERAL		
Names: chinese wolfberry leaf extract, lignanamide		**CAS #**: 913545-16-1
Molecular weight:	**Biobased**: Y	**Mixture**: Y
Additional information: extract of the leaves of lycium chinense, solanaceae		
USE		
Manufacturers: Carrubba		
Recommended for products: ointments, cosmetic ingredient for skin conditioning		

2.22 LIPOSOMES

GENERAL		
Names: liposome		**CAS #**: 123465-35-0
Molecular weight:	**Biobased**: Y	**Mixture**: Y
Additional information: Liposomal delivery systems are microscopic vesicles that consist of an aqueous center with a phospholipid membrane. Phospholipids contain glycerol bonded to two essential fatty acids and a phosphate group with a polar head. The essential fatty acids portion of this biomolecule is hydrophobic and is located toward the outside of the lipid bilayer, whereas the phosphate group is hydrophilic and faces the aqueous interior. These phospholipid walls are identical to those that comprise other human cell membranes. Liposomes can differ in size, with a range in diameter between 150-3500 nm, and they can be found in unilamellar and multilamellar forms. Unilamellar vesicles are small, exceptionally stable, molecules as they are formed via a high shear processing method. The ingredients to "die for liposomes" are the unilamellar structure and offer high stability for the incorporation into personal care products. Liposomal encapsulation has been used for antioxidants based on vitamins A, C, and E their combinations with beta-carotene.		
PHYSICAL		
Color: golden, milky, yellow	**State**: solid/liquid dispersion	**Odor**: characteristic
Freezing point, ^{o}C: 0	**Boiling point**, ^{o}C: 100	**pH**: 4.5-6.5
ECOLOGICAL		
Aquatic toxicity, LC50, mg/l: *Daphnia magna* 682		
USE		
Manufacturers: Active Concepts, Adina, Aroma Alternatives Ltd, Formulator Sample Shop		
Outstanding properties: natural delivery system for lightening and evening skin tone; liposomal vitamin C is a technological breakthrough in nutrient assimilation and offers incredible health benefits. Vitamin C is one of the most widely recognized and used antioxidants in the world. This antioxidant plays a critical role in helping the immune system, joints, and arteries heal and function properly. The liposomes protect against degradation, which can be caused by direct exposure to UV rays and temperature changes. Vitamin E and beta-carotene protect cell membranes, while vitamin C removes free radicals from inside the cells.		
Recommended for products: cosmetics; skin care, hair care; in skin care products they act as antioxidants and antiaging		
Concentrations used: 1-10%		

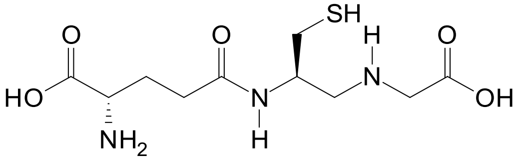
2.23 MITOCHONDRIA-TARGETED ANTIOXIDANTS

GENERAL		
Names: mitoquinol, mitoquinone mesylate, mitochondria-targeted antioxidants		
CAS #: 845959-50-4, 845959-55-9, 1569257-94-8		
Molecular weight: 528-680	**Biobased**: N	**Mixture**: N
Additional information: mitochondria are vital parts of human cells. They generate the majority of adenosine triphosphate, which supplies the energy to cells. Mitochondria are also involved in signaling between cells and cell death, otherwise known as apoptosis.		
PHYSICAL		
Color: brown, colorless, purple	**State**: semi-solid, solid	
Solubility: DMSO, ethanol, methanol		
Max. UV absorbance, nm: 268, 275, 290		
ECOLOGICAL		
Partition coefficient: >99		
USE		
Manufacturers: Cayman Chemical Co., ENZO, MedKoo Biosciences, Santa Cruz Biotechnology, Inc.		
Outstanding properties: mitochondria-targeted antioxidants protect against oxidative damage to the mitochondria. It has superoxide and alkyl radical scavenging properties. An antioxidant that targets the mitochondria in living cells to protect them from oxidative damage. Mitochondria are an essential organelle in most cells that use oxygen to break down molecular carbohydrates and fat to produce energy in the form of ATP. Antioxidants have undergone clinical trials in humans. Most recently it has been shown that those who take the antioxidant that specifically targets cellular powerhouses, or mitochondria, see age-related vascular changes reverse by the equivalent of 15 to 20 years within six weeks, according to new University of Colorado Boulder research. The antioxidant component of MitoQ is the same ubiquinone as found in Coenzyme Q10. The antioxidant prevents lipid peroxidation-induced apoptosis and protects mitochondria from oxidative damage.		

2.24 OIL-DERIVATIVES

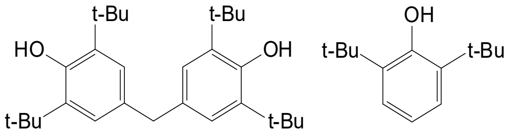
GENERAL		
Names: horseradish oil, krill oil, oil-derivatives, sunflower seed oil, wild carrot seed oil		
CAS #: 8001-21-6, 8015-88-1, 8016-13-5, 84775-62-2, 84929-61-3		
Biobased: Y		**Mixture**: Y
Additional information: triglyceride contains linoleic acid as the main component		
PHYSICAL		
Color: brown, orange, red, yellow		**State**: solid/liquid
Odor: carrot-like, fatty, mild, mustard, vanilla		**Freezing point**, °C: 5
Specific gravity: 0.88-1.15	**Solubility**: ethanol, oils	**Refractive index**: 1.39-1.50
HEALTH		
Autoignition temp., °C: 355	**Flash point**, °C: >65->260	**Carcinogenicity**: N
Mutagenicity: N	**RTECS #**: FI0790000	**LD50 oral rat**, mg/kg: 443,690
ECOLOGICAL		
Aquatic toxicity, LC50, mg/l: *Daphnia magna* >100; *Fathead minnow* 57; *Zebra fish* 10,000		
Partition coefficient: 22.9		
USE		
Manufacturers: Alban Muller, Flavex Naturextrakte GmbH, Floratech, MakingCosmetics Inc., Penta International Corporation, Schiff Nutrition		
Recommended for products: multi-functional cosmetic active ingredient for personal care product such as lip balms or make-up products; cosmetics, for sun protection cremes, in food and supplements as coloring and active ingredient		
Concentrations used: 0.01-5%		

2.25 PEPTIDES



GENERAL		
Names: glutathione, peptide, tripeptide		**CAS #**: 70-18-8, 49557-75-7
Molecular weight: 304-742	**Biobased**: N	**Mixture**: N
PHYSICAL		
Color: blue, white	**Odor**: faint, odorless	**State**: solid
Freezing point, °C: 192-195	**Specific gravity**: 1.32	
HEALTH		
Carcinogenicity: N	**RTECS #**: MC0556000	**LD50 oral rat**, mg/kg: >5000
USE		
Manufacturers: abcam, Biovision, Sinoway Industrial Co., Ltd.,		
Outstanding properties: exogenous antioxidants can convert free radicals into oxygen and water, neutralizing them. Scavenger of hydroxyl radicals reduces ROS, and forms disulfide bonds with cysteine residues of proteins. It protects against toxicity and disease. Stimulation of collagen and glycosaminoglycan synthesis in skin fibroblasts and promotion of blood vessels growth. Activates skin's main antioxidant protein – superoxide dismutase.		
Recommended for products: skin care cosmetics		

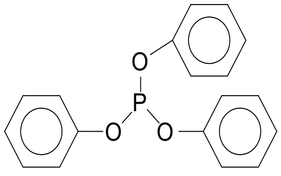
2.26 PHENOLICS

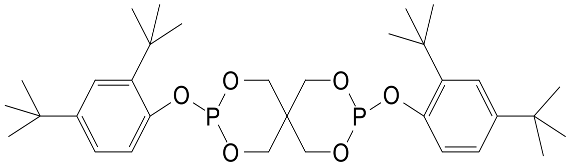


GENERAL		
Names: phenolics, sterically hindered phenolics		
CAS #: 77-62-3, 79-74-3, 85-60-9, 88-24-4, 118-82-1, 119-47-1, 128-39-2, 501-94-0, 991-84-4, 1709-70-2, 1843-03-4, 1879-09-0, 2082-79-3, 6683-19-8, 23128-74-7, 27676-62-6, 32687-78-8. 33145-10-7, 35074-77-2, 35443-68-2, 35958-30-6, 36443-68-2, 40601-76-1, 41484-35-9, 61167-58-6, 65140-91-2, 68610-51-5, 70331-94-1, 90498-90-1, 144429-84-5, 125643-61-0, 1261240-30-5, 504394-57-4		
Molecular weight: 138-1178	**Biobased**: N/Y	**Mixture**: Y/N
PHYSICAL		
Acid #, mg KOH/g: <1.0	**Ash**, %: 0.05-0.25	**Viscosity**, mPas: 200-650
pK$_a$: 11.48	**Freezing point**, °C: <-30->260	**Boiling point**, °C: 158-822
Color: amber, beige, colorless, cream, green, off-white, white, yellow		
State: solid/liquid	**Odor**: faint, kerosene-like, odorless, phenolic	
Specific gravity: 0.85-1.21	**pH**: 5.0-10.5	**Refractive index**: 1.49-1.58
Solubility: acetone, benzene, chloroform, cyclohexane, cyclohexanone, diethylether, dimethylacetamide, ethanol, ethyl acetate, heptane, MEK, methanol, methylene chloride, mineral oil, n-hexane, THF, styrene, toluene, xylene		
Thermogravimetric analysis, %/°C: 1/160; 10/180; 10/190; 25/210; 5-20/220; 1-10/230; 5/260; 20/278; 1/280; 10/288; 20/300; 5/310; 10/320; 10-40/340; 5-10/350; 10/365; 25/385; 25/387; 93/425, 95/500		
HEALTH		
Autoignition temp., °C: >250-500		**Flash point**, °C: 118-321
Carcinogenicity: N	**Mutagenicity**: N	**Teratogenicity**: N
RTECS #: DA8340900, DC3750000, PA3500000, SK8265000, SL9650000, SL9800000, SM0400000, SM1157000, ZE6825000		
UN #: 3077		
ECOLOGICAL		
Aquatic toxicity, LC50, mg/l: Algae 3-1000; *Bluegill sunfish* 43-100; *Daphnia magna* 0.45-1000; *Fathead minnow* 0.12; *Rainbow trout* 47-67: *Zebra fish* 74->1000		
Biodegradation probability: not readily to inherently biodegradable		
Bioconcentration factor: <2.3-840		**Partition coefficient**: -0.08-23

USE
Manufacturers: Addivant, Adeka, BASF, Chemtura, Chitec, Cytec, Dongguan Baoxu Chemical Technology.,ltd., Everspring Chemical Co., Ltd., Inabata, Oxiris chemicals, Schäfer Additivsysteme GmbH, Vanderbilt Chemicals
Recommended for polymers: ABS, BR, cellulosics, CPR, EMA, EPDM, EPM, EPR, EVA, HIPS, IP, IR, IIR, MABS, MBS, NBR, NR, PA, PB, PBT, PC, PE, PET, PMMA, POM, PP, PS, PU, PVB, PVC, PVDC, SB, SBR, SBS, SEBS, SEPS, SIS, SMA, TPE, TPU
Recommended for products: adhesives, alloys, automotive, biodiesel, building and construction, caps, coatings, cosmetics, dielectric films, engine oils, fats, fibers, film, foams, food packaging, fuel hoses, gaskets, gasoline, greases, hot melts, inner tubes, jet fuels, latex for carpet backing, lids, lubricants, medical devices, molded parts, oils, pharmaceuticals, pipes, plastics, rotomolding, sealants, seals, sheets, solar panels, tackifiers, tapes, textiles, tire cord, waxes, wire & cable
Concentrations used: 0.05-3

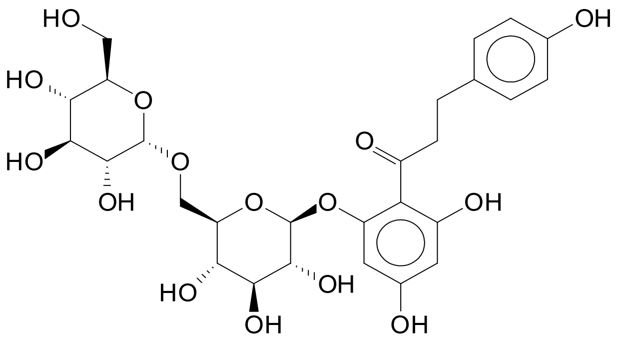
2.27 PHOSPHITES, DIPHOSPHITES, AND DIPHOSPHONITES





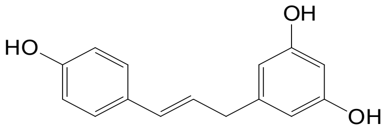
GENERAL		
Names: diphosphite, diphosphonites, phosphites		
CAS #: 101-02-0, 3050-88-2, 3806-34-6, 15647-08-2, 25448-25-3, 26523-78-4, 26544-23-0, 26741-53-7, 31570-04-4, 80584-86-7, 80693-00-1, 96152-48-6, 119345-01-6, 126050-54-2		
Molecular weight: 310-2100	**Biobased**: N	**Mixture**: N/Y
PHYSICAL		
Acid #, mg KOH/g: <0.1-<2	**Ash**, %: 0.05	**State**: liquid/solid
Color: colorless, off-white, white, yellow		**Boiling point**, °C: >280->400
Freezing point, °C: -20-240	**Odor**: faint, odorless, phenolic, pleasant	
Specific gravity: 0.89-1.184	**pH**: 6	**Refractive index**: 1.516-1.528
Solubility: acetone, cyclohexane, ethanol, n-hexane, methanol, toluene		
Thermogravimetric analysis, %/°C: 5/197; 10/217; 5/224; 10/250; 5/256; 10/271; 5-50/300; 50/325; 10/329; 50/360		
Viscosity, mPas: 10-4000		**Vapor density**: 10.7
HEALTH		
Autoignition temp., °C: 400-440		**Flash point**, °C: 108-380
Mutagenicity: N	**Carcinogenicity**: N	
RTECS #: TH1575000	**LD50 oral rat**, mg/kg: >2000->6000	
UN #: 3077, 3082		
ECOLOGICAL		
Aquatic toxicity, LC50, mg/l: *Daphnia magna* 524		
Partition coefficient: >6-18	**Biodegradation probability**: not readily biodegradable	
USE		
Manufacturers: Addivant, Adeka, BASF, Chitec, Songwon Industrial Co. Ltd.		
Recommended for polymers: ABS, EVA, HIPS, NBR, PA, PBT, PC, PE, PMMA, PP, PPO, PRT, PS, PU, PVC, rubber, SBC, SBS		
Recommended for products: adhesives, appliance, automotive, coatings, engineering plastics, films, foams, food packaging, hot melts, wire and cable		

2.28 POLYPHENOLS



GENERAL		
Names: caffeic acid, epigallocatechin gallate, neochlorogenic acid, phloridzinyl glucoside, polyphenols		
CAS #: 331-39-5, 906-33-2, 989-51-5, 1232681-33-2		
Molecular weight: 180-599	**Biobased**: Y	**Mixture**: Y
PHYSICAL		
State: solid	**Color**: off-white, tan, white, yellow	
Odor: characteristic	**pK$_a$**: 4.62	**Boiling point**, °C: 317-945
Freezing point, °C: 106-350	**Specific gravity**: 1.478-1.86	**Refractive index**: 1.71
Solubility: chloroform, DMF, DMSO, ethanol, ethyl acetate, hexane, methanol		
HEALTH		
Flash point, °C: 198-414		**RTECS #**: GD8950000
ECOLOGICAL		
Partition coefficient: -1.77 to 1.065		
USE		
Manufacturers: Coompo Research Chemicals, Santa Cruz Biotechnology, Inc., Seppic		
Recommended for products: multi-functional cosmetic active ingredient for personal care products, skin care, anti-aging, soothing, free radical scavenging, anti-oxidant products, pharmaceuticals, supplements for boosting athletic performance, dietary supplements		
Concentrations used: 0.1-2%		

2.29 STILBENE DERIVATIVES

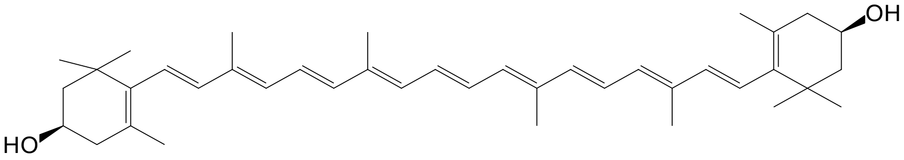


GENERAL		
Names: stilbene derivatives		**CAS #**: 501-36-0
Molecular weight: 228	**Biobased**: Y	**Mixture**: N
Additional information: can be obtained from skin of grapes, blueberries, raspberries, mulberries, peanuts		
PHYSICAL		
Color: white, yellow	**State**: solid/liquid	**Odor**: characteristic
Freezing point, °C: 261-263	**Specific gravity**: 1.0-1.1	**pH**: 5-9
USE		
Manufacturers: Sinoway Industrial Co., Ltd.		
Recommended for products: dietary supplements, medicine, health care products, food, cosmetics and other fields.		
Concentrations used: 1-5%		

2.30 SULFUR-CONTAINING COMPOUNDS

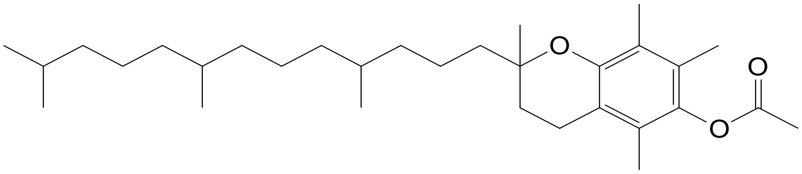
GENERAL		
Names: dibutyldithiocarbamate, molybdenum-sulfur combination, sulfur-based, sulfur-containing phenolic, zinc diamyldithiocarbamate		
CAS #: 10254-57-6, 15337-18-5, 41484-35-9, 110553-27-0		
Molecular weight: 423-642	**Biobased**: N	**Mixture**: N/Y
PHYSICAL		
State: liquid/solid	**Color**: amber, green, off-white, white, yellow	
Freezing point, °C: 14- >63	**Specific gravity**: 0.97-1.12	**Odor**: mild, odorless
Viscosity, mPas: 13-85	**pH**: 6.4	
Solubility: chloroform, DMSO, ethanol, ethyl acetate, n-hexane, methanol, methylene chloride, petroleum, toluene		
HEALTH		
Autoignition temp., °C: 330	**Flash point**, °C: 135-191	**LD50 oral rat**, mg/kg: >5000
ECOLOGICAL		
Aquatic toxicity, LC50, mg/l: *Bluegill sunfish* >100		**Partition coefficient**: 10.5
Bioconcentration factor: does not significantly accumulate in organisms		
USE		
Manufacturers: BASF, Vanderbilt Chemicals		
Recommended for polymers: ABS, BR, EPDM, EPR, IR, MBS, NBR, NR, PA, PE, POM, PS, PU, PVC, SB, SBR, SBS, SIS		
Recommended for products: adhesives, compressor and gear oil, grease, hydraulic oil, lubricants, oils, plastics, sealants, turbine oil, wire & cable		
Concentrations used: 0.05-1%		

2.31 TERPENOIDS



GENERAL		
Names: astaxanthin, carothene, β-cryptoxanthin, lutein, terpenoids, xantophyll		
CAS #: 127-40-2, 472-61-7, 472-70-8		
Molecular weight: 552-597	**Biobased**: Y	**Mixture**: Y/N
Additional information: lutein is a xanthophyll isolated from the herbs of Tagetes erecta (Marigold Flower Extract), as well found in leafy vegetables, such as kale, spinach, turnip greens, collard greens, romaine lettuce, watercress, swiss chard, and mustard greens. natural astaxanthin obtained from the microalgae, haematococcus pluvialis, is a natural carotenoid that can be found in arctic marine environments, it gives the pink and red color to salmon, shrimp, and lobster. Cryptoxanthin can be isolated from fruits such as papaya and oranges.		
PHYSICAL		
Ash, %: ≤5.0%	**State**: solid	**Color**: orange, red, yellow
Freezing point, °C: 169-216	**Boiling point**, °C: 774	**Specific gravity**: 0.974-1.071
Solubility: acetone, benzene, chloroform, DMF, hexane, oil, pyridine		
HEALTH		
RTECS #: CJ1310000		
USE		
Manufacturers: AstaReal Co. Ltd, Cayman Chemical, Santa Cruz Biotechnology, Inc., Sinoway Industrial Co., Ltd.		
Outstanding properties: lutein prevents cardiovascular sclerosis, coronary heart disease caused by aging and tumor diseases. Astaxanthin is the most powerful antioxidant and anti-inflammatory known to science. Provides unique membrane protection because with its long-chain structure and polar end groups can span the bilayer membrane incrementing resilience against oxidative stress. Astaxanthin quenches free radicals both in the water and fat-loving zone of the membrane in contrast to most antioxidants, which work either in the inner (Vitamin E and beta-carotene) or outer (Vitamin C) side of the membrane. Antioxidant activity of cryptoxanthin may help in preventing free radical damage to cells and DNA, as well as stimulate the repair of oxidative damage to DNA. Potential chemopreventative agent against lung cancer as well as other types of cancer.		
Recommended for products: cosmetics, health care products, medicine		

2.32 TOCOPHEROLS



GENERAL		
Names: alpha-tocopherol, tocopherol acetate, tocopherols		
CAS #: 59-02-9, 1406-18-4, 7695-91-2, 10191-41-0		
Molecular weight: 430-472	**Biobased**: Y/N	**Mixture**: Y/N
PHYSICAL		
Acid #, mg KOH/g: 1-<2	**Color**: amber, brown, colorless, yellow	
Freezing point, °C: <-20-27.5	**State**: liquid	**Boiling point**, °C: >255-343
Specific gravity: 0.88-0.98	**Odor**: fatty, odorless, oily, slight	
Solubility: DMSO, DMF, methylene chloride, oils		**Refractive index**: 1.45-1.506
Viscosity, mPas: 4200-5200		
HEALTH		
Autoignition temp., °C: 382-420		**Carcinogenicity**: N
Flash point, °C: 82.5->260	**LD50 oral rat**, mg/kg: >2000->10000	
RTECS #: DJ2900000, GA8746000		**Mutagenicity**: N
ECOLOGICAL		
Aquatic toxicity, LC50, mg/l: Algae ; *Bluegill sunfish* ; *Daphnia magna* >20.6-500; *Fathead minnow* ; *Rainbow trout* >100: *Zebra fish*		
Biological oxygen demand: 70-80% BOD of the ThOD (63 days)		
Partition coefficient: >6 to 22.9		
USE		
Manufacturers: ADM, Alban Muller, BASF, Cayman Chemical, Floratech, SigmaAldrich		
Recommended for products: antioxidant for food products, cosmetic products for sun care protection, film, food packaging, medical, the multi-functional cosmetic active ingredient for personal care product, supplement		
Concentrations used: 0.01-1%		

3

PHYSICS AND CHEMISTRY OF OXIDATION AND ANTIOXIDANTS

The principles of photophysics and photochemistry can be found in two separate chapters, elsewhere.[1] In this chapter, peculiarities of oxidation and its prevention by antioxidants are discussed for different groups of antioxidants. The focus of the evaluation of research findings is on the mechanism of action of antioxidants, their stability, and eventual methods of its improvement.

3.1 ACIDS

This section will be the best illustrated by the reactions of phenolic acids, which form a popular group of acids used as antioxidants. Their major representatives include caffeic, coumaric, ellagic, ferulic, gallic, salicylic, and sinupic acids and their esters. They act in a similar manner to other phenolic compounds, protecting components in the neighborhood by three different mechanisms:[2]

hydrogen atom transfer from phenolic acid to radical

$$\mathrm{PhOH} + \dot{\mathrm{R}} \longrightarrow \mathrm{PhO}^{\cdot} + \mathrm{RH}$$

electron-proton transfer

$$\mathrm{PhOH} + \dot{\mathrm{R}} \longrightarrow \mathrm{PhOH}^{+\cdot} + \mathrm{R}^{\ominus} \longrightarrow \mathrm{Ph}\dot{\mathrm{O}} + \mathrm{RH}$$

sequential proton loss-electron transfer

$$\mathrm{PhOH} \longrightarrow \mathrm{PhO}^{\ominus} + \mathrm{H}^{\oplus}$$
$$\mathrm{PhO}^{\ominus} + \dot{\mathrm{R}} \longrightarrow \mathrm{Ph}\dot{\mathrm{O}} + \mathrm{R}^{\ominus}$$
$$\mathrm{R}^{\ominus} + \mathrm{H}^{\oplus} \longrightarrow \mathrm{RH}$$

The radical scavenging activities of phenolic antioxidants are related to the phenolic O-H bond dissociation enthalpy, ionization potential, proton dissociation enthalpy, proton affinity, and electron transfer enthalpy.

Table 3.1 contains information on the O-H bonds dissociation enthalpies of phenolic acids.

Table 3.1. The O–H bonds dissociation enthalpies of phenolic acids. [Data from ref. 2].

Acid	Enthalpies in different media, kcal/mol			
	gas	benzene	ethanol	water
gallic acid				
3-OH	77.9	78.5	79.2	79.3
4-OH	78.0	77.7	77.0	76.9
5-OH	85.9	84.6	82.8	82.7
caffeic acid				
3-OH	85.4	84.1	82.2	82.0
4-OH	7.37	74.3	75.1	75.2
salicylic acid				
2-OH	92.4	108.5	89.7	89.3
ferulic acid				
4-OH	82.1	81.1	79.4	79.2

The ionization potentials of selected acid are given in Table 3.2.

Table 3.2. The ionization potential of phenolic acids. [Data from ref. 2].

Acid	Enthalpies in different media, kcal/mol			
	gas	benzene	ethanol	water
gallic acid	185.9	159.1	125.1	116.9
caffeic acid	182.5	156.0	121.8	113.6
salicylic acid	196.9	168.4	133.2	125.0
ferulic acid	177.7	152.3	119.2	111.1

The proton dissociation enthalpies of selected acid are given in Table 3.3.

Table 3.3. The proton dissociation enthalpies of phenolic acids. [Data from ref.2].

Acid	Enthalpies in different media, kcal/mol			
	gas	benzene	ethanol	water
gallic acid				
3-OH	203.4	38.9	-3.1	3.8
4-OH	203.6	38.1	-5.3	1.4
5-OH	211.5	45.1	0.6	7.2
caffeic acid				
3-OH	218.1	50.5	5.4	12.0
4-OH	206.4	40.7	-1.6	5.2
salicylic acid				
2-OH	210.7	61.0	1.5	7.9
ferulic acid				
4-OH	219.6	49.1	5.2	11.7

The proton affinities of selected acid are given in Table 3.4.

Table 3.4. The proton affinity of phenolic acids. [Data from ref.2].

Acid	Proton affinities in different media, kcal/mol			
	gas	**benzene**	**ethanol**	**water**
gallic acid				
3-OH	327.7	88.8	35.1	39.4
4-OH	328.0	88.2	33.2	37.4
5-OH	342.7	100.4	41.8	45.6
caffeic acid				
3-OH	339.2	99.1	42.3	46.2
4-OH	318.6	82.4	31.1	35.6
salicylic acid				
2-OH	341.8	99.7	42.5	46.4
ferulic acid				
4-OH	331.2	92.8	38.1	42.2

The electron transfer enthalpies of selected acid are given in Table 3.5.

Table 3.5. The electron transfer enthalpies of phenolic acids. [Data from ref.2].

Acid	Enthalpies in different media, kcal/mol			
	gas	**benzene**	**ethanol**	**water**
gallic acid				
3-OH	65.4	83.5	89.1	87.3
4-OH	66.3	83.1	88.8	87.1
5-OH	58.4	80.7	86.1	81.9
caffeic acid				
3-OH	61.5	79.4	84.9	82.6
4-OH	70.3	83.3	89.1	89.5
salicylic acid				
2-OH	65.8	86.5	92.3	106.4
ferulic acid				
4-OH	66.1	80.6	86.3	85.9

The above data for 20 phenolic acids (available elsewhere)[2] led to the conclusion that the extended delocalization and intra-molecular hydrogen bonds are the two main contributions to the stability of the radicals.[2] The C=O or C=C in COOH, COOR, C=CCOOH, and C=CCOOR groups, and ortho-diphenolic functionalities were stabilizing the specific radical species to enhance the radical scavenging activities, while the presence of the single OH in the ortho position of the COOH group disfavored the activities.[2] The hydrogen atom transfer mechanism was thermodynamically preferred in the gas phase and benzene, whereas the sequential proton loss-electron transfer mechanism was preferred in water and ethanol (see chemical equations above).[2]

In the case of hydroxycinnamic acid, the electron-donating groups (−OH, $-OCH_3$) in the ortho- or para-positions of 4-OH governed kinetic processes in methanol by the sequential proton loss electron transfer, unlike in ethyl acetate in which the preferred reaction mechanism was that of hydrogen atom transfer.[3] According to still another contribution, gallic acid followed an electron transfer mechanism, but its antiproliferative activity also depended on its excellent absorption capacity and hydrophilic nature.[4]

Ferulic acid is a free radical scavenger, but also an inhibitor of enzymes, catalyzing free radical generation, and enhancing scavenger enzyme activity.[5] Ferulic acid has a protective role for the main skin structures: keratinocytes, fibroblasts, collagen, and elastin.[5]

Caffeic acid acted as both a metal chelator and as a hydrogen donor, preventing the deleterious action promoted by free radicals.[6]

The synthetic phenolics participate in the formation of a phenolic radical which neither rapidly catalyzes the oxidation of other unsaturated fatty acids nor reacts with oxygen to form antioxidant hydroperoxides which decompose into free radicals.[7] Synthetic phenolic radicals can potentially react with each other forming phenolic dimers.[7] The phenolic radicals can also react with other peroxyl radicals in termination reactions resulting in the formation of phenolic-peroxyl species adducts.[7] The oxidized synthetic phenolic undergoes numerous degradation reactions forming compounds that contain active hydroxyl groups capable of further scavenging free radicals.[7] The net antioxidant activity of synthetic phenolics in food depends on the activity of the original phenolic and some of its degradation products.[7]

The *cis*-ferulic acid and *trans*-ferulic acid (including less energetic rotamers) displayed similar antioxidant reactivities.[8] The planar structure of ferulic acid supported by π-electron delocalization influenced its ability to neutralize free radicals.[8] The hydrogen atom transfer was the preferable mechanism in the gas-phase, and the sequential proton loss electron transfer was preferred in polar media.[8] Schematic diagram of the reaction of ferulic action with radicals is given in Figure 3.1.

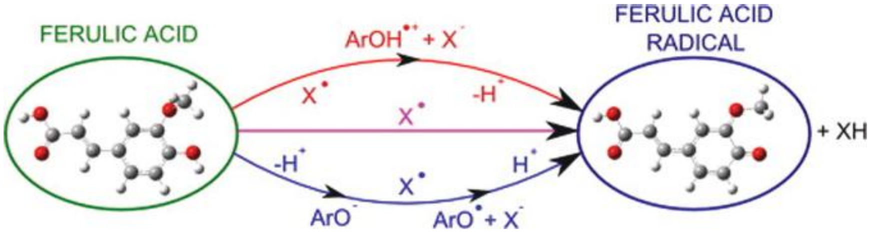


Figure 3.1. Antioxidant activity of ferulic acid. [Adapted, by permission, from Urbaniak, A; Szeląg, M; Molski, M, *Comput. Theor. Chem*., **1012**, 33-40, 2013.]

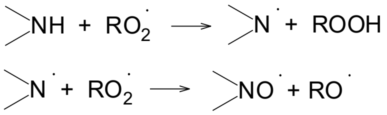
References

1 Wypych, G, **Handbook of Materials Weathering**, 6th Edition, *ChemTec Publishing*, Toronto, 2018.
2 Chen, Y; Xiao, H; Zheng, J; Liang, G, *PlosOne*, Mar. 24, 2015.
3 Shang, Y-J; Liu, B-Y; Zhao, M-M, *Czech J. Food. Sci*., **33**, 210-6, 2015.
4 Velderrain-Rodríguez, GR; Torres-Moreno, H; Villegas-Ochoa, MA; Ayala-Zavala, JF;

Robles-Zepeda, RE; Wall-Medrano, A; González-Aguilar, GA, *Molecules*, **23**, 695, 2018.
5 Zduńska, K; Dana, A; Kolodziejczak, A; Rotsztejn, H; *Skin Pharmacol. Physiology*, 31. 332-6, 2018.
6 Magnani Spagnol, C; Pires Assis, R; Lourenço Brunetti, I; Borges Isaac, VL; Corrêa, MA, *Spectrochim. Acta Part A: Molec. Biomolec. Spectroscopy*, **219**, 358-66, 2019.
7 Decker, EA; Chen, B; Panya, A; Elias, RJ, **Oxidation in Foods and Beverages and Antioxidant Applications. Understanding Mechanisms of Oxidation and Antioxidant Activity**, *Woodhead Publishing*, 2010, pp. 225-48.
8 Urbaniak, A; Szeląg, M; Molski, M, *Comput. Theor. Chem*., **1012**, 33-40, 2013.

3.2 AMINES

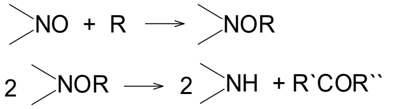
The mechanism of the antioxidant action of diarylamines based on radicals formation originated in the late 1960s, followed a few years later with understanding the differences in the mechanism at lower and higher temperatures.[1] According to the present understanding, the diarylamine is first oxidized by a peroxyl radical[1]



$$>NH + RO_2^{\cdot} \longrightarrow >N^{\cdot} + ROOH$$

$$>N^{\cdot} + RO_2^{\cdot} \longrightarrow >NO^{\cdot} + RO^{\cdot}$$

From reaction with alkyl radical N-alkoxydiarylamine is formed which is unstable at higher temperatures and decomposes to complete the inhibition cycle[1]



$$>NO + R \longrightarrow >NOR$$

$$2 >NOR \longrightarrow 2 >NH + R`COR``$$

One complete inhibition cycle traps two radicals (one peroxyl and one alkyl).[1] At high temperatures, the rate-determining step is not the hydrogen transfer but the subsequent regeneration of the amine *via* N–O homolysis and in-cage disproportionation.[1] There is a difference in behavior between low temperatures (where the protection is non-catalytic with low stoichiometric factors for inhibition) and high temperatures (above 100°C), where the protection becomes catalytic (high stoichiometric factors).[1]

The stability and efficiency of these antioxidants depend on the completeness of conversion to the original structure and on the side reactions in which non-radical products are produced stopping the catalytic inhibition chain, but these products (>NOR) can still contribute to inhibition producing nitroxide radicals which may eventually return to work in inhibition chain.[1]

Antioxidant effectiveness is negatively affected by non-nitrogen heteroatoms (O, S, and Br). Only molecules containing nitrogen atoms with NMR chemical shifts under −277 ppm have been usable as antioxidants.[2] The critical electron density at nitrogen atoms of the operating antioxidant is crucial for the catalytic inhibition.[2] A necessary (but not sufficient) condition for a hydrogen atom transfer from an antioxidant N atom to a $ROO^{\cdot}$ peroxyl radical is the higher value of the N–H bond dissociation enthalpy than that of the ROO–H (~88 kcal/mol).[2] Another necessary condition for the "catalytic cycle" with the eventual capture of many radicals (included in Denisov cycle) is the stability of the corresponding N-alkoxyamine.[2]

Autoxidation, photooxidation, thermal, and enzymatic oxidation are the major oxidative processes that cause quality deterioration in biodiesel fuels.[3] The formation of nitroxides and benzoquinone imines are responsible for the antioxidant properties of secondary aromatic amines.[3] Primary aromatic amines have no antioxidant properties because they do not generate nitroxides.[3] The tertiary amines are oxidation promoters rather than inhibitors.[3] The use of aromatic amines as stabilizers in biodiesel is less popular because most of the aromatic amines tend to discolor the substrates as oxidation progresses.[3] However, the secondary aromatic amines have many advantages over phenolic antioxidants.[3] The hydrogen-donating ability of aromatic amine is superior to phenols because the N−H bond in aromatic amine is not as strong as the O−H bond of phenols.[3] The hindered phenolic antioxidants trap only two peroxyl radicals per molecule, whereas secondary aromatic amines can scavenge 50 (alkylated diphenylamines) to 500 (hindered cyclic secondary amine derivatives) peroxyl radicals per molecule even at 130°C.[3] The aromatic amine antioxidants follow a cyclic process in which a nitroxyl radical is regenerated and consumes more radicals; therefore, one molecule of the aromatic amine can trap a large number of peroxyl radicals before the nitroxyl radical is destroyed, which lowers the required quantity of antioxidant.[3]

Amine- and phenolic-based antioxidants combinations showed synergistic activity in biodiesel stabilization.[4]

Hindered amine liquid stabilizers (HALS or HAS) are common UV stabilizers used in polymeric materials. They perform all essential functions expected from antioxidants, including scavenging and deactivation of radicals, recovery of initial structure (Denisov cycle), reaction with ozone, energy transfer, peroxide decomposition, and thermal stabilization. Extensive discussion of their properties, mechanisms of action, and stability in various systems was included in monographic sources.[5,6]

The 5-hydroxyindole exhibited long induction period, 1.7 times that of BHT.[7] The rates of oxidation during the induction period correlated with the dissociation energies of the N–H bond.[7]

Twenty amino acids had antioxidant activities in soybean oil heated to 180°C.[8] Amino acids with thiol, thioether, or amine groups had higher antioxidant activity.[8] Amino acids with amide, carboxylic acid, imidazole, or phenols had lower activity.[8] Antioxidant activity increased with increasing hydrophobicity.[8]

References

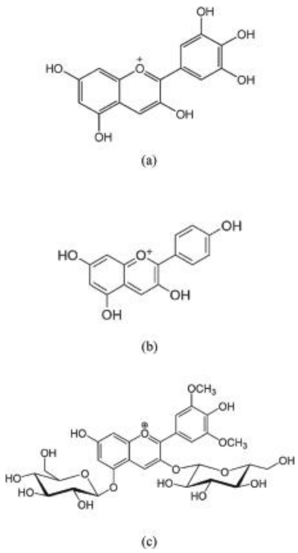
1 Puškárová, I; Šoral, M; Breza, M, *Polym. Deg. Stab.*, **130**, 189-93, 2016.
2 Puškárová, I; Šoral, M; Breza, M, *Polym. Deg. Stab.*, **144**, 1-6, 2017.
3 Varatharajan, K; Pushparani, DS, *Renewable Sustainable Energy Rev.,* **82**, 3, 2017-28, 2018.
4 van der Westhuizen, I; Focke, WW, *Fuel*, **219**, 126-31, 2018.
5 Wypych, G, **Handbook of Materials Weathering**, 6th Edition, *ChemTec Publishing*, Toronto, 2018.
6 Wypych, G, **Handbook of UV Degradation and Stabilization**, 3rd Edition, *ChemTec Publishing*, Toronto, 2020.
7 Nishiyama, T; Suzuki, T; Hashiguchi, S; Shiotsu, S; Fujioka, M, *Polym. Deg. Stab.*, **75**, 3, 549-54, 2002.
8 Hwang, H-S; Winkler-Moser, JK, *Food Chem*., **221**, 1168-77, 2017.

3.3 ANTHOCYANIDINS

The anthocyanidin ethyl acetate extract was capable of reducing cell proliferation and inducing apoptotic death of lymphoid tumor cells.[1]

Pelargonidin was the most efficient anthocyanidin against hydroxyl radicals.[2] Slightly reduced activity of malvin have been associated with glycosylation, which decreased the antiradical capacity of anthocyanins by reducing the coplanarity to the rings.[2] Structures of anthocyanidins are presented in Figure 3.2.

Malvidin-3-0-glucoside (malvidin), an anthocyanidin, is highly present in red grape skin and red wine. Its biological activity is poorly characterized, although a role in tumor cell inhibition has been found.[3] Malvidin also has a cardioprotective performance due to its antioxidant, vasodilator, anti-inflammatory, anti-fibrotic, anti-apoptotic, and metabolic properties.[3]



(a)

(b)

(c)

Figure 3.2, Chemical structures. [Adapted, by permission, from Dimitrić Marković, JM; Pejin, B; Milenković, D; Amić, D; Marković, ZS, *Food Chem*., **218**, 440-6, 2017.]

References

1 Papademetrio, DL; Trabucchi, A; Cavaliere, V; Ricco, R; Álvarez, E, *Rev. Brasileira de Farmacognosia*, **23**, 3, 455-63, 2013.
2 Dimitrić Marković, JM; Pejin, B; Milenković, D; Amić, D; Marković, ZS, *Food Chem*., **218**, 440-6, 2017.
3 Quintieri, AM; Baldino, N; Filice, E; Seta, L; Angelone, T, *J. Nutritional Biochem.*, **24**, 7, 1221-31, 2013.

3.4 ASCORBATES

Ascorbic acid, commonly known as vitamin C, is a water-soluble ketolactone, which exists in most vegetables and fruits.[1] Ascorbic acid is employed in food processing, pharmaceutical, and cosmetics.[1]

Ascorbic acid is a strong antioxidant, which reacts with hydroperoxide according to the following reaction:[2]

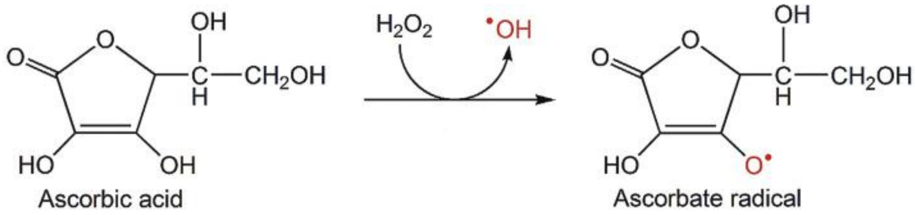


Figure 3.3. The reaction between ascorbic acid and hydrogen peroxide produces hydroxyl and ascorbate radicals. [Adapted, by permission, from Jing, Y; Diao, Y; Yu, X, *Reactive Functional Polym*., **135**, 16-22, 2019.]

Prevention of cancer risks against oxidative damage was achieved at lower doses of vitamin C, but, at high doses, reactive oxygen species, cytotoxicity, and apoptosis have been generated.[3]

Ascorbic acid has oxidative and reactive properties, which can cause problems of degradation and instability in food systems, leading to undesirable modifications in sensory properties of color and taste.[4] Encapsulated in solid lipid microparticles gradually released ascorbic acid in an aqueous medium, following Higuchi kinetics. Encapsulated ascorbic acid can be used for a controlled release.[4]

Conformers with minimal intramolecular stabilization had the lowest energies of deprotonation while conformers exhibiting multiple hydrogen bonds had larger energies of deprotonation.[5] The higher energy conformations are favored in the deprotonation of the ascorbic acid antioxidant mechanism of action.[5]

The vitamin occurs in 3 isomeric forms, including L-ascorbic acid, D-arabo-ascorbic acid, and L-arabo–ascorbic acid (L- ascorbic acid is produced commercially).[6] Ascorbic acid is synthesized by almost all higher plant species.[6] Animals having the capacity to oxidize L-gulono-1,4-lactone can synthesize ascorbic acid.[6] Three different biosynthetic pathways have been proposed for ascorbic acid synthesis in plants.[6] Ascorbic acid prevents plants from oxidative damage.[6] It is involved in the response of plants to all the stresses, such as drought, salt, chilling and heat stress, metals, and ozone stress.[6]

Storage of maize starch encapsulated ascorbyl palmitate at 40°C under both dark and UV radiation conditions did not affect the amount released and the ability to scavenge the free radicals.[7] The antioxidant activity of free ascorbyl palmitate exponentially decreased at 40°C under UV radiation condition.[7]

Ascorbyl palmitate and sodium ascorbyl phosphate differ in stability and hydro-lipophilic properties.[8] They are widely used in cosmetic and pharmaceutical preparations.[8] High concentrations of ascorbyl palmitate reduced the extent of its degradation.[8] Light accelerated the degradation of ascorbyl palmitate.[8] Sodium ascorbyl phosphate was stable in microemulsions.[8]

Stability of ascorbyl palmitate in nanoemulsions was improved by oil-loaded solid lipid nanoparticle.[9] Higher lipid concentrations, and hydrogenated phospholipid in dispersions offered better protection. After one month there was still 85% of non-degraded ascorbyl palmitate in the formulation.[9]

The skin protects itself from oxidative stress, generated by sunlight and pollution, with enzymic and nonenzymic antioxidants.[10] The major nonenzymic antioxidants include L-ascorbic acid, glutathione, α-tocopherol, and ubiquinone/ubiquinol. L-ascorbic acid protects the aqueous space and is the most plentiful antioxidant in the skin.[10] Reduced ascorbic acid can be regenerated by glutathione.[10] The ascorbyl-6-palmitate, in comparison to L-ascorbic acid, is toxic to keratinocytes in the presence of ultraviolet B.[10] Ascorbyl-6-palmitate may be oxidized, generating the corresponding ascorbyl free radical.[10] In the aqueous phase, ascorbyl free radical is relatively weak, and it would be readily reduced by other aqueous phase antioxidants. In the membrane, however, it may cause irreversible damage before it is reduced.[10]

Ascorbyl palmitate is readily and reversibly oxidized to dehydroascorbic palmitate. When the dehydroascorbic lactone ring is irreversibly opened, giving rise to 2,3-diketo-gulonic palmitate, the antioxidant activity is lost (Figure 3.4).[11]

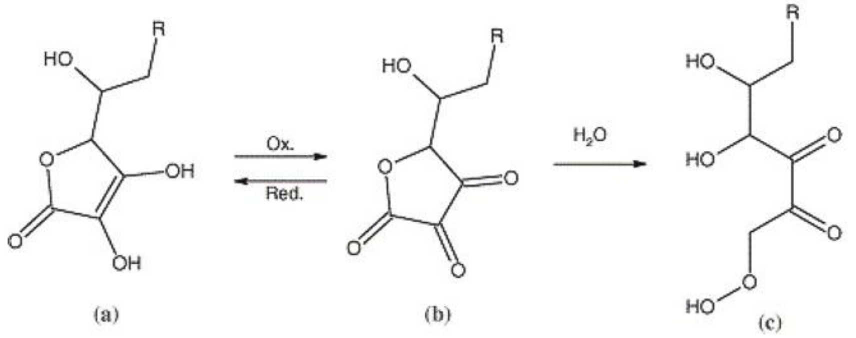


Figure 3.4. Degradation of ascorbyl palmitate (a) into dehydroascorbic acid (b) and 2,3-diketo-gulonic acid (c). R represents the palmitoyl residue. [Adapted, by permission, from Giuffrida, F; Destaillats, F; Herrero Egart, M; Hug, B; Dionisi, F, *Food Chem*., **101**, 3, 1108-14, 2007.]

Several antioxidant mechanisms have been proposed to explain the role of ascorbic acid/ascorbyl palmitate in oils.[12] They include singlet oxygen quenching, metal chelating, and free-radical-scavenging potentially resulting in regeneration of oxidized tocopherols.[12] During the synergistic interaction of α-tocopherol-ascorbyl palmitate, tocopherols are spared at the expense of ascorbyl palmitate during oxidation.[12] Ascorbyl palmitate is used to regenerate tocopherols.[12] Ascorbyl palmitate donates hydrogen to the tocopheroxyl radical formed by α-tocopherol, donating hydrogen to the lipid radical.[12]

To determine whether the uptake of ascorbic acid increased the antioxidant activity cells, the reactive oxygen species were generated by UV-B exposure.[13] The UV-B exposure increased the intracellular content of peroxides as monitored by measuring the fluorescent emission of 2′,7′-dichlorofluorescein.[13] Cells exposed to exogenous ascorbate 2-phosphate were able to prevent the increase in intracellular peroxides induced by UV-B completely.[13]

References

1 Cao, M Hou, Y; Zhang, E; Tu, S; Xiong, S, *Chemosphere*, **229**, 200-5, 2019.
2 Jing, Y; Diao, Y; Yu, X, *Reactive Functional Polym*., **135**, 16-22, 2019.
3 de Carvalho Melo-Cavalcante, AA; da Rocha Sousa, L; Oliveira Barros Alencar, MV; de Oliveira Santos, JV; de Castro e Sousa JM, *Biomedicine Pharmacotherapy*, **109**, 1394-405, 2019.
4 dos Santos Carvalho, J; Boesso Oriani, V; Marangoni de Oliveira, G, Dupas Hubinger, M, *LWT*, **101**, 306-14, 2019.
5 Juhasz, JR; Pisterzi, LF; Gasparro, DM Almeida, DRP; Csizmadia, IG, *J. Mol. Struct.: THEOCHEM*, **666-667**, 401-7, 2003.
6 Kaur, R; Nayyar, H, **Oxidative Damage to Plants. Antioxidant Networks and Signaling. Ascorbic Acid: A Potent Defender Against Environmental Stresses**, *Academic Press*, 2014, pp 235-87.
7 Bamidele, OP; Emmambux, MN, *Carbohydrate Polym*., **216**, 217-23, 2019.
8 Špiclin, P; Gašperlin, M; Kmetec, V, *Int. J. Pharm.*, **222**, 2, 271-9, 2001.
9 Grabnar, PA; Zajc, N; Kristl, J, *J. Drug Delivery Sci. Technol.*, **16**, 6, 443-8, 2006.
10 Pinnell, SR, J. *Investigative Dermatol.*, **119**, 5, 991, 2002.
11 Giuffrida, F; Destaillats, F; Herrero Egart, M; Hug, B; Dionisi, F, *Food Chem*., **101**, 3, 1108-14, 2007.
12 Karabulut, I, *Food Chem*., **123**, 3, 622-7, 2010.
13 Savini, I; D’Angelo, I; Ranalli, M; Melino, G; Avigliano, M, *Free Radical Biol Med.,* **26**, 9-10, 1172-80, 1999.

3.5 BENZOFURANONES

Figure 3.5 shows the mechanism of action of benzofuranone.

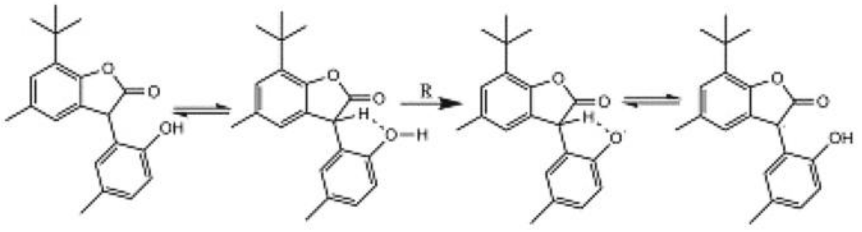


Figure 3.5. Antioxidant mechanism of benzofuranone in the presence of intramolecular hydrogen bonding. [Adapted, by permission, from Meng, X; Xin, Z; Wang, X-f, *Polym. Deg. Stab.*, **95**, 10, 2076-81, 2010.]

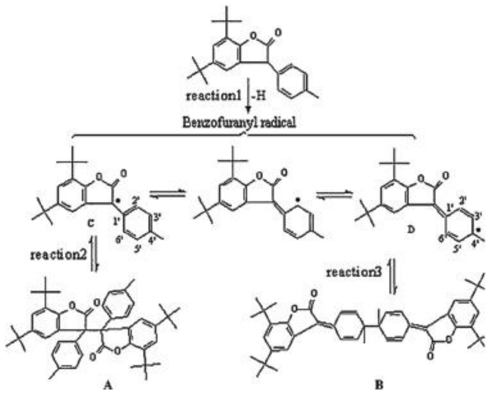


Figure 3.6. Benzofuranyl radicals. [Adapted, by permission, from Meng, X; Gong, W; Xin, Z; Cai, Z, *Polym. Deg. Stab.*, **91**, 12, 2888-93, 2006.]

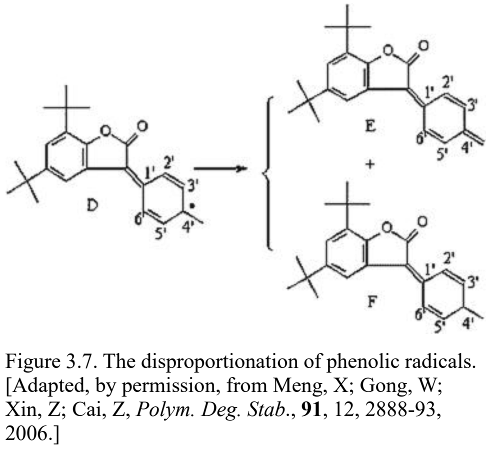


Figure 3.7. The disproportionation of phenolic radicals. [Adapted, by permission, from Meng, X; Gong, W; Xin, Z; Cai, Z, *Polym. Deg. Stab.*, **91**, 12, 2888-93, 2006.]

Structure affects the antioxidant activity of benzofuranone compounds.[1] Benzofuranone compounds substituted by a strong electron-donating substituent are better than the benzofuranone compounds substituted by a weak electron-donating substituent.[1] The hydrogen bonding makes the hydrogen of the hydroxyl group in 2′-position more reactive.[1] The hydrogen bonding can offset the steric hindrance of the hydroxyl group to some extent and enhance the antioxidant activity.[1]

The formation of antioxidative products due to the dimerization (Figure 3.6) and disproportionation (Figure 3.7) of benzofuranyl radicals is the main reason that induces the discoloration of stabilized polypropylene.[2] The benzofuranyl radicals C after hydrogen donation can react with themselves to form dimerization products A and in a similar process the radicals D form dimerization products B (Figure 3.6).[2]

The formation of products E and F with conjugated structure from radical D due to disproportionation of benzofuranyl radicals induced the discoloration of stabilized polypropylene.[2] Products B, E, and F are the main products that induce the discoloration of stabilized polypropylene.[2]

The hydrogen donation kinetics of four 3-aryl-benzofuranones with different chemical structures toward tert-butoxy radicals were studied using laser flash photolysis technique.[3] The position of the substituted methyl group has a very important effect on the hydrogen donating ability of benzofuranone toward tert-butoxy radicals.[3] If the methyl group was in 2′-position, the hydrogen donation of 3-aryl-benzofuranone toward tert-butoxy radicals was prevented, and the hydrogen donating ability was weakened.[3]

References

1 Meng, X; Xin, Z; Wang, X-f, *Polym. Deg. Stab.*, **95**, 10, 2076-81, 2010.
2 Meng, X; Gong, W; Xin, Z; Cai, Z, *Polym. Deg. Stab*., **91**, 12, 2888-93, 2006.
3 Meng, X; Xin, Z; Li, Y; Cai, Z, *Polym. Deg. Stab*., **92**, 1, 184-8, 2007.

3.6 BENZIMIDAZOLES

Zinc dimethacrylate and 2-sulfur-benzimidazole/N-4(phenyl–phenyl)-maleimide were simultaneously used as synergistic antioxidants to improve the thermooxidative aging resistance of peroxide vulcanized ethylene-propylene-diene monomer for its application at high temperatures.[1] The synergistic mixture of antioxidants protected EPDM from deterioration at 180°C for 216 h.[1]

The energetic analysis of the potential energy surface and HOMO and LUMO levels evidenced the existence of excited-state intramolecular proton transfer in hydroxy benzimidazole derivative.[2]

The oxidation inhibition efficiency of these compounds in the protection of oxidation of oils depended on their structure.[3] The 2(1-H benzo(d)imidazole-2-y1)thio) N-butyl acetamide was found to be the most efficient antioxidant for base oils.[3] The most effective concentration was at 500 ppm.[3]

References

1 Ning, N; Ma, Q; Zhang, Y; Zhang, L; Tian, M, *Polym. Deg. Stab*., **102**, 1-8, 2014.

2 Jayabharathi, J; Thanikachalam, V; Jayamoorthy, K; Srinivasan, N, *Spectrochim. Acta Part A: Molec. Biomol.Spectroscopy*, **105**, 223-8, 2013.

3 Basta, JS; El-Bassoussi, AA; Salem, AA; Nessim, MI; Attia, SK, *Egyptian J. Petroleum*, **26**, 4, 933-41, 2017.

3.7 BENZOQUINONES

Oxidative stress resulting from iron and reactive oxygen species homeostasis breakdown has been implicated in several diseases. Rapanone prevents iron or free radical mitochondrial damage by multiple mechanisms. Antioxidant roles result from iron-chelation and radical scavenging (Figure 3.8).

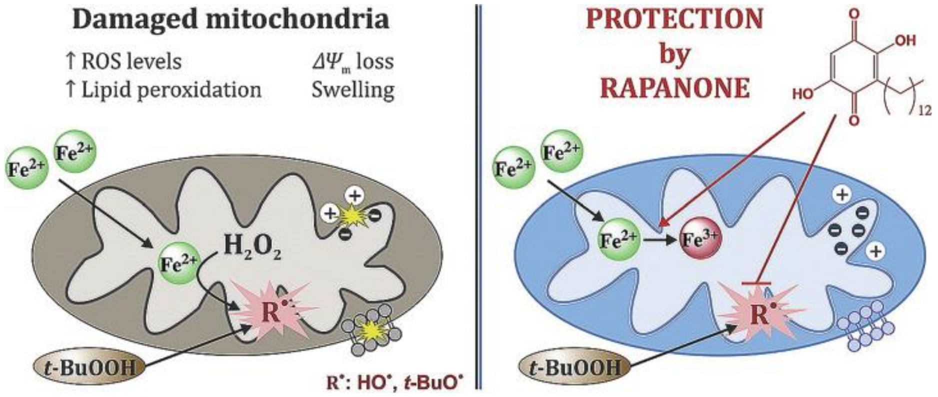


Figure 3.8. Protection by rapanone. [Adapted, by permission, from de la Vega-Hernández, K; Antuch, M; Cuesta-Rubio, O; Núñez-Figueredo, Y; Pardo-Andreu, GL, *J. Inorg. Biochem.*, **170**, 134-47, 2017.]

Coenzyme Q10 is a component of cellular membranes and belongs to the class of benzoquinones that mainly differ with regards to the length and composition of their hydrophobic tail.[2] The quinone group can accept electrons from various biological sources and is converted by one-electron transfer to the unstable semi-quinone or by a two-electron transfer to more stable hydroquinone.[2] This feature makes CoQ10 the *bona fide* cellular electron transfer molecule within the mitochondrial respiratory chain, and also makes it a potent cellular antioxidant.[2]

Depending on the quinone/hydroquinone ratio, the polymeric antioxidants may accelerate or slightly retard the rate of rubber vulcanization.[3] Blending the polymeric antioxidant in equal amount with an amine antioxidant leads to a pronounced improvement in its efficiency, and the mixture does not affect the rheological or other properties of the rubber.[3]

Oxidative stress of mitochondrial origin, i.e., elevated mitochondrial superoxide production, belongs to major factors determining aging and oxidative-stress-related diseases.[4] Antioxidants, such as the mitochondrial-targeted coenzyme Q, MitoQ10, may prevent or cure these pathological conditions.[4] Conjugation of the lipophilic triphenylphosphonium cation to a ubiquinone moiety has produced a compound, MitoQ, which accumulates selectively in mitochondria.[5] MitoQ passes easily through all biological membranes and, because of its positive charge, is accumulated several hundred-fold within mitochondria driven by the mitochondrial membrane potential.[5] Figure 3.9 shows the mechanism of accumulation of MitoQ into cells.[5]

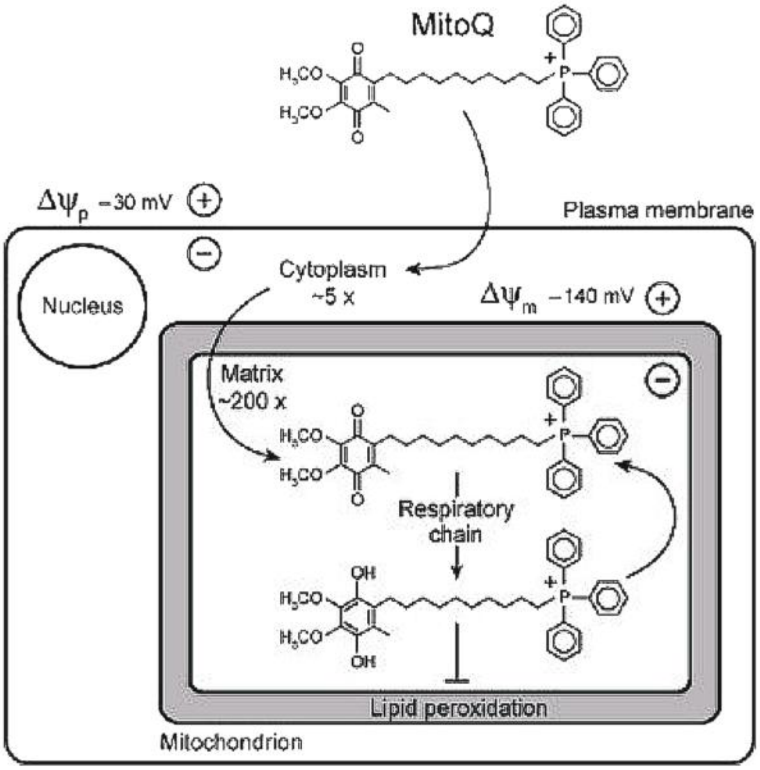


Figure 3.9. Accumulation of MitoQ into cells and mitochondria. MitoQ first passes through the plasma membrane and accumulates in the cytosol driven by the plasma membrane potential (Δψp). From there, MitoQ is further accumulated several hundred-fold in mitochondria driven by the mitochondrial membrane potential (Δψm). MitoQ is then reduced to the active antioxidant ubiquinol form by complex II in the mitochondrial respiratory chain. Interaction with ROS produces the oxidized ubiquinone form which can subsequently be reduced again by the respiratory chain. In mitochondria, MitoQ will be mainly adsorbed to the inner surface of the mitochondrial inner membrane with the antioxidant moiety located within the hydrophobic bilayer. [Adapted, by permission, from Cochemé, HM; Kelso, GF; James, AM; Ross, MR; Murphy, MP, *Mitochondrion*, **7**, Suppl., S94-S102, 2007.]

CoQ cytoprotective mechanisms can be divided into bioenergetic function and antioxidant activity.[6] To understand the extent to which these processes may occur in cells during cell stress, it is necessary to measure the ability of the CoQ hydroquinone to both restore the bioenergetic status and prevent membrane peroxidation and reactive oxygen species formation.[6]

References

1 de la Vega-Hernández, K; Antuch, M; Cuesta-Rubio, O; Núñez-Figueredo, Y; Pardo-Andreu, GL, *J. Inorg. Biochem*., **170**, 134-47, 2017.
2 Gueven, N; Woolley, K; Smith, J, *Redox Biol.*, **4**, 289-95, 2015.
3 Sabaa, MW; Madkour, TM; Yassin, AA, *Polym. Deg. Stab*., **22**, 3, 205-22, 1988.
4 Plecitá-Hlavatá, L; Ježek, J; Ježek, P, *Int. J. Biochem. Cell Biol.*, **41**, 8-9, 1697-707, 2009.
5 Cochemé, HM; Kelso, GF; James, AM; Ross, MR; Murphy, MP, *Mitochondrion*, **7**, Suppl., S94-S102, 2007.
6 Chan, TS; Wilson, JX; O'Brien, PJ, *Methods Enzymology*, **382**, 89-104, 2004.

3.8 CURCUMIN

Five mechanisms were considered: single electron transfer (SET), radical adduct formation (RAF), hydrogen atom transfer from neutral curcumin (HAT), H atom transfer from deprotonated curcumin (HAT-D), and sequential proton loss electron transfer (SPLET).[1] These mechanisms are explained by the equations below:[1]

single-electron transfer (SET) (H_3CU stands for curcumin)

$$H_3CU + R^{\cdot} \longrightarrow H_3CU^{+\cdot} + R^{-}$$

radical adduct formation (RAF)

$$H_3CU + R^{\cdot} \longrightarrow [H_3CU - R]^{\cdot}$$

hydrogen atom transfer from neutral curcumin (HAT)

$$H_3CU + R^{\cdot} \longrightarrow H_2CU^{\cdot} + RH$$

hydrogen atom transfer from deprotonated curcumin (HAT-D)

$$H_3CU \longrightarrow H_2CU^{\ominus} + H^{\oplus}$$
$$H_2CU^{-} + R^{\cdot} \longrightarrow HCU^{-\cdot} + RH$$

sequential proton loss electron transfer (SPLET)

$$H_3CU \longrightarrow H_2CU^{\ominus} + H^{\oplus}$$
$$H_2CU^{\ominus} + R^{\cdot} \longrightarrow H_2CU^{\cdot} + R^{\ominus}$$
$$H_2CU^{\cdot} \longrightarrow HCU^{-\cdot} + H^{\oplus}$$

The SPLET mechanism was used to explain that rates of reactions become orders of magnitude faster when they took place in alcohols and that the addition of acetic acid reduced the rates to the level of non-hydroxylic solvents.[1] The anionic curcumin was more reactive towards free radicals than the neutral form, and when its concentration decreased, so did the antioxidant character of curcumin.[1] This reasoning also supported a hydrogen atom transfer mechanism from the deprotonated curcumin (HAT-D).[1]

The curcumin + 2,2-diphenyl-1-picryl-hydrazyl reaction took place mainly through the SPLET mechanism, while the reaction with OCH_3 and other alkoxyl radicals was governed by the HAT mechanism.[1] The single electron-transfer reactions mechanism (SET) might contribute to some extent to the overall curcumin + free radical reactions provided that the free radicals have high electron-withdrawing character and that the reaction occurs in a highly polar environment; otherwise this mechanism is not expected to contribute to a significant extent to the antioxidant activity of curcumin.[1]

Curcumin exists almost exclusively in its enol form in benzene solution and 99.5% enol-0.5% keto in water solution.[1]

Curcumin pyrazole (CP) & isoxazole (CI) are diketo modified derivatives of curcumin. CP has higher HOMO value, and lower bond dissociation energy.[2] Lower pK_a of CP radical cation tends to orient the reaction mechanism by sequential electron transfer-proton-transfer, SET-PT.[2] Figure 3.10 shows the effect of modification of curcumin structure on the mechanism of its action as an antioxidant.[2]

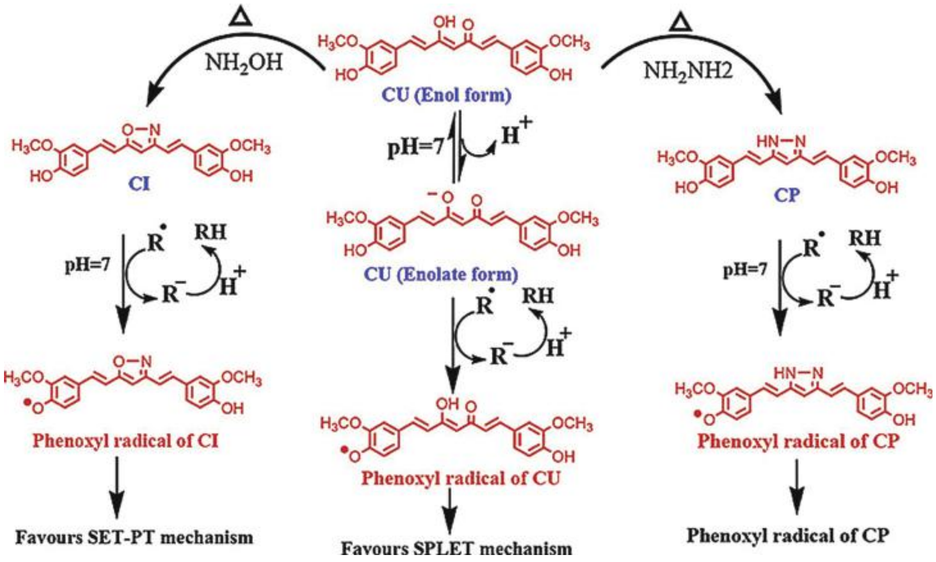


Figure 3.10. The effect of chemical structure on the mechanism of action of curcumin derivatives. [Adapted, by permission, from Shaikh, SAM; Singh, BG; Barik, A; Balaji, NV; Priyadarsini, KI, *J. Molec. Struct.*, **1193**, 166-76, 2019.]

CP had higher reactivity than CI and CU for scavenging $N_3^•$ and $CCl_3O_2^•$ radicals.[2] Elevated HOMO energy level, higher electron density and lower pK_a of one-electron oxidized radical were the deciding factors for such higher free radical scavenging activity of CP in comparison with CI and CU.[2] The replacement of the diketo moiety with pyrazole group in CU increased stability of the polyphenol and its *in vitro* free radical scavenging activity.[2]

The encapsulation of curcumin into egg white protein nanoparticles was used to protect the antioxidant activity of curcumin.[3] The curcumin loading capacity of the egg white protein nanoparticles was strongly linked to the structural transitions of the protein during heat denaturation, and the microscopic properties of the particles such as particle size and zeta-potential.[3] Fibrous particles were formed at lower pH (3.0), and were associated with a higher curcumin loading than the granular particles formed at pH 3.8.[3] Ethanol led to an increase in β-sheet structure, the formation of a coarser gel structure during heat denaturation, as well as an increase in particle diameter.[3] The highest curcumin loading capacities were 11.53 and 9.89 mg/g protein (with a final curcumin concentration of 312.5 μM and 268 μM respectively), at pH 3.0 and 3.8, respectively.[3] Encapsulation in egg white protein nanoparticles was shown to both effectively slow the degradation ratio as well as protect the antioxidant activity of encapsulated curcumin.[3]

Curcumin encapsulated in yeast microcarriers had substantially higher thermal stability.[4] Native yeast cells provided the oxidative barrier against peroxyl radicals due to the presence of endogenous antioxidant systems.[4]

Metal chelation enhanced the antioxidant properties of curcumin, which acted as an active metal chelating agent as well as an antioxidant.[5] Curcumin was found useful in chelation therapy for the cure of metal induced-neurodegenerative diseases.[5]

Curcumin had effective 2,2-diphenyl-1-picrylhydrazyl scavenging, 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) scavenging, N,N-dimethyl-p-phenylenediamine dihydrochloride scavenging, superoxide anion radical scavenging, hydrogen peroxide scavenging, ferric ions (Fe^{3+}) reducing power and ferrous ions (Fe^{2+}) chelating activities.[6] Curcumin can be used in the pharmacological and food industry because of these properties.[6]

References

1 Galano, A; Álvarez-Diduk, R; Ramírez-Silva, MT; Alarcón-Ángeles, G; Rojas-Hernández, A, *Chem. Phys.*, **363**, 1-3, 13-23, 2009.
2 Shaikh, SAM; Singh, BG; Barik, A; Balaji, NV; Priyadarsini, KI, *J. Molec. Struct.*, **1193**, 166-76, 2019.
3 Chang, C; Meikle, TG; Su, Y; Wang, X; Yang, Y, *Food Chem.*, **280**, 65-72, 2019.
4 Young, S; Nitin, N, *Food Chem.*, **275**, 1-7, 2019.
5 Mary, CPV; Vijayakumar, S; Shankar, R, *J. Molec. Graphics Modelling*, **79**, 1-14, 2018.
6 Ak, T; Gülçin, I, *Chemico-Biol. Interactions*, **174**, 1, 27-37, 2008.

3.9 COUMARIN

Hydroxy 4-phenyl coumarins may be considered as potential therapeutic candidates for pathological conditions characterized by free radical overproduction.[1] The 7,8-dihydroxy-4-phenyl coumarin had good antioxidant activity, and the activity of 5,7-dihydroxy-4-phenyl coumarin was found to be moderate.[1]

The coumarin-substituted dihydropyrazoles were employed to scavenge 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonate) cationic radical, 2,2′-diphenyl-1-picrylhydrazyl radical, and galvinoxyl radical.[2] The double phenolic hydroxyl groups were beneficial for enhancing the abilities of coumarin-substituted dihydropyrazoles to quench the radicals.[2]

The insertion of organic phenols in a simple coumarin structure produced new derivatives with improved antioxidant capacity in comparison to coumarin.[3]

References

1 Veselinović, JB; Veselinović, AM; Vitnik, ŽJ; Vitnik, VD; Nikolić, GM, *Chemico-Biol. Interactions*, **214**, 49-56, 2014.
2 Xi, G-L; Liu, Z-Q, *Eur. J. Medicine Chem.*, **68**, 385-93, 2013.
3 Pérez-Cruz, K; Moncada-Basualto, M; Morales-Valenzuela, J; Barriga-González, G; Olea-Azar, C, *Arabian J. Chem.*, **11**, 4, 525-37, 2018.

3.10 ENZYME

Reactive oxygen species are generated in the plants during cellular metabolism.[1] The extreme environmental conditions, such as drought, salinity, or floods lead to an enhanced level of these reactive oxygen species in plants, causing deterioration of lipids, proteins, and nucleic acids, and ultimately death of the plant.[1] The reactive oxygen species play a critical role as the signaling molecules throughout the entire cell death pathway, but they can cause oxidative burst if there is an imbalance between their generation and their scavenging.[1] Cells develop a balanced system to counteract the effect of reactive oxygen species, such as antioxidative defense system, which comprises antioxidant enzymes, such as superoxide dismutase, catalase, glutathione peroxidases, and non-enzymatic antioxidants which cooperatively reduce oxidative state.[1]

To colonize their host and generate an infection, microbial pathogens must escape the oxidative and nitrosative burst response of phagocytic cells.[2] To maintain reactive oxygen species at sub-lethal concentrations, microbial pathogens display various antioxidant mechanisms and among them, superoxide dismutases, catalases, enzymes of the glutathione, or thioredoxin systems, as well as other peroxidases, flavohemoglobins, and nitrate or nitrite reductases were identified as protection factors.[2]

Reactive oxygen species are produced during the normal cellular function.[3] Reactive oxygen species include hydroxyl radicals, superoxide anion, hydrogen peroxide, and nitric oxide.[3] Under normal conditions, antioxidant systems of the cell minimize the perturbations caused by reactive oxygen species.[3] When reactive oxygen species generation is increased to the extent that overcomes the cellular antioxidants, the result is oxidative stress.[3] Antioxidants are substances that delay or prevent the oxidation of cellular oxidizable substrates.[3] Antioxidants exert their effect by scavenging superoxide, or by activating of a battery of detoxifying/defensive proteins.[3] The prevention of oxidation is an essential process in all aerobic organisms, as decreased antioxidant protection may lead to cytotoxicity, mutagenicity, and/or carcinogenicity.[3]

References

1 Kapoor, D; Singh, S; Kumar, V; Romero, R; Singh, J, *Plant Gene*, **19**, art. 100182, 2019.

2 Staerck, C; Gastebois, A; Vandeputte, P; Calenda, A; Fleury, MJJ, *Microbial Pathogenesis*, **110**, 56-65, 2017.

3 Matés, JM, *Toxicology*, **153**, 1-3, 83-104, 2000.

3.11 FLAVONOIDS

Thirteen flavonoids (quercetin, morin, myricetin, luteolin, fisetin, kaempferol, galangin, apigenin, chrysin, EC, ECG, EGC, and EGCG) were used to investigate their main antioxidant mechanism as well as a structure-activity relationship by quantum chemical calculation and verifying by the *in vitro* typical antioxidant assays.[1] The bond dissociation enthalpy (BDE) was much lower than ionization enthalpy and proton affinity values, and the bond dissociation enthalpy rank of 13 flavonoids was similar to that of their antioxidant activity determined by the *in vitro* trials.[1]

In hydrogen atom transfer (HAT) mechanism, one H-atom of flavonoids (Fl-OH) was transferred to the free radical (R·) and formed phenoxyl radical (Fl-O·), which was more stable than R·; thus the further chain reaction was blocked.[1] Higher stability of Fl-O· represented a stronger antioxidant activity of flavonoids.[1]

$$\mathrm{R}^{\cdot} + \text{Fl-OH} \longrightarrow \mathrm{RH} + \text{Fl-O}^{\cdot}$$

In single electron transfer (SET) mechanism, a flavonoid molecule could donate an electron to the free radical thus became radical cation:[1]

$$\mathrm{R}^{\cdot} + \text{Fl-OH} \longrightarrow \mathrm{R}^{-} + \text{FL-OH}^{+\cdot}$$

This mechanism could be further subdivided into two mechanisms with respect to the reaction process: single electron transfer followed by proton transfer (SET-PT)[1]

$$\begin{aligned} &\text{Fl-OH} \longrightarrow \text{Fl-OH}^{\oplus} + \mathrm{e}^{\ominus} \\ &\text{Fl-OH}^{\oplus} \longrightarrow \text{Fl-O} + \mathrm{H}^{\oplus} \end{aligned}$$

and sequential proton loss electron transfer (SPLET):[1]

$$\begin{aligned} &\text{Fl-OH} \longrightarrow \text{Fl-O}^{\ominus} + \mathrm{H}^{\oplus} \\ &\text{Fl-O}^{\ominus} \longrightarrow \text{Fl-O} + \mathrm{e}^{\ominus} \end{aligned}$$

The first step of SET-PT was one electron transferred from flavonoid molecule to free radical, and followed by deprotonation of the radical cation.[1] As for SPLET, the first step was deprotonation of flavonoid, thus forming a flavonoid anion, then an electron was transferred from flavonoid anion to free radical.[1]

It was revealed that flavonoids thermodynamically preferred HAT mechanism in polar media.[1] The number and position of phenolic hydroxyl showed great influences on the antioxidant activity of flavonoids, and the flavonoids possessing both of C3 hydroxyl group and catechol moiety exhibited stronger antioxidant activity than with one or none of them.[1]

The antioxidant activity was enhanced in sodium bis(2-ethylhexyl)phosphate micelles whereas reduced in sodium bis(2-ethylhexyl)sulfosuccinate micelles.[2] Thus micellar media can be easily employed to tune the antioxidant activity of flavonoids.[2] Increased antioxidant activity of flavonoids in sodium bis(2-ethylhexyl)phosphate micelles cured the oxidative stress and other biological damages by scavenging the overproduced reactive oxygen species.[2] The decreased antioxidant activity finds major application in the field of “oxidation therapy” a promising anticancer therapy to kill cancer cells.[2] Figure 3.11 shows the interaction of flavonoid with surfactants.[2]

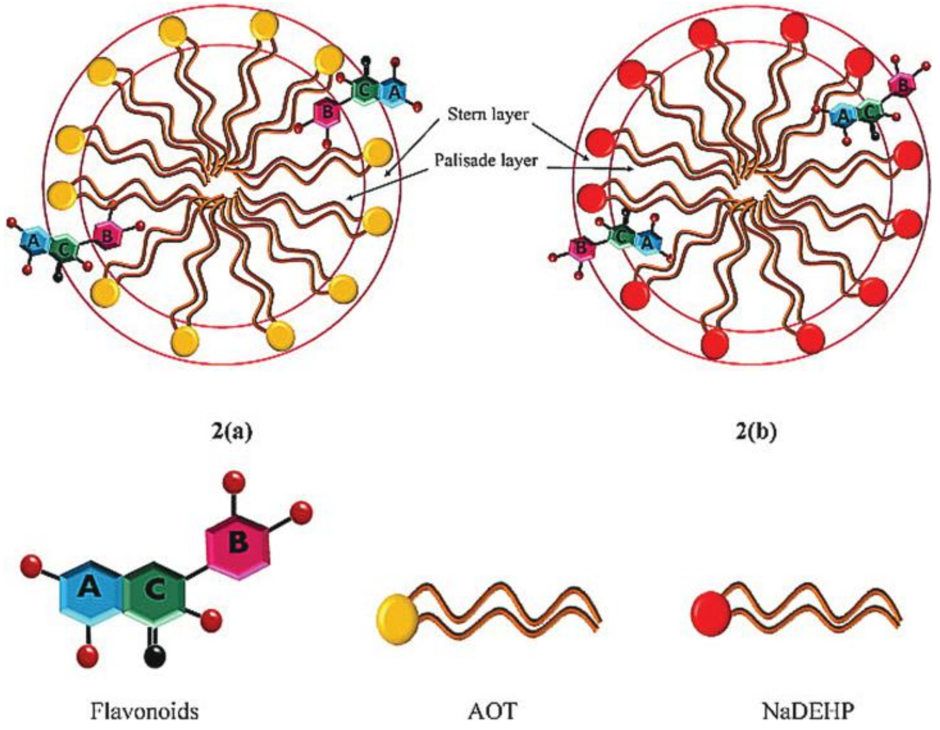


Figure 3.11. Locations of flavonoids in (a) sodium bis(2-ethylhexyl)sulfosuccinate micelles, (b) sodium bis(2-ethylhexyl)phosphate micelles. [Adapted, by permission, from Singh, O; Kaur, R; Kumar Mahajan, R, *Spectrochim. Acta Part A: Molec. Biomolec. Spectroscopy*, **170**, 77-88, 2017.]

Flavonoids are polar organic molecules, and they are absorbed in the outer portion of palisade layer of micelles, near to the water-micelle interface.[2] This decreases the work required for micellization by decreasing the repulsions between the head-groups.[2] Depending on absorption, different functional groups of flavonoids are exposed which influences their reactivity.[2]

The electronic properties of studied flavonoid compounds and their antioxidant activity can be well correlated by three variables: (i) polarizability, (ii) change at carbon 3’ (iii) change at carbon 5.[3]

Most flavonoids outperform well-known antioxidants, such as ascorbate (vitamin C) and α-tocopherol (vitamin E), in *in vitro* antioxidant assays because of their strong capacity to donate electrons or hydrogen atoms.[4] Flavonoids are a family of plant secondary metabolites of >9000 individual molecules found in all tissues and organs.[4] In plants, flavonoids are involved in plant-pathogen interactions, pollination, light screening, seed development, and allelopathy.[4]

Due to their prooxidant properties, flavonoids are able to cause oxidative damage by reacting with various biomolecules, such as lipids, proteins, and DNA.[5]

Fruit and vegetable consumption is associated with a decreased incidence of cardiovascular diseases, cancer, and other chronic diseases.[6] The beneficial health effects have been attributed, in part, to antioxidant flavonoids present in these foods.[6] Most flavonoids are extensively metabolized *in vivo*, which can affect their antioxidant capacity.[6]

References

1 Chen, X; Deng, Z; Zhang, C; Zheng, S; Li, H, *Food Res. Int.*, in press, 2019.
2 Singh, O; Kaur, R; Kumar Mahajan, R, *Spectrochim. Acta Part A: Molec. Biomol. Spectroscopy*, **170**, 77-88, 2017.
3 de Queiroz Ferreira, R; José Greco, S; Delarmelina, M; Cacilda Weber, K, *Electrochim. Acta*, **163**, 161-66, 2015.
4 Hernández, I; Alegre, L; Van Breusegem, F; Munné-Bosch, S, *Trends Plant Sci.*, **14**, 3, 125-32.
5 Procházková, D; Boušová, I Wilhelmová, N, *Fitoterapia*, **82**, 4, 513-23, 2011.
6 Lotito, SB; Frei, B, *Free Radical Biol. Med.*, **41**, 12, 1727-46, 2006.

3.12 GRAPHENE

Graphene oxide was simultaneously reduced and functionalized with 2-mercaptobenzimidazole *via* a one-pot method.[1] The thermooxidative aging resistance of rubber composites containing modified graphene was also superior to that of rubber composites with reduced graphene because of the elimination of the blooming effect of the grafted 2-mercaptobenzimidazole molecules.[1]

The antioxidant-grafted graphene oxide was obtained by grafting hindered amine and hindered phenol, respectively, onto the surface of the graphene oxide.[2] The polyketone composites containing modified graphene oxide showed substantially improved thermal stability and mechanical performance compared to polyketone due to the presence of the antioxidant-grafted graphene oxide.[2]

The thermo-oxidative aging resistance of natural rubber was improved by functionalized graphene grafted with 2-tert-butyl-6-(3-tertbutyl-2-hydroxy-5-methylphenyl) methyl-4-methylphenyl acrylate onto graphene oxide using (3-mercaptopropyl) trimethoxysilane as bridging agent.[3] The excellent thermo-oxidative aging resistance was attributed to the synergistic antioxidative effect of hindered phenol groups and thioether bonds and the barrier properties of graphene sheets slowing diffusion of oxygen.[3] Figure 3.12 shows the proposed mechanism.[3]

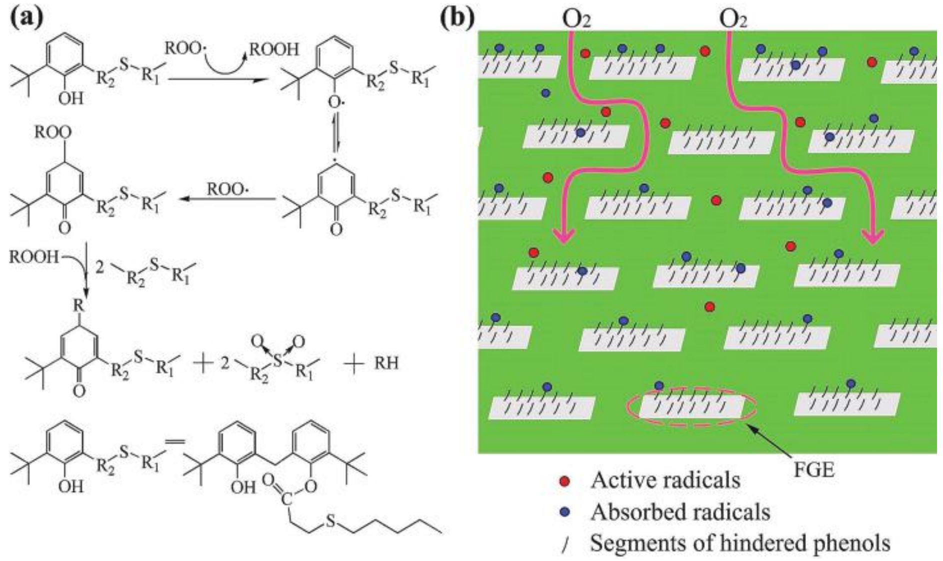


Figure 3.12. Antioxidative mechanism of functionalized graphene in natural rubber/functionalized graphene nanocomposites. [Adapted, by permission, from Zhang, L; Li, H; Lai, X; Liao, X; Zeng, X, *Compos. Part A: Appl. Sci. Manuf.*, **107**, 47-54, 2018.]

The sonochemical method has been developed for the functionalization of graphene oxide with 5-aminoindazole.[4] As compared to graphene oxide; the functionalized graphene oxide has demonstrated an enhanced antioxidant efficacy of 69.4-72%, evaluated with 2,2-diphenyl-1-picrylhydrazyl free radical assay.[4]

References

1 Zhong, B; Luo, Y; Chen, W; Luo, Y; Jia, D, J. *Coll. Interface Sci*., **550**, 190-8, 2019.
2 Lim, M-Y; Oh, J; Kim, HJ; Kim, KY; Lee, J-C, *Eur. Polym. J.*, **69**, 156-67, 2015.
3 Zhang, L; Li, H; Lai, X; Liao, X; Zeng, X, *Compos. Part A: Appl. Sci. Manuf*., **107**, 47-54, 2018.
4 Maktedar, SS; Malik, P; Avashthi, G; Singh, M, *Ultrasonics Sonochem*., **39**, 208-17, 2017.

3.13 HYDROQUINONE

Oxidation is the major problem in biodiesel commercialization. Autooxidation is caused by air, heat, light, and metallic contaminants which affect the fuel characteristics of biodiesel.[1] Addition of synthetic antioxidants improves the oxidation stability of biodiesel.[1] Pyrogallol/tert-butyl hydroquinone in proportion 1:3 formed synergistic mixtures which were giving antioxidant protection to Jatropha and Karanja biodiesels at low levels of 500-700 ppm.[1] Figure 3.13 shows proposed mechanism of synergism which is based on regeneration of tert-butyl hydroquinone by pyrogallol.[1]

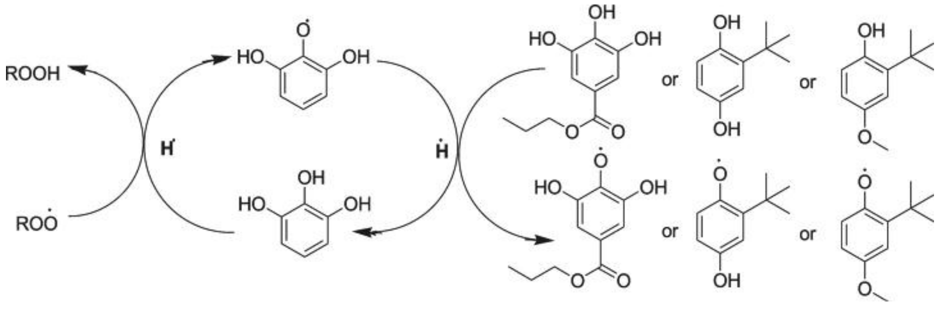


Figure 3.13. Mechanism of synergistic interaction of pyrogallol primary antioxidant, leading to regeneration of primary antioxidant. [Adapted, by permission, from Rawat, DS; Joshi, G; Lamba, BY; Tiwari, AK; Kumar, P, *Energy*, **84**, 643-55, 2015.]

Antioxidants, including tert-butyl hydroquinone, butylated hydroxyanisole, butylated hydroxytoluene, ferulic acid, epigallocatechin gallate, and vitamin C, and their corresponding oxidation products, were tested for their influence on elimination of acrylamide and inhibition of acrylamide formation.[2] The antioxidants did not influence acrylamide formation, but their corresponding oxidation products were able to directly destruct acrylamide and its precursor, asparagine, thus inhibiting acrylamide formation.[2]

References

1 Rawat, DS; Joshi, G; Lamba, BY; Tiwari, AK; Kumar, P, *Energy*, **84**, 643-55, 2015.
2 Ou, S; Shi, J; Huang, C; Zhang, G; Yang, B, *J. Hazardous Mater.*, **182**, 1-3, 863-8, 2010.

3.14 HYDROXYLAMINES

Using the ONIOM-G3B3 method, the bond dissociation enthalpies of coenzyme Q (81.6-82.1 kcal/mol), flavonoids (78.7-105.6), olives (80.1-89.0), curcumins (80.2-87.0), indolinonic hydroxylamines (61.4-72.0), phenothiazines (76.9-87.7), and edaravones (76.8-79.9) antioxidants used as food additives were predicted.[1] The hydroxylamine analogs may have much stronger antioxidant activity than the natural antioxidant α-tocopherol.[1] The antioxidant activity is increased when the stronger electron-withdrawing group C=O is replaced by the electron-donating substituent C=NR.[1]

A cataract is the world's leading cause of blindness and a disease for which no efficacious medical therapy is available.[2] Opacification of lenses was induced by H_2O_2 or the cataractogenic sugar xylose.[2] Tempol-H, the hydroxylamine of the nitroxide Tempol (4-hydroxy-2,2,6,6-tetramethylpiperidine-N-oxyl), gave the most promising results.[2] It significantly inhibited opacification of rat lenses in an H_2O_2-induced cataract system as well as opacification of rhesus monkey lenses induced by xylose.[2] Tempol-H inhibited the loss of glutathione, the leakage of protein, and decreased the ability of cultured lenses to accumulate ^{3}H-choline from the medium, all of which were associated with the development of lens opacification.[2] The antioxidative activity of Tempol-H and its ability to redox cycle make it an attractive candidate as a therapeutic agent for the prevention of aging-related cataract.[2]

A commercial hindered piperidine was not an effective melt stabilizer for polypropylene, whereas related nitroxyl radicals and hydroxylamine were highly effective.[3] The results were explained on the basis of an oxidative transformation of the piperidine to the nitroxyl during processing and the involvement of the latter in a cyclical regenerative process in which the nitroxyl acts as a chain-breaking acceptor antioxidant and the derived hydroxylamine as a chain-breaking donor antioxidant.[3] The same mechanism operates during photooxidation of polymer films containing these additives.[3] The nitroxyl radical concentration reaches a stationary concentration, irrespective of whether it is added as nitroxyl or as parent amine.[3] The derived hydroxylamines are substantially more effective than the nitroxyl radicals as ultraviolet stabilizers.[3]

References

1 Li, M-J; Liu, L; Fu, Y; Guo, Q-X, *J. Molec. Struct.: THEOCHEM*, **815**, 1-3, 1-9, 2007.
2 Zigler, JS; Qin, C; Kamiya, T; Krishna, MC; Russell, P, *Free Radical Biol. Med.*, 35, 10, 1194-202, 2003.
3 Bagheri, R; Chakraborty, KB; Scott, G, *Polym. Deg. Stab.*, **4**, 1, 1-16, 1982.

3.15 ISOFLAVONES

Oxidation of lipids causes atherosclerosis.[1] Scavenging of lipid peroxyl radicals contributes to the antiatherosclerotic effects of naturally occurring compounds such as the isoflavones.[1] Genistein is present in relatively high concentrations in food products containing soy.[1] Soy isoflavones are capable of inhibiting lipoprotein oxidation *in vitro* and suppressing the formation of plasma lipid oxidation products *in vivo*.[1] Polyphenols exhibit antioxidant effects *via* a mechanism that is analogous to tocopherol-mediated peroxidation.[1] Polyphenols react with lipid peroxyl radicals, forming hydroperoxide and polyphenol radical.[1] The polyphenol radical would react with a second lipid peroxyl radical in the case of a classical antioxidant such as BHT, but in the case of polyphenols, the radical reacts with an unsaturated fatty acid to initiate lipid peroxidation.[1] Polyphenol-mediated peroxidation decreases the antioxidant efficacy of the compound as is shown in Figure 3.14.[1] Genistein (Gen) reacts with peroxyl radicals (ROO•) to form the corresponding phenoxyl radical (Reaction 1, Figure 3.14), which abstracts a hydrogen atom from a polyunsaturated fatty acid (LH) regenerating genistein and forming a carbon-centered radical (L•) that reacts with oxygen to form another lipid peroxyl radical (Reaction 2, Figure 3.14).[1] Polyunsaturated fatty acids reduce the phenoxyl radical, thereby regenerating genistein, and that this process competes kinetically with the termination reactions that occur with peroxyl radicals (Reactions 2 and 3, Figure 3.14).[1] An antioxidant effect can be explained by the slower rate at which the isoflavone radical initiates oxidation events compared to a lipid peroxyl radical, accounting for the lack of isoflavone consumption.[1]

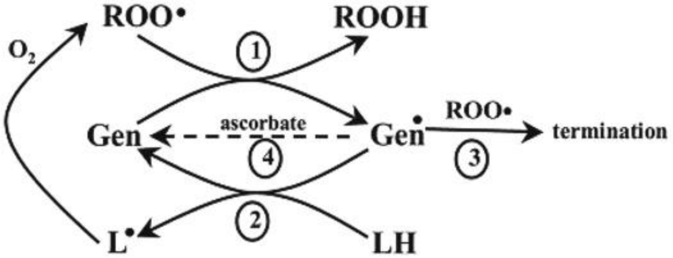


Figure 3.14. A scheme of a process by which genistein inhibits lipid peroxidation. Reaction of genistein (Gen) with peroxyl radicals (ROO•) generates the corresponding phenoxyl radical (Gen•) and hydroperoxide (ROOH) (Reaction 1). To account for the inhibition of lipid oxidation and the lack of loss of Gen it is proposed that Gen• is reduced by reaction with polyunsaturated fatty acids (LH) to form Gen and a carbon centered lipid radical (L•) that, in turn, reacts with oxygen (O_2) to re-form ROO• (Reaction 2). This process competes with termination reactions between Gen• and ROO• that would result in consumption of the isoflavone (Reaction 3). The effects of ascorbate will depend on the competition of its reaction with Gen• with LH. When ascorbate concentrations are relatively higher such that Reaction 4 is favored over Reaction 2, a synergistic inhibition of oxidation will be observed. [Adapted, by permission, from Patel, RP; Boersma, BJ; Crawford, JH; Hogg, N; Darley-Usmar, V, *Free Radical Biol. Med.*, **31**, 12, 1570-81, 2001.]

Equol (an estrogenic metabolite of daidzein) has greater antioxidant activity than the parent isoflavone compounds genistein and daidzein present in soy.[2] Equol inhibits low-density lipoprotein oxidation.[2] An antioxidant effect of equol was mediated by inhibition of superoxide radical ($O_2^{-\bullet}$) production.[2]

The consumption of soybean products is linked to many health benefits, including reduced risk of cardiovascular diseases and cancer, and soy isoflavones are considered one of the major bioactive compounds.[3]

Excessive UV-B radiation resulted in reduced cell volume, irregular cell shape, and increased cell space.[4] The antioxidant enzymes activities were enhanced by UV-B. UV-B triggered the formation of H_2O_2, resulting in oxidative stress.[4] At the same time, the antioxidant system, including the enzymatic (enhanced the antioxidant enzymes activities) and nonenzymatic (accumulated isoflavones) were activated to minimize oxidative damage.[4]

The effect of cooking process on soybean isoflavones, aiming at understanding the conversion of β-glucosides and aglycones isoflavones during the process and the relation with antioxidant activity has been studied.[5] The β-glucosides isoflavones were significantly increased from 223.01 (raw) to 727.29 mg/g (frying at 160°C for 2 min), but boiling showed only a slight increase to 258.14 mg/g.[5] All bioactive ingredients were aggressively destroyed by overprocessing.[5]

References

1 Patel, RP; Boersma, BJ; Crawford, JH; Hogg, N; Darley-Usmar, V, *Free Radical Biol. Med.*, **31**, 12, 1570-81, 2001.

2 Hwang, J; Wang, J; Morazzoni, P; Hodis, HN; Sevanian, A, *Free Radical Biol. Med.*, **34**, 10, 1271-82, 2003.

3 Mani, V; Ming, LC, **Tempeh and Other Fermented Soybean Products Rich in Isoflavones. Fermented Foods in Health and Disease Prevention**, *Academic Press*, 2017, pp. 453-74.

4 Ma, M; Wang, P; Yang, R; Zhou, T; Gu, Z, *Food Chem.*, **275**, 628-36, 2019.

5 Chen, L; Teng, H; Xiao. *J. Food Sci. Human Wellness*, **8**, 2, 195-201, 2019.

3.16 LIGNANAMIDE

Lignanamides have attracted considerable interest within the chemical and biological research communities.[1] They were found in the roots of *Capsicum annuum* var. grossum (Solanaceae), *Hyoscyamus niger, Lycium chinense, Lycium barbarum, Solanum surattense, Solanum tuberosum,* and *Withania sominfera*.[1] The antioxidant and anti-inflammatory activities of lignanamides have been confirmed.[1]

References

1 Chen, H; Li, Y-J; Sun, Y-J; Gong, J-H; Feng, W-S, *Fitoterapia*, **122**, 119-25, 2017.

3.17 OIL COMPONENTS

The oxidative stress is considered a possible reason for Tardive dyskinesia (the serious side effects of long-term antipsychotic treatment).[1] Preclinical and clinical studies indicated that neurotoxic free radical production was likely a consequence of antipsychotic medication.[1] Administration of rice bran oil (antioxidant) to rats prevented these pathophysiological effects.[1] Rice bran oil inhibited lipid peroxidation in erythrocytes and in all tissues initiated by free radical generation, because tocopherol, tocotrienol, γ-oryzanol, and polyphenol, and their components are present in rice bran.[1] These compounds are free radical scavengers, and they are consumed when tissues are exposed to oxidative stress.[1]

Sandalwood essential oil extracted from *Santalum album* L. trees was mainly composed of α- and β-santalols.[2] The oil displayed an excellent *in vitro* and *in vivo* antioxidant activity.[2] It activated the Nrf2-mediated antioxidant mechanism to resist stress.[2]

The effect of *Pimpinella saxifraga* essential oil (PSEO) addition (1-3%) in sodium alginate coating on the bacterial and oxidative stability of cheese was studied during refrigerated storage.[3] Anethole, pseudoisoeugenol, and p-anisaldehyde were the main components.[3] Cheese was improved by reducing the weight loss, preserving the pH and color, and enhancing oxidative and bacterial stability without unpleased flavor for consumers.[3]

Oil extraction from green coffee seeds generates residual mass that is discarded by agribusiness and has not been previously studied.[4] The extracts of the green seeds and the residue contained the phenolic compounds chlorogenic acid and caffeine.[4] The residue extract showed antioxidant potential in DPPH, ABTS, and pyranine assays and low cytotoxicity.[4]

Phytosteryl lipoate was synthesized through the enzymatic route with the maximum conversion of 71.2%.[5] The antioxidant ability of phytosteryl lipoate was better than phytosterol by peroxide value determination.[5]

References

1 Samad, N, *J. Food Drug Analysis*, **23**, 3, 370-8, 2015.
2 Mohankumar A; Kalaiselvi D; Levenson C; Shanmugam G; Sundararaj P, *Ind. Crops Prod.*, **140**, art. 111623, 2019.
3 Ksouda, G; Sellimi, S; Merlier, F; Falcimaigne-Cordin, A; Hajji, M, *Food Chem.*, **288**, 47-56, 2019.
4 Castro, ACCM; Oda, FB; Almeida-Cincotto, MGJ; Davanço, MG; Santos, AG, *Food Chem.*, **246**, 48-57, 2018.
5 Wang, H; Jia, C; Xia, X; Karangwa, E; Zhang, X, *Food Chem.*, **240**, 736-42, 2018.

3.18 PEPTIDES

Proteins undergo oxidative modifications because they have oxidatively labile amino acid residues, which can impart an antioxidative function on specific protein regions.[1] The activity of peptides is higher than that of the intact protein because of smaller peptide chain length, which increases their accessibility to prooxidants.[1] Peptides are also more antioxidative compared to free amino acids due to the stable nature of peptidyl radicals formed during oxidation, which do not possess sufficient energy to propagate the oxidative reactions.[1]

Antioxidative peptides are natural food ingredients, which can be used for functional food formulation and for enhancing food quality.[1]

Peptides generated from the digestion of milk proteins have antioxidative properties.[2] Milk peptides are composed of 5-11 amino acids including hydrophobic amino acids, proline, histidine, tyrosine, or tryptophan in the sequence.[2] Antioxidant activity of the hydrolysates depends on amino acid sequences of peptides derived, depending on the protease specificity.[2]

Casein phosphopeptides have binding capabilities of bivalent ions and enhanced solubilities of many important minerals, such as calcium and iron.[3] They are also effective in reducing 2,2′-azobis(2-amidinopropane) dihydrochloride and Fe^{2+}-induced liposomal peroxidation and showed direct scavenging affinity for the hydrophilic 2,2′-azinobis-3-ethylbenzothiazoline-6-sulfonic acid radical.[3] Bovine casein, which contains these phosphopeptides, has both primary and secondary antioxidant properties, causing direct free radical scavenging and sequestering of potential metal prooxidants.[3]

Some natural biopeptides have antioxidant activity, such as glutathione (γ-Glu-Cys-Gly), carnosine (β-alanyl-L-histidine), homocarnosine (γ-aminobutyryl-L-histidine), and anserine (β-alanyl-N-methyl-L-histidine).[4] Glutathione is a tripeptide, protecting cells from free radicals.[4] Carnosine is a dipeptide scavenging free radicals, chelating metal ions, and inhibiting LDL cholesterol oxidation and hydroxyl and peroxyl radical-induced DNA scission.[4]

Tyr, Trp, Cys, and Met residues played a dominant role in antioxidant dipeptides. Antioxidant dipeptides mainly acted as direct radical scavengers.[4] Tyr- and Trp-containing dipeptides were the most potent radical scavengers.[4]

Methionine sulfoxide reductase B2 is a mitochondrial protein that protects cells from oxidative stress.[5] The antioxidant activity suggests that methionine sulfoxide reductase B2 may play a role in the pathophysiology of Alzheimer's disease by attenuating both amyloidogenesis and tau phosphorylation.[5] Methionine sulfoxide reductase B2 may serve as a potential therapeutic target for Alzheimer's disease.[5]

Antioxidant casein hydrolysates were produced from buffalo casein and bovine casein using alcalase, trypsin, pepsin, or papain.[6] The highest degree of hydrolysis (molecular weights <3.5 kDa) were observed in bovine casein (87.28%) and buffalo casein (83.90%) using alcalase, and the next highest was using trypsin (65.84% and 63.42%, respectively).[6] Hydroxyl radical scavenging capacity, superoxide scavenging activity, oxygen radical absorbance capacity, and Fe^{3+} reducing power for alcalase-buffalo casein hydrolysates and trypsin-bovine casein hydrolysates were 81.16% and 84.55%, 66.84% and 70.30%.[6]

Fats and oils that are high in polyunsaturated fatty acids are generally regarded as beneficial to human health yet are extremely liable to oxidative deterioration.[7] Proteins and peptides are capable of inhibiting oxidative rancidity by radical scavenging, metal chelation, two-electron peroxide reduction, and aldehyde quenching.[7] The antioxidant activity of native food proteins can be modified by heating, enzymatic hydrolysis, or through Maillard chemistry.[7] Peptides have better antioxidative performance than the native proteins from which they were derived.[7]

References

1 Udenigwe, CC; Udechukwu, MC; Yiridoe, C; Gibson, A; Gong, M, *J. Funct. Foods*, **20**, 195-203, 2016.
2 Pihlanto, A, *Int. Dairy J.*, **16**, 11, 1306-14, 2006.
3 Kitts, DD, *Trends Food Sci. Technol.*, **16**, 12, 549-54, 2005.
4 Zheng, L; Zhao, Y; Dong, H; Su, G; Zhao, M, *J. Funct. Foods*, **21**, 485-96, 2016.
5 Xiang, X-J; Song, L; Deng, X-J; Tang, Y; Chen, G-J, *Exp. Neurology,* **318**, 145-56, 2019.
6 Shazly, AB; Mu, H; Liu, Z; Abd El-Aziz, M; Chen, J, *Food Chem.*, **274**, 261-7, 2019.
7 Elias, RJ; Decker, EA, **Protein antioxidants for the stabilization of lipid foods: current and potential applications. Oxidation Foods and Beverages and Antioxidant Applications,** *Woodhead Publishing*, 2010, pp. 249-71.

3.19 PHENOLICS

Phenolic antioxidants form a group of commonly used additives for this purpose. Their properties, applications, and behavior in protecting materials exposed to UV radiation are discussed in details in specialized monographic sources.[1,2]

Phenolic derivatives antioxidant abilities are due to their high ability to deactivate singlet oxygen species $O_2(^1\Delta_g)$ through a physical process and synergistic effect in the presence of commercial antioxidants.[3] Phenolic derivatives have an antioxidant protective effect toward $O_2(^1\Delta_g)$-mediated degradation of methyl linoleate and tryptophan.[3] 3-hydroxyphenethyl alcohol gave the best performance.[3]

Phenolic compounds are primary antioxidants.[4] They act according to two mechanisms: hydrogen-atom transfer (HAT) or single-electron transfer (SET).[4] The HAT mechanism occurs when an antioxidant compound quenches free radical species by donating hydrogen atom according to the following equation[4]

$$RO_2^{\cdot} + ArOH \longrightarrow ROOH + ArO^{\cdot}$$

The free radical formed in this reaction is substantially more stable than $RO_2^{\cdot}$.[4] The SET mechanism occurs when an antioxidant transfers a single electron to aid in the reduction of potential target compounds, as follows[4]

$$RO_2^{\cdot} + ArOH \longrightarrow RO_2^{-} + [ArOH]^{+\cdot}$$

The resultant radical-cationic antioxidant compound is then deprotonated by interacting with water according to the following reactions[4]

$$[ArOH]^{+\cdot} + H_2O \rightleftharpoons ArO^{\cdot} + H_3O^{+}$$
$$RO_2^{-} + H_3O^{+} \rightleftharpoons ROOH + H_2O$$

HAT and SET chemical processes can occur simultaneously as a sequential proton-loss electron transfer (SPLET), which is also termed as a proton-coupled electron transfer (PCET).[4] Presence of ionic metals (Cu, Fe) promotes the production of hydroxyl radicals by the Fenton reaction, as follows[4]

$$Fe^{2+} + H_2O_2 \longrightarrow Fe^{3+} + \overset{\cdot}{O}H + \overset{\ominus}{O}H$$

Radiolysis products from irradiated polyethylene resins were investigated using liquid chromatography coupled to photodiode array and mass spectrometry detection.[5] The resins were γ-irradiated at doses used in food applications.[5] Nonylphenol and 2,4-di-tert-butylphenol were also produced by the irradiation.[5] Octadecyl 3-(3,5-di-tert-butyl-4-hydroxyphenyl)propionate formed a dehydrogenated product (loss of two hydrogens).[5]

Piperidine-based compounds provide polyolefin thermosets with oxidative stability without compromising the yields of peroxide-initiated crosslinking and monomer grafting.[6] Unlike phenolic, nitroxyl and phosphite antioxidants that lower the concentration of macroradical intermediates that support polyolefin modifications.[6] Additives based upon 2,2,6,6-tetramethylpiperidine have little to no effect on the extent of LLDPE crosslinking or the conversion of vinyltriethoxysilane to grafted hydrocarbon adducts.[6] The 4-acryloyloxy-2,2,6,6-tetramethylpiperidine-N-oxyl can also be used as an alkyl radical scavenger bearing an oligomerizable functional group.[6]

Three reactive antioxidants with hindered phenol and hindered amine antioxidant functions were examined for their grafting efficiency in polyethylene and their retention and stabilizing performance in peroxide-crosslinked polyethylene pipe material.[7] The presence of the graftable antioxidants did not affect crosslinking of the PEX pipes which remained high at >85%.[7] Retention of the graftable antioxidants and long-term stability of pipes was significantly higher than when conventional antioxidants have been used.[7]

References

1 Wypych, G, **Handbook of Materials Weathering**, 6th Edition, *ChemTec Publishing*, Toronto, 2018.
2 Wypych, G, **Handbook of UV Degradation and Stabilization**, 3rd Ed., *ChemTec Publishing*, Toronto, 2020.
3 Casadey, R; Challier, C; Senz, A; Criado, S, *Food Chem.*, **285**, 275-81, 2019.
4 Amarowicz, R; Pegg, RB, *Adv. Food Nutrition Res.*, in press, 2019.
5 Celiz, MD; Morehouse, KM; DeJager, LS; Begley, TH, *Polym. Deg. Stab.*, **165**, 196-206, 2019.
6 Twigg, C; Ford, K; Parent, JS, *Polymer*, **176**, 293-9, 2019.
7 Al-Malaika, S; Riasat, S; Lewucha, C, *Polym. Deg. Stab*., **145**, 11-24, 2017.

3.20 PHOSPHITES

Hydroperoxides are chemically reduced to alcohol and phosphite which is oxidized to the phosphate.[1] Phosphites play the key role in capturing aerobic radicals to produce more stable free radicals, such as aromatic phenoxy and alkyl radicals, as follows[1]

$$\mathrm{ROOH + P(OR_1)_3 \longrightarrow ROH + O{=}P(OR_1)_3}$$

$$\mathrm{RO^{\cdot} + P(OR_1)_3 \longrightarrow ROP(OR_1)_3 + R_1O^{\cdot}}$$

$$\mathrm{RO^{\cdot} + P(OR_1)_3 \longrightarrow O{=}P(OR_1)_3 + R^{\cdot}}$$

Phosphite antioxidants are extensively used in the polymer industry, but they are highly susceptible to hydrolysis leading to reduced antioxidative activity.[1] Melt-blended phosphites with layered double hydroxides are resistant to hydrolysis.[1] Phosphite gradually hydrolyzes.[1] The phosphoric acid is created, which catalyzes the hydrolysis reaction of the phosphite, accelerating self-catalysis effect, which leads to loss of antioxidative activity. (Figure 3.15).[1]

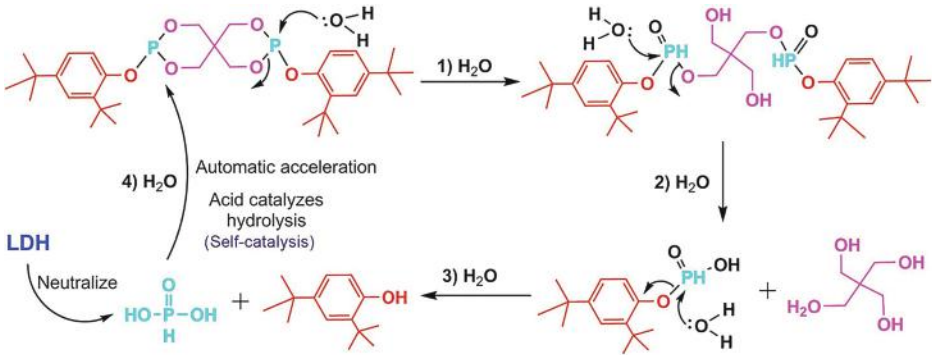


Figure 3.15. Mechanism hindering hydrolysis of hybridized phosphite antioxidant. [Adapted, by permission, from Sun, S; Wang, L; Song, P; Ding, L; Bai, Y, *Chem. Eng. J.*, **328**, 406-16, 2017.]

After hybridization, the basic hydrotalcite can neutralize the phosphoric acid, thus greatly slowing down the hydrolysis process and remarkably improving hydrolysis stability of phosphite-based antioxidants.[1] Also, granular layered double hydroxide plates create the "maze effect" lowering diffusion.[1]

The stabilizing efficiency of three-phosphorus secondary antioxidants of different chemical structures (phosphonite, phosphite, and phosphine) was compared in a Phillips type polyethylene.[2] The antioxidant consumption was strongly affected by the type of the phosphorous secondary antioxidant.[2] Phosphine showed the best melt stabilizing efficiency, while phosphonite was found to protect the polymer most effectively from discoloration.[2]

The migration of the antioxidant additives pentaerythrityl tetrakis(3,5-di-tert-butyl-4-hydroxyphenyl)propionate (Irganox 1010) and tris(2,4-di-tert-butylphenyl)phosphite (Irgafos 168) from polyolefinic packaging into oily vehicles was investigated.[3] The leaching of the two antioxidants varied depending on the polyolefin crystallinity and structure.[3] Migration of Irgafos 168 was greater than that of Irganox 1010, and the release of both antioxidants increased at a higher temperature (50°C).[3]

Effects of γ-irradiation on residual and migration levels of 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 were investigated in the linear low density polyethylene treated with doses from 0 to 200 kGy.[4] Migration of Irgafos 168 from the LLDPE pouch into food simulants (distilled water, acetic acid or ethanol) was not detected at dose levels up to 200 kGy while that of the Irganox 1076 was detected in a decreasing mode with increasing dose.[4]

A high molar mass phenolic phosphite antioxidant, tetrakis-(2,5-di-tert-butyl-4-hydroxyphenyl)-2,5-di-tert-butyl-hydroquinonediyl diphosphite, was used in polymethylmethacrylate.[5] The 0.5 wt.% of phenolic phosphite antioxidant retarded the 10% weight loss temperature and reduced the maximum rate of weight loss.

References

1 Sun, S; Wang, L; Song, P; Ding, L; Bai, Y, *Chem. Eng. J.*, **328**, 406-16, 2017.

2 Földes, E; Maloschik, E; Kriston, I; Staniek, P; Pukánszky, B, *Polym. Deg. Stab.,* **91**, 3, 479-87, 2006.

3 Marcato, B; Guerra, S; Vianello, M; Scalia, S, *Int. J. Pharm.*, **257**, 1-2, 217-25, 2003.

4 Jeon, DH; Park, GY; Kwak, IS; Lee, KH; Park, HJ, *LTW - Food Sci. Technol.*, **40**, 1, 151-6, 2007.

5 Chang, TC; Yu, PY; Hong, YS; Wu, TR; Chiu, YS, *Polym. Deg. Stab.*, **77**, 1, 29-34, 2002.

3.21 POLYPHENOLS

Under conditions of oxidative stress, cholesterol aggregates into discrete membrane bilayer domains that precipitate the formation of extracellular crystals, a hallmark feature of the advanced atheroma in cardiovascular disease.[1] Membrane-directed antioxidants, such as polyphenolic esters, alkylated to increase their lipophilicity and bioavailability, may reduce cholesterol domain formation and associated pathology.[1] The antioxidant potential of rosmarinic acid esters depended on alkyl chain length.[1] The mechanism of this effect was attributed to the influence of alkyl chain length on the optimal depth of the polyphenols in the lipid bilayer.[1]

Tea catechins, an important class of polyphenols, have antioxidant activity.[2] Eight major reaction products were isolated and identified from the oxidation reaction between epicatechin and peroxyl radicals generated by thermolysis of the azo initiator azo-bis-isobutyrylnitrile.[2]

Polyphenols are secondary metabolites of plants involved in defense against ultraviolet radiation or aggression by pathogens.[3] More than 8000 polyphenolic compounds have been identified so far in plants.[3] They arise from a common intermediate, phenylalanine, or a close precursor, shikimic acid.[3] Polyphenols chelate transition metal ions, scavenge molecular species of active oxygen, inhibit lipid peroxidation by trapping the lipid alkoxyl radical, and modify lipid packing order and decrease the fluidity of the membranes because of which polyphenols hinder the diffusion of free radicals and restrict peroxidative reactions.[3] Polyphenols outperform tocopherol because of their strong capacity to donate electrons or hydrogen atoms.[3]

Beneficial effects of red wine are entirely attributed to the polyphenols.[4] Grape juice was much more effective than red wine or dealcoholized red wine at the same polyphenol dose in inhibiting atherosclerosis and improving lipids and antioxidant parameters.[4]

Polyphenols derived from colored rice varieties constitute food alternative in combating obesity and obesity-related diseases.[5] The antioxidant and anti-inflammatory properties of polyphenols from colored rice varieties may have the ability to neutralize oxidative stress and modulate inflammatory responses in obese populations.[5]

Coffee contains polyphenols that may exert beneficial effects, especially antioxidant activity, on human health upon consumption.[6] Coffee had a polyphenolic content of 42.61 mg gallic acid equivalent/g coffee and was composed of 3-chlorogenic acid (16.61 mg/g), 4- and 5-chlorogenic acids (13.62 mg/g).[6]

References

1 Sherratt, S; Villeneuve, P; Jacob, R; Durand, E; Mason, RP, *Biophys. J.*, **112**, 3, Suppl. 1, 318a, 2017.
2 Sang, S; Tian, S; Wang, H; Stark, RS; Ho, C-T, *Bioorg. Med. Chem.*, **11**, 16, 3371-8, 2003.
3 Rodrigo, R; Libuy, M, **Modulation of Plant Endogenous Antioxidant Systems by Polyphenols. Polyphenols in Plants**, *Academic Press*, 2014, pp. 65-85.
4 Vinson, JA; Teufel, K; Wu, N, *Artherosclerosis*, **156**, 1, 67-72, 2001.
5 Callcott, ET; Santhakumar, AB; Luo, J; Blanchard, CL, *J. Appl. Biomed.*, **16**, 4, 255-62, 2018.
6 Priftis, A; Goutzourelas, N; Halabalaki, M; Ntasi, G; Kouretas, D, *Mechanism Aging Development*, **172**, 115-22, 2018.

3.22 STILBENE DERIVATIVES

Resveratrol (3,5,4′-*trans*-trihydroxystibene) is a natural phytoalexin present in grapes and red wine, which possesses a variety of biological activities including antioxidant activity.[1] The synthetic 4,4′-dihydroxy-*trans*-stilbene had substantially higher antioxidant activity than resveratrol.[1] The p-OH phenoxyl radical (p-semiquinone), the oxidation intermediate for 4,4′-DHS, was stabilized by the 4′-OH group by resonance through the *trans* double bond and it was easier to oxidize to form the final product para-quinone as depicted in Figure 3.16.[1]

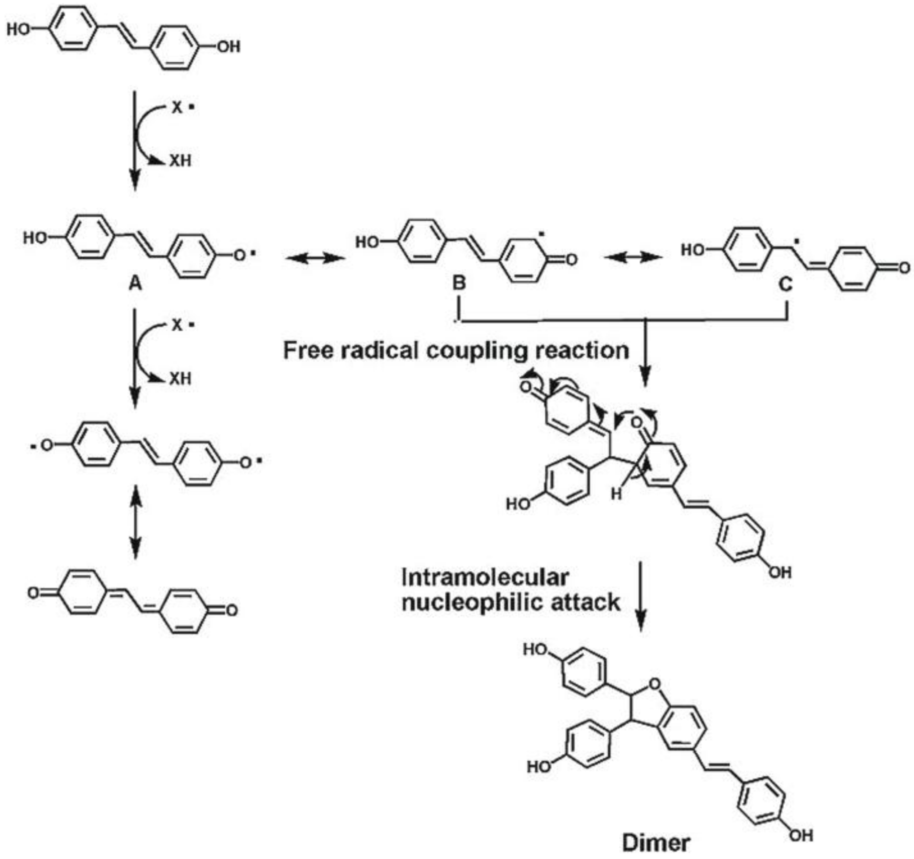


Figure 3.16. Antioxidant mechanism of 4,4’-dihydroxy-trans-stilbene. X$^{\cdot}$ denotes free radical. [Adapted, by permission, from Fan, G-J; Liu, X-D; Qian, Y-P; Shang, Y-J; Zhou, B, *Bioorg. Med. Chem*., **17**, 6, 2360-5, 2009.]

The hydrogen atom transfer (HAT) mechanism is the most important and dominant mechanism in vacuo, the sequential proton loss electron transfer (SPLET) mechanism is the most thermodynamically favorable pathway in water.[2] The antioxidant potency depends on the geometry of the neutral compounds, their phenoxy radicals, cation and anion structure, the number and position of the hydroxyl and methoxy groups, semiquinone and quinone structures.[2] The elongation of the conjugated links, the induced effect of both hydroxyl and methoxy groups, the intramolecular hydrogen bond effect after hydrogen abstraction also contribute strongly to antioxidant activity.[2]

Resveratrol can be used for minimizing or preventing lipid oxidation in pharmaceutical products, retarding the formation of toxic oxidation products, maintaining nutritional quality, and prolonging the shelf life of food products and pharmaceuticals.[3]

References

1 Fan, G-J; Liu, X-D; Qian, Y-P; Shang, Y-J; Zhou, B, *Bioorg. Med. Chem*., **17**, 6, 2360-5, 2009.

2 Benayahoum, A; Amira-Guebailia, H; Houache, O, *Comptes Rendus Chimie*, **18**, 2, 149-59, 2015.

3 Gülçin, I, *Innovative Food Sci. Emerging Technol.,* **11**, 1, 210-8, 2010.

3.23 SULFUR-CONTAINING COMPOUNDS

The polymer-soluble 4-alkyl-2-mercapto thiazolines are effective antioxidants for polypropylene.[1] They act as reservoirs for sulfur acids which behave as peroxidolytic antioxidants by reaction with hydroperoxides.[1] Two pairs of products (VIII a,b and IX a,b, Figure 3.17) are involved in the antioxidant action of the 4-alkyl-2-mercapto thiazoline compounds.[1] The disulfide is the initial transformation product.[1] The oxidative transformation products of 4-alkyl-2-mercapto thiazolines have an appreciable UV absorbance above 290 nm, which probably contributes to their photoantioxidant activity.[1]

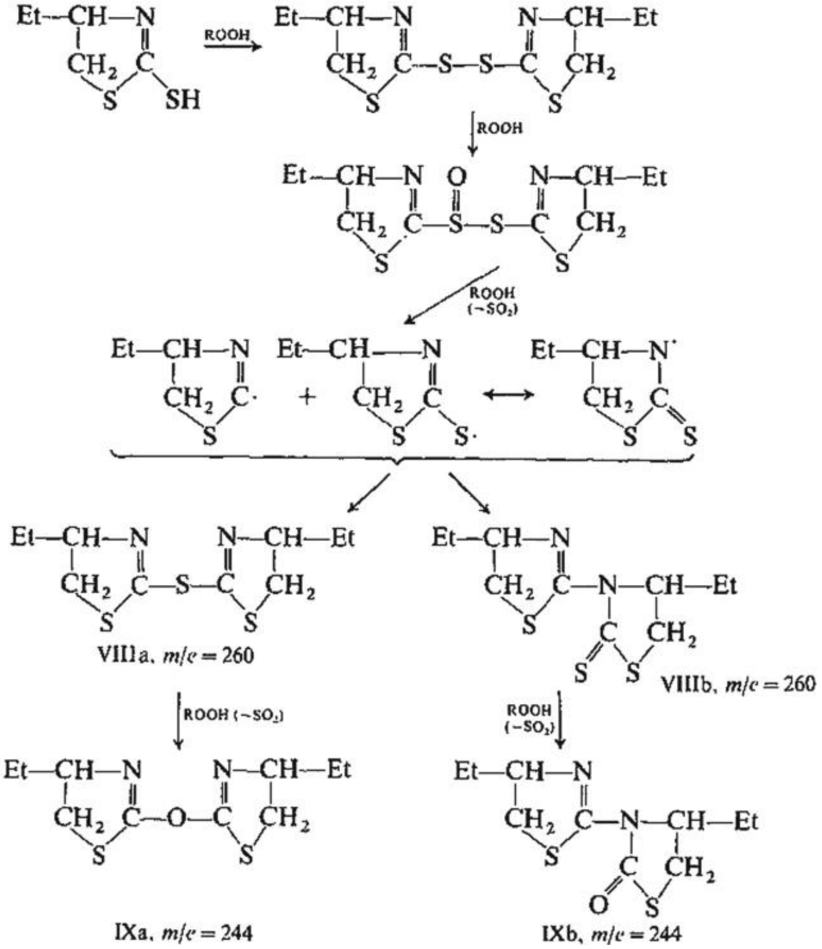


Figure 3.17. The mechanism for the oxidative transformation of 4-ethyl-2-mercapto thiazoline. [Adapted, by permission, from Al-Malaika, S; Chakraborty, KB; Scott, G; Tao, ZB, *Polym. Deg. Stab.*, **13**, 3, 261-76, 1985.]

Sulfur and selenium antioxidants can prevent oxidative stress that is an underlying cause of cardiovascular disease, Alzheimer's disease, and cancer.[2] Oxidation potentials of the sulfur or selenium compounds do not correlate with their ability to prevent DNA damage, highlighting the importance of metal coordination rather than reactive oxygen species scavenging as an antioxidant mechanism.[2] The chemical environment of the sulfur or selenium significantly affect DNA damage prevention.[2]

Metals such as Cu^I and Fe^{II} generate hydroxyl radical by reducing endogenous hydrogen peroxide (H_2O_2).[3] Metal complexation by sulfur antioxidants provides significant protection against cellular damage.[3] Sulfur compounds can selectively prevent oxidative DNA damage from either Cu^I or Fe^{II}.[3]

The antioxidant pathways have evolved to minimize the threat of excessive reactive oxygen species and to regulate reactive oxygen species as signaling entities.[4] Reactive oxygen species are chemically and functionally similar to reactive sulfur species and both reactive oxygen species and reactive sulfur species were metabolized by the antioxidant enzymes, superoxide dismutase and catalase.[4]

The bis(indol-3-yl)sulfides interact with a free radical source (FR), through one of two pathways, involving either single electron transfer (SET) or hydrogen abstraction (Figure 3.18).[5] In the first case, electron transfer from the antioxidant to the active radical would yield an anion (FR^-) and a cation radical species like *i*.[5] A structure resembling *i* has also been proposed as an intermediate for the hypervalent iodine-mediated SET oxidation of indole derivatives.[5] In the case of N-unsubstituted compounds, the electron transfer may be followed by proton transfer from the cation radical to the anion, generating species *ii*.[5]

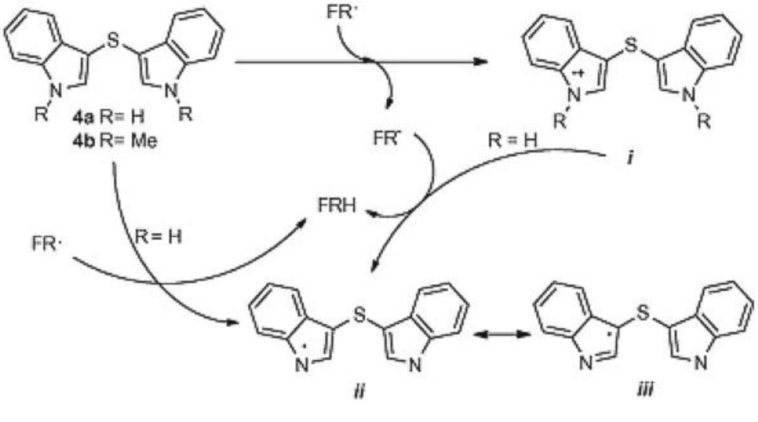


Figure 3.18. The mechanism of the antioxidant activity of the bis(indol-3-yl)sulfides (**4**). [Adapted, by permission, from Silveira, CC; Mendes, SR; Soares, JR; Victoria, FN; Savegnago, L, *Tetrahedron Lett.*, **54**, 36, 4926-9, 2013.]

When the indolic nitrogen is unsubstituted, a direct transfer of hydrogen between the antioxidant and the active radical may take place, furnishing the corresponding nitrogen-centered indolyl radical (*ii*), which is the resonant form of *iii*.[5]

Sulfur dioxide has antiseptic and antioxidant properties, and it is the most used preservative additive in winemaking and conservation.[6] It is the simplest chemical compound playing the role of antioxidant for many centuries.[6] It inhibits the action of dissolved oxygen; this slow process allows to protect wines from chemical oxidation, such as the oxidation of some polyphenols and some odorous substances.[6] In Europe concentration of sulfur dioxide is limited by law: 150 mg/L of total SO_2 for red wines, 200 mg/L for white wines, but in other countries it is different (e.g., 350 ppm in the USA, 250 mg/L in Australia).[6]

References

1 Al-Malaika, S; Chakraborty, KB; Scott, G; Tao, ZB, *Polym. Deg. Stab.*, **13**, 3, 261-76, 1985.
2 Zimmerman, MT; Bayse, CA; Ramoutar, RR; Brumaghim, JL, *J. Inorg. Biochem*., **145**, 30-40, 2015.
3 Battin, EE; Brumaghim, JL, *J. Inorg. Biochem.*, **102**, 12, 2036-42, 2008.
4 Olson, KR; Gao, Y, *Free Radical Biol. Med*., **135**,1-14, 2019.
5 Silveira, CC; Mendes, SR; Soares, JR; Victoria, FN; Savegnago, L, *Tetrahedron Lett.*, **54**, 36, 4926-9, 2013.
6 Giacosa, S; Río Segade, S; Cagnasso, E; Caudana, A; Gerbi, V, **SO_2 in Wines: Rational Use and Possible Alternatives. Red Wine Technology**. *Academic Press*, 2019, pp. 309-21.

3.24 TERPENOIDS

Over 30,000 types of chemicals can be synthesized by plants, which is about four times more than the microbial production of chemicals.[1] These include phenolic compounds, such as flavonoids, terpenoids, saponins, and triterpenoids.[1]

Guava is suggested by both traditional medicine and dietary supplements manufacturers for use in the case type 2 diabetes and associated diseases including hypertension and nephropathies.[2] It contains well over 230 chemical structures belonging to phenolic acids, flavonoids, tannins, and terpenoids (mono- and sesquiterpenes, triterpenes, and carotenoids).[2]

Limonene, linalool, and citral are common non-phenolic terpenoid components of essential oils, with attributed controversial antioxidant properties.[3] Their antioxidant behavior is attributed to their higher rate of self-termination and cross-termination as compared to the oxidizable substrate, thereby increasing the overall chain-termination and cutting the efficiency of autoxidation.[3] This termination-enhancing antioxidant activity differs from the chain-breaking behavior of common phenolic antioxidants by three main aspects of practical relevance:[3] i) their antioxidant performance is less pronounced than that of phenols and requires higher concentrations; ii) it is not linearly related to their concentration, hence it is much less predictable; iii) its effectiveness depends on the rate of chain-termination of the oxidizable substrate, being higher for substrates that have more modest chain-termination (whereas for phenols it depends on the substrate's rate of propagation).[3]

Phenolic compounds and terpenoids were identified in the bay and sage leaves extracts, which had high antioxidant activity.[4] A multilayer antioxidant packaging containing extract of these leaves was used for packaging to scavenge free radicals and delay oxidation of fried potatoes.[4] Lipid oxidation decreased by 40% and 31% for packaging with 60% sage and 80% bay ethanol extracts, respectively.[4]

For humans, carotenoids with provitamin A activity are important for vision, influence the human immune function and gap-junctional communication.[5] Antioxidative capacity is responsible for the health-promoting properties of fruits and vegetables.[5] Three main ways of antioxidant action of carotenoids have been detected until now (i.e., quenching of singlet oxygen, hydrogen transfer, or electron transfer).[5]

The main mechanism of photoprotection against singlet oxygen by carotenoids is physical quenching, which occurs by following mechanism[5]

$$^1O_2^* + \text{carotenoid} \rightarrow {}^3O_2 + {}^3\text{carotenoid}^*$$

$$^3\text{carotenoid} \rightarrow \text{carotenoid} + \text{thermal energy}$$

The long, conjugated polyene system of carotenoids permit dissipation of the excess energy *via* vibrational and rotational interactions with the solvent.[5] The carotenoid proceeds unchanged from this reaction, ready to begin another cycle of singlet oxygen quenching. It has been estimated that each carotenoid can quench 1000 singlet oxygen molecules before it reacts chemically.[5]

The effects of ozone upon 3-year-old trees of Clementina mandarin have been studied.[6] Exposure to ozone reduced total chlorophylls, carotenoid, and carbohydrate concentrations in leaves.[6] The ozone exposure triggered protective mechanisms against oxidative stress in citrus.[6]

References

1 Yang, X; Lei, Z; Yu, Y; Xiao, L; Zhang, Z, *South African J. Botany*, **121**, 178-85, 2019.
2 Habtemariam, S, **The chemical and pharmacological basis of guava (Psidium guajava L.) as potential therapy for type 2 diabetes and associated diseases. Medicinal Foods as Potential Therapies for Type-2 Diabetes and Associated Diseases**. *Academic Press*, 2019, pp. 251-305.
3 Baschieri, A; Ajvazi, MD; Folifack Tonfack, JL; Valgimigli, L; Amorati, R, *Food Chem.*, **232**, 656-63, 2017.
4 Oudjedi, K; Manso, S; Nerin, C; Hassissen, N; Zaidi, F, *Food Control*, **98**, 216-26, 2019.
5 Graßmann, J, *Vitamins Hormones*, **72**, 505-35, 2005.
6 Iglesias, DJ; Calatayud, A; Barreno, E; Primo-Millo, E; Talon, M, *Plant Phys. Biochem.*, **44**, 2-3, 125-31, 2006.

3.25 TOCOPHEROLS

Tocopherol, a fat-soluble compound having vitamin E activity, has antioxidant activity.[1] It is synthesized by photosynthetic organisms.[1] Tocopherol is crucial for seed storage and germination.[1] Vegetable oils, including soybean, sunflower, and almond oil, are rich in tocopherol.[1] Tocopherol is also found in other food sources, such as peanuts, asparagus, tomatoes, and carrots, and in smaller quantities in animal fats.[1] Tocopherol is sensitive to light because of its conjugated triene structure.[1] It reacts irreversibly with singlet oxygen to form tocopherol hydroperoxydienone, tocopherylquinone, and quinine epoxide, which protects other food components from singlet oxygen oxidation.[1] Ascorbic acid acts as a synergist with tocopherol by donating hydrogen atoms to tocopherol radical.[1] The regeneration of tocopherol leads to its reuse and prevention of tocopherol oxidation.[1]

Peroxyl radicals formed during oxidation require the action of a chain-breaking antioxidant to inhibit propagation.[2] Tocopherol breaks the destructive propagative cycle and intercepts the peroxyl radical more rapidly than polyunsaturated fatty acids.[2] The tocopherol donates its phenolic hydrogen atom to the radical and converts it to a hydroperoxide product, followed by reaction with another peroxyl radical to yield inactive, non-radical products, according to the following reactions[2]

$$\mathrm{TOH} + \mathrm{ROO}^{\cdot} \longrightarrow \mathrm{TO}^{\cdot} + \mathrm{ROOH}$$

$$\mathrm{TO}^{\cdot} + \mathrm{ROO}^{\cdot} \longrightarrow \text{inactive products}$$

This mechanism is illustrated in Figure 3.19.[2]

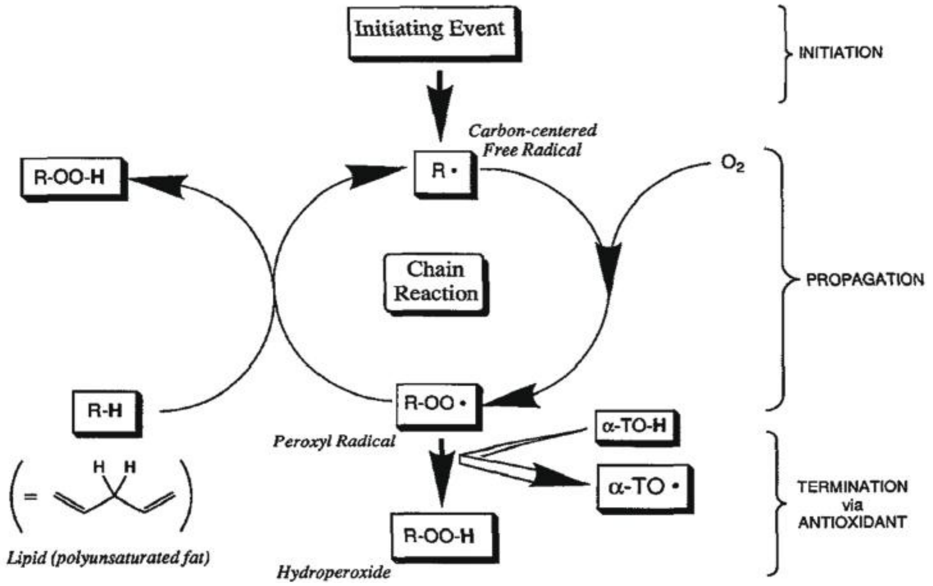


Figure 3.19. Three phases of the free radical chain mechanism of lipid peroxidation. The RH group contains the unsaturated unit common to all polyunsaturated acids. [Adapted, by permission, from Burton, GW; Traber, MG, *Annu. Rev. Nutrition*, **10**, 357-82, 1990.]

α-Tocopherol displayed a prooxidant effect on flaxseed oil.[3] The primary and secondary antioxidants activities were essential for antioxidants to protect flaxseed oil.[3] All natural antioxidants, except alpha tocopherol, delayed primary and secondary oxidation, and increased the oxidative stability index.[3] Among the natural hydrophobic antioxidants, the α-tocopherol displayed the highest capacity in scavenging free radicals followed by eugenol and β-carotene.[3]

Meat and poultry processors in the U.S. use butylated hydroxyanisole, butylated hydroxytoluene, tert-butylhydroquinone, propyl gallate, and tocopherols to prevent lipid and protein oxidation.[4] There is a trend towards utilizing natural antioxidants as replacements for synthetic ones.[4] Tocopherols may not exceed 0.03% on the basis of the product's fat content.[4] In red meat products, tocopherols may not be used in combination with other antioxidants, whereas in poultry products, tocopherols may be combined with other antioxidants up the concentration of 0.02% of fat content.[4]

Transfersomes were prepared from polysorbates (i.e., Tween) and loaded with tocopherol acetate, a naturally-occurring phenolic compound with antioxidant activity.[5] The vesicles delivered tocopherol to the skin and showed biocompatibility *in vitro* in keratinocytes and fibroblasts.[5] The transfersomes protected skin cells from the oxidative damage induced by hydrogen peroxide and promoted cell proliferation and migration, which resulted in an acceleration of skin wound closure (Figure 3.20).[5]

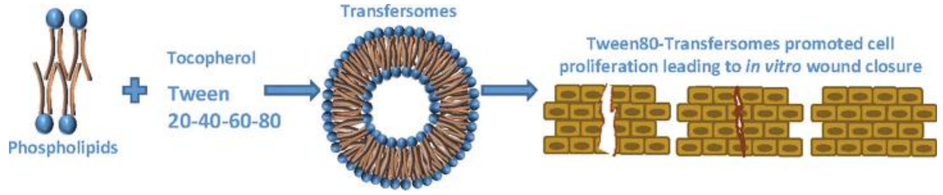


Figure 3.20. Skin protection and repair. [Adapted, by permission, from Caddeo, C; Manca, ML; Peris, JE; Usach, I; Manconi, M, *Int. J. Pharm.*, **551**, 1-2, 34-41, 2018.]

The inner layer of multilayer food packaging was made of hydrophobic polymer (PLLA) with tocopherol.[6] Controlled delivery of benzoic acid and tocopherol from multilayered microparticles provided a significant reduction in bacterial growth and inhibition of lipid oxidation over a period of 60 days.[6]

Migration of α-tocopherol adsorbed onto silica, and amino-functionalized mesoporous silica from LDPE polymer films was studied with special attention to the effect of the pore size and the chemical functionality of the internal walls of the mesophase.[7] The antioxidant diffusivity of films containing the functionalized mesoporous silica decreased by 60% as compared to films containing free tocopherol, resulting from the reduced pore size of the functionalized carrier and interaction between tocopherol molecules and amine groups.[7]

The α-tocopherol (the most active component of vitamin E) and synthetic phenolic antioxidant Irganox®1010 increased surface oxidation of high-density polyethylene and two types of cycloolefin copolymer in comparison with the neat polymers during

Weather-O-Meter exposure, showing prooxidant activity of tocopherols.[8] The prooxidant activity α-tocopherol was stronger in comparison with Irganox®1010.[8]

The nature of oxidative transformation products of the biological antioxidant α-tocopherol formed during melt extrusion of polyethylene and polypropylene was investigated.[9] The mechanism of melt stabilizing action of tocopherol in polypropylene was proposed (Figure 3.21).[9]

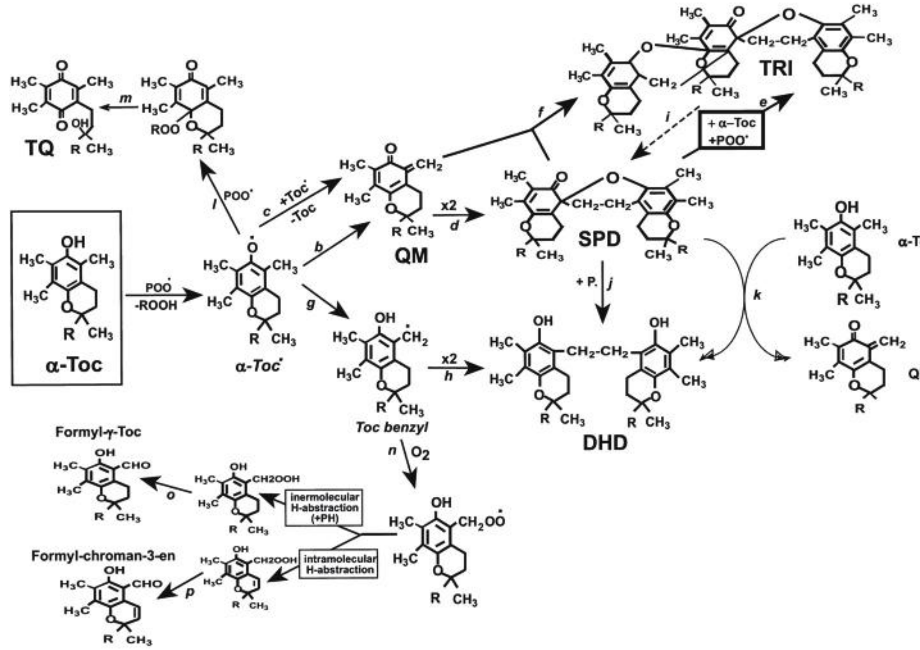


Figure 3.21. The mechanism of melt stabilizing action of tocopherol in polypropylene. [Adapted, by permission, from Al-Malaika, S; Issenhuth, S, *Polym. Deg. Stab.*, **65**, 1, 143-51, 1999.]

The oxidation of the tocopheroxyl radical in polypropylene leads to the formation of coupled and quinonoid-type products, such as spirodimer, SPD, trimer, TRI, dihydroxy dimer, DHD. Similar products have been isolated from the oxidation of α-tocopherol with a variety of oxidizing agents in polar and non-polar solvents at lower temperatures.[9] The almost exclusive formation of 5-methide-derived products, reported in the literature involving oxidation of tocopherol in solvents and polymers, has been explained in terms of the higher spin density at the 5-methyl position of α-tocopherol relative to the 7-methyl position as revealed by ESR spectroscopy.[9] The 5-methide-derived tocopherol-oxidation products formed in PP during melt processing (i.e., SPD, TRI, DHD) occur, most likely, by way of the quinone-5-methide.[9] The latter route, which yields quinone-5-methide and α-tocopherol, is a radical-radical disproportionation reaction which involves hydrogen atom transfer from the 5-methyl group of one α-tocopherol radical to the phenoxyl oxygen atom of the other radical.[9] Replacement of the 5-methyl group of α-tocopherol by a 5-trideuteromethyl group was found to retard the reaction rate.[9]

The melt stabilizing effect of α-tocopherol was found to be much higher than that of the commercial synthetic hindered phenol antioxidant Irganox 1010 especially at very low concentrations.[10] Higher concentration of α-tocopherol imparted greater discoloration to the polymer than Irganox 1010 examined at the same concentrations.[10] The incorporation of a phosphite antioxidant or polyhydric alcohol (non-antioxidant) reduced polymer discoloration, which was attributed to the reduction of the overall concentration of transformation products, formed from tocopherol as a result of its antioxidant function, the interaction of co-additives with colored transformation products, and regeneration of tocopherol.[10]

Supercritical carbon dioxide impregnation was used to adsorb α-tocopherol on monolayer and multilayer poly(ethylene terephthalate)/polypropylene films to obtain active packaging.[11] The migration tests confirmed that tocopherol was released by control release process from packaging.[11]

References

1 Duncan, SE, Chang, H-H, *Adv. Food Nutrition*, **67**, 25-73, 2012.
2 Burton, GW; Traber, MG, *Annu. Rev. Nutrition*, **10**, 357-82, 1990.
3 Mohanan, A; Nickerson, MT; Ghosh, S, *Food Chem*., **266**, 524-33, 2018.
4 Oswell, NJ; Thippareddi, H; Peg, RB, *Meat Sci.,* **145**, 489-79, 2018.
5 Caddeo, C; Manca, ML; Peris, JE; Usach, I; Manconi, M, *Int. J. Pharm.*, **551**, 1-2, 34-41, 2018.
6 Biswal, AK; Saha, S, *Coll. Surf. B: Biointerferences*, **175**, 281-90, 2019.
7 Gargiulo, N; Attianese, I; Buonocore, GG; Caputo, D; Lavorgna, M, *Microporous Mesoporous Mater*., **167**, 10-5, 2013.
8 Šlouf, M; Michálková, D; Gajdošová, V; Dybal, J; Pilař, J, *Polym. Deg. Stab*., **166**, 307-24, 2019.
9 Al-Malaika, S; Issenhuth, S, *Polym. Deg. Stab*., **65**, 1, 143-51, 1999.
10 Al-Malaika, S; Goodwin, C; Issenhuth, S; Burdick, D, *Polym. Deg. Stab*., **64**, 1, 145-56, 1999.
11 Franco, P; Incarnato, L; De Marco, I, *J. CO_2 Utilization*, **34**, 266-73, 2019.

4

OXIDATION IN LIVING CELLS

4.1 INTRODUCTION

It seems that knowledge of chain reaction involving free radicals is a part of science curricula for a long time, but, in fact, only in the 1950s the major step was discovered which contributed to the present understanding.[1] Studies of exposure to nuclear radiation made it clear that free radicals are formed, but their formation becomes really detrimental to the stability of a material when radicals are in the presence of oxygen. It is the oxygen reaction with free radicals which propagates extensive damage due to the chain reactions. Without the presence of free radicals, the reaction with oxygen is not possible because molecular oxygen at the ground triplet state having two unpaired electrons of the same spin cannot react with carbon with all paired electrons due to a very high activation energy which cannot be produced in biological systems.[1]

In polymers and materials, radicals are formed due to exposure to radiation or the presence of ozone. It is possible to use chemical stabilizers to prevent to some extent the formation of radicals in polymers. In living systems, radicals are produced due to the so-called oxidative stresses which are triggered by various circumstances, drought, low and high temperatures, etc., and the formation of oxidants is a part of signaling systems. They are all parts of the normal functioning of living things. It is not possible to prevent their formation in a similar manner as in non-living materials.

The primary radicals formed in living organisms include hydroxyl and alkoxyl radicals. Both types of radicals are very reactive, and they can react with any molecule in the neighborhood. Addition of antioxidants cannot eliminate them because the reaction rate of antioxidant is not very different from the reaction of any native substances present in the surroundings. For these reasons, oxidants (H_2O_2) and radicals when formed cannot be combated in the living matter by chemical antioxidants but have to be dealt with enzymes which either prevent the formation of radicals by reacting with hydrogen peroxide or reducing hydroperoxides formed from radicals.

For example, the enzyme catalase can decompose hydrogen peroxide in a two-step process, as follows[2]

$$\text{Catalase} + H_2O_2 \rightarrow \text{Compound I} + H_2O$$

$$\text{Compound I} + H_2O_2 \rightarrow \text{Catalase} + H_2O + O_2$$

where Compound I is an oxoferryl porphyrin π-cation radical.[2]

Examples of antioxidative defense systems, which comprise antioxidant enzymes, include such enzymes as superoxide dismutase, catalase, glutathione peroxidases, etc.

Hydroperoxyl radicals react with good rates with phenolic antioxidants such as α-tocopherol. This chain-breaking reaction leads to the formation of tocopheryl radical, which is relatively stable and does not lead to chain reaction unless in the presence of metal ions. Ascorbic acid and ascorbates (see Chapter 3) may return tocopherol radical to its original form. Glutathione, an active component of peroxidases, can reduce hydroperoxides and can also act as a direct radical scavenger. These and other components of chain-breaking reactions will be discussed below in reference to microorganisms, plants, fish, animals, and humans.

4.2 MICROORGANISMS

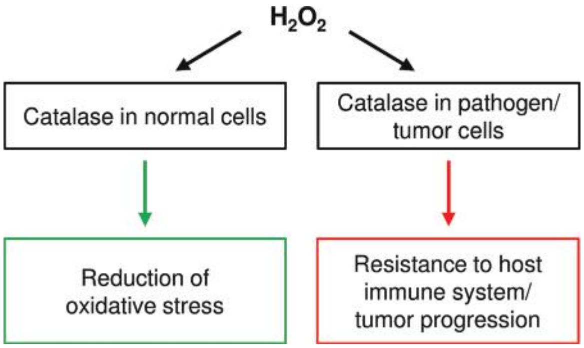


Figure 4.1. Difference in catalase performance in normal and pathogenic cells. [Adapted, by permission, from Gebicka, L; Krych-Madej, J, *J. Inorg. Biochem*., **197**, art 110699, 2019.]

Catalases, catalyzing the decomposition of hydrogen peroxide to water and molecular oxygen, are important for the antioxidant defense system of cells of almost all aerobic organisms.[2] Catalases react with hydrogen peroxide, and with oxidizing species such as hydroxyl radicals, superoxides, nitric oxides, peroxynitrites, hypochlorous acids, and singlet oxygen.[2]

Hydrogen peroxide is generated *in vivo* mainly in mitochondria, but also in other eukaryotic cell compartments, such as peroxisomes and endoplasmic reticulum (Figure 4.1).[2] Its concentration is regulated by catalase, several isoforms of glutathione peroxidases, and peroxiredoxins.[2] The oxidative stress is defined as an imbalance between oxidants and antioxidants in favor of the oxidants, leading to the disruption of redox signaling, control, and/or molecular damage.[2] Hydrogen peroxide at the physiological concentration plays a significant role in the cell signaling, by controlling such processes as differentiation and proliferation, as well as recruitment of immune cells.[2] Under pathological conditions, additional activation of enzymes producing $O_2^{\cdot -}$ (and as a consequence H_2O_2) and nitric oxide (NO) occurs, which results in an increase of H_2O_2 level above the optimal range, and generation of other oxidative species.[2]

The intracellular content of lactic acid bacteria may be a source of metabolites with antioxidant properties, which play an important role in the prevention of oxidative stress-related diseases.[3] A synergistic interaction was observed between glutathione and lipid or proteinaceous components.[3] Antioxidant enzymes, such as superoxide dismutase and glutathione peroxidase and glutathione can contribute to the antioxidant properties.[3]

Xylene caused oxidative stress in yeast cells of *Saccharomyces cerevisiae*.[4] Xylene caused fragmentation of mitochondria and the nuclear accumulation of an oxidative stress-responsive transcription factor, followed by the transcriptional activation of its target genes in yeast cells treated with xylene.[4] High salinity stress (1 M NaCl) causes pronounced but transient translation repression, and yeast cells can recover the translation activity within 2 h, demonstrating that yeast cells can adapt to the high salinity stress, unlike in the case of xylene.[4] The pronounced translation repression continued at least for 6 h in the presence of 0.03 vol% xylene, which suggests the greater difficulty faced by yeast cells to regain translation activity under severe xylene stress.[4]

The response of *Lactobacillus reuteri* against hydrogen peroxide-induced oxidative stress has been studied in the presence of resveratrol.[5] Resveratrol protected *L. reuteri* against protein carbonylation through various mechanisms including direct scavenging of reactive oxygen species, upregulation of the dhaT gene, and promoting the synthesis of sulfur-containing compounds.[5]

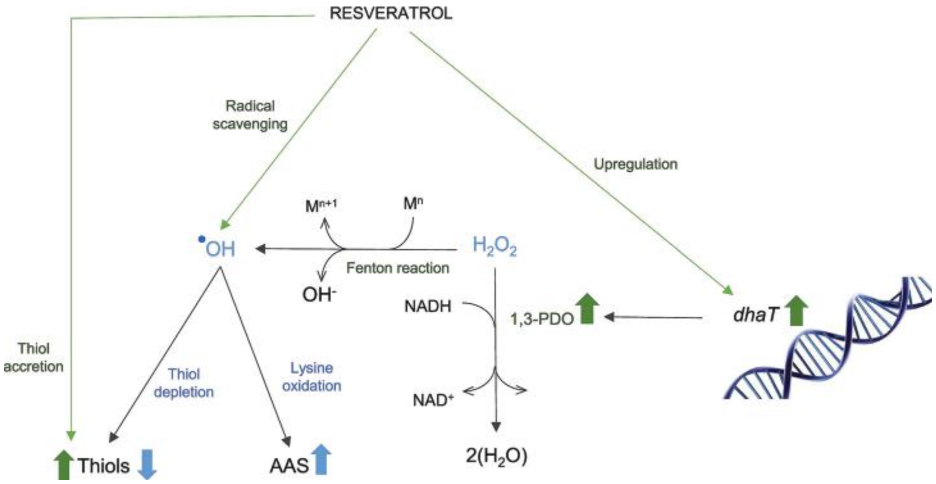


Figure 4.2. General scheme of the mechanisms by which resveratrol may protect *Lactobacillus reuteri* proteins against hydrogen peroxide-induced oxidative stress. [Adapted, by permission, from Arcanjo, NO; Andrade, MJ; Padilla, P; Rodríguez, A; Estévez, M, *Free Radical Biol. Med*., **135**, 38-45, 2019.]

Curtobacterium sp. caused the degradation of protein synthesis in infected plants.[6] The high rate of lipid peroxidation was observed in plants infected with bacteria.[6] The significant reduction of antioxidants such as carotenoids, catalase, and polyphenol oxidase activities were found in bacterium treated plants, which suggests that *Curtobacterium* sp. caused the oxidative stress and declined the antioxidants to suppress the growth of petunia plants.[6] The bacterium strongly influenced the antioxidants enzyme activities to reduce plant growth.[6] Non-enzymatic antioxidants were decreased during stress conditions.[6] One of the major plant pigments, carotenoids (non-enzymatic antioxidants) acted as a scavenger of singlet oxygen by quenching process, which was helpful to reduce the oxidative stress and photooxidation.[6]

Helicobacter pylori is a gram-negative, microaerophilic bacterium that can lead to the development of gastric cancer.[7] Reactive oxygen species and reactive nitrogen species produced by the immune and epithelial cells damage the host cells and can result in DNA damage.[7] *H pylori* causes this damaging response while blunting the host's efforts to kill the bacteria.[7] The long-lasting inflammation and oxidative stress may result in gastric carcinogenesis.[7]

The reactive oxygen species can be beneficial, but they may react with proteins, DNAs, lipids, and other biomolecules that should be stable, leading to enzyme dysfunction, genetic mutation, and lipid peroxidation (Figure 4.3).[8] The most vulnerable macromolecules include Fe–S dehydratases, mononuclear iron proteins, DNA, and lipids.[8] As lipids in most bacteria are not prone to peroxidation because of the lack of polyunsaturated fatty acids, the primary targets of reactive oxygen species are in the cytoplasm, which coincides with the fact that most of the reactive oxygen species scavenging enzymes also reside intracellularly.[8] These proteins not only comprise the basal line of defense to limit intracellular reactive oxygen species levels generated endogenously during normal growth but also function as the crucial part of the oxidative stress response system once the reactive oxygen species and associated cellular damages are over the physiologically safe limit.[8]

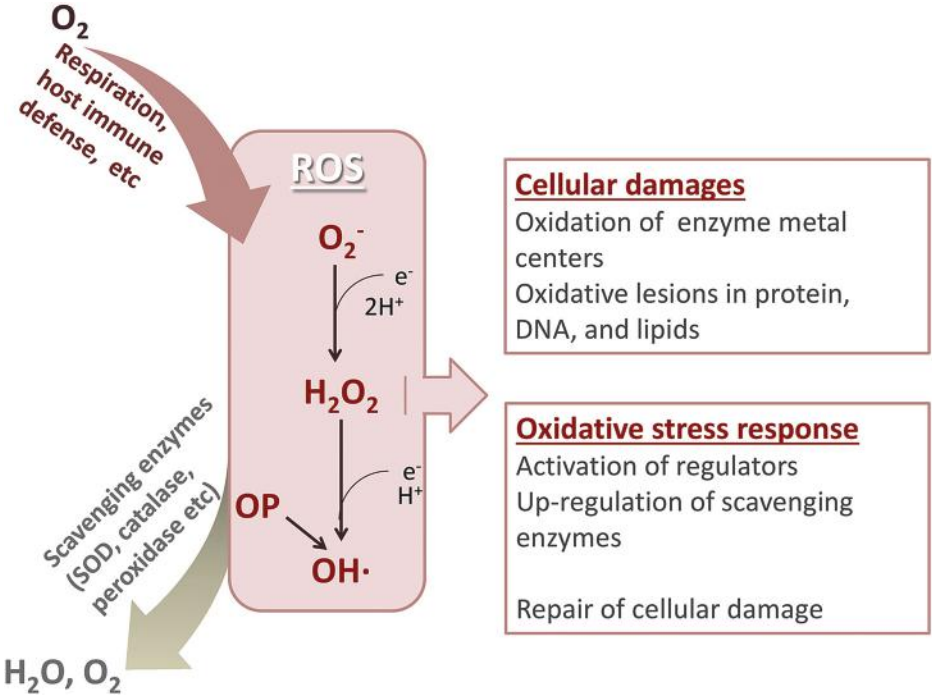


Figure 4.3. Sources, sinks and consequences of reactive oxygen species (ROS) in microbes. The sources of the ROS species (namely O_2^-, H_2O_2, and OH•) mainly include respiration, and immune defense by animal and plant hosts. These ROS can cause various cellular damages and induce oxidative stress response. Dedicated scavenging enzymes are responsible for cleansing out the damaging O_2^- and H_2O_2. [Adapted, by permission, from Fu, H; Yuan, J; Gao, H, *Arch. Biochem. Biophys*., **584**, 28-35, 2015.]

4.3 PLANTS

Reactive O_2 species are produced in both unstressed and stressed cells, and plants have well developed defense systems, involving both limiting their formation their removal.[9] The superoxide dismutases constitute the first line of defense against reactive oxygen species.[9] Chloroplasts, mitochondria, and peroxisomes are thought to be the most important generators of reactive oxygen species.[9] It is, therefore, crucial that superoxide dismutases are present for the removal of O_2^- in the compartments where they are formed.[9]

Based on the metal cofactor used by the superoxide dismutase (SOD), it can be classified into three groups: iron SOD, manganese SOD, and copper-zinc SOD, and they are located in different compartments of the cell.[9] Iron SODs are located in the chloroplast, manganese SODs in the mitochondrion and the peroxisome, and copper-zinc SODs in the chloroplast, the cytosol, and possibly the extracellular space.[9]

Glyphosate (the most used herbicide in the world) has been associated with several environmental contamination risks.[10] Presence of glyphosate inhibited growth, an accumulation of hydrogen peroxide and superoxide anion, an increase in lipid peroxidation, proline, and non-protein thiols, a decrease of the content of reduced ascorbate, and an upregulation of antioxidant enzymes.[10] Salicylic acid (a hormone-like substance) is able to enhance the efficiency of the antioxidant system in plants and their tolerance to oxidative stress.[10] The exogenous application of salicylic acid mitigated the effects of glyphosate on growth, amount of H_2O_2 and degree of lipid peroxidation.[10] It has also contributed to the reduction of reduced ascorbate content, production of non-protein thiols and increased antioxidant enzymatic activity, particularly superoxide dismutase, catalase, ascorbate peroxidase, and glutathione S-transferase.[10]

Plants can be exposed to several kinds of stresses that increase the production of reactive oxygen species, such as hydrogen peroxide, singlet oxygen, and hydroxyl radicals. When reactive oxygen species production outreaches safe level, oxidative damage to nucleic acids, lipids, metabolites, and proteins occurs, leading to cell death.

The growth, reproduction, and survival are a major goal in plant (and other living species) life.[11] Organisms must allocate resources to growth, reproduction, and self-maintenance for survival in a given environment. Two figures below characterize the effects of choices and trade-offs in plants.[11]

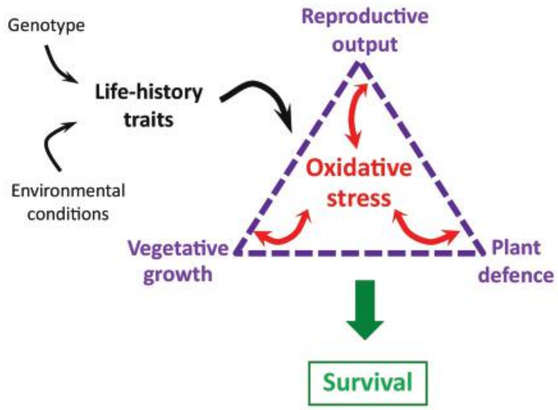


Figure 4.4. Illustration of the possible roles of oxidative stress as a master regulator of trade-offs at the organism level in plants. [Adapted, by permission, from Morales, M; Munné-Bosch, S, *Trends Plant Sci*., **21**, 12, 996-9, 2016.]

Figure 4.4 illustrates the roles of oxidative stresses at different organism level in plants.[11] Figure 4.5 illustrates the effects of these decisions.[11] Trade-offs occur on different organizational levels in plants.[11] On a cellular level, the recent identification of transcription factors helps in identification of trade-offs between plant defense against various biotic versus abiotic stresses.[11] Signaling pathways may be common or differential.[11] The capacity for cell division, cell expansion, defense responses, and senescence is interconnected and finely regulated to give the most adequate response to organ-level trade-offs.[11]

On the organ level, the trade-offs occur between the induction of defenses and responses to either biotic or abiotic stresses.[11] For instance, investment in defense against pathogens can affect the response of the plant to environmental stresses, such as drought or salinity.[11] The enhanced photoprotection can limit plant defense against pathogens.[11] On organism level, the trade-offs among vegetative growth, reproduction, and defense are strongly determined by life-history traits, such as iteroparity and/or semelparity, growth habit, and maximum lifespan.[11] Environmental stresses may trigger oxidative stress, limit vegetative growth, and reduce reproduction capacity.[11] The enhanced reproduction can increase oxidative stress in vegetative tissues, but cause damage or limit protection at the whole-plant level?[11] Oxidative stress might act as

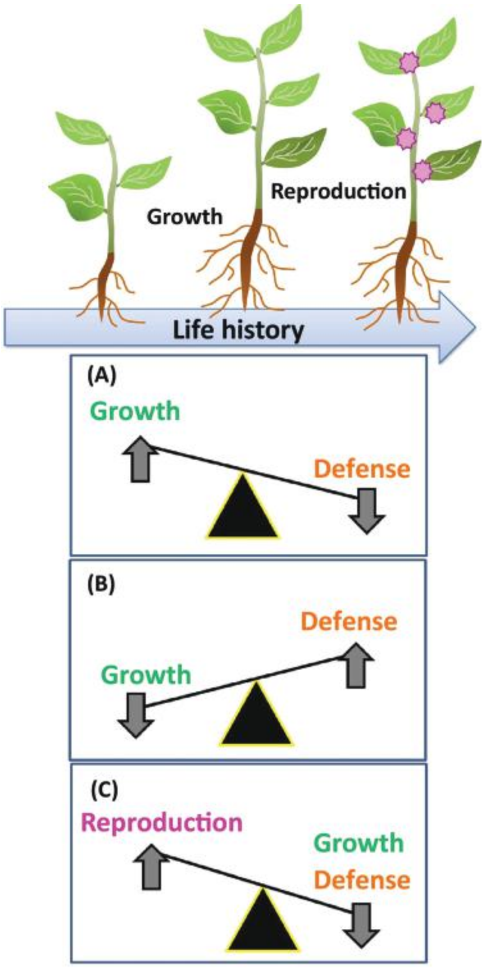


Figure 4.5. Life-history trade-offs in plants. (A) Growth is a metabolically demanding activity that removes resources from self-maintenance processes. Increased investments in growth may compromise defense responses in the short term, but may improve defense responses and reproductive fitness later in life. (B) An increased investment in defenses, either in response to biotic or abiotic stressors, reduces growth capacity, leading to negative effects on growth and reproduction. However, defense responses are essential for survival and, if plants are repeatedly exposed to these stressors, as occurs commonly in nature, investments in defense not only are the sole way to guarantee survival, but can also allow optimization of reproductive fitness under stress conditions in the long term. (C) Large investments in reproduction strongly compromise vegetative growth and defense responses. However, plants are generally adapted to flower and form fruits during the most favorable periods of the year. If biotic and/or abiotic stressors appear during reproduction, the latter may be strongly compromised. [Adapted, by permission, from Morales, M; Munné-Bosch, S, *Trends Plant Sci*., **21**, 12, 996-9, 2016.]

a master regulator of plant trade-offs and, thus, have a key positive role in survival (Figure 4.5).[11] All trade-offs determine in plants (and other living species) overall outcome and fate of the living organism.[11]

In response to chilling stress, production of H_2O_2 was increased in parallel with the reduction in sedoheptulose-1,7-bisphosphatase activity in tomato plants.[12] Under chilling stress, compared with wild-type plants, transgenic plants had increased carbon dioxide fixation and reduced electrolyte leakage.[12] Overexpression of sedoheptulose-1,7-bisphosphatase contributed to chilling tolerance by enhancing photosynthetic carbon fixation, decreasing H_2O_2 level, and promoting carbohydrate accumulation in transgenic plants.[12]

Rice suffers damage when oxidative stress is induced by environmental constraints.[13] Oxidative stress causes increased production of reactive oxygen species, including superoxide radicals, hydrogen peroxide, and singlet oxygen.[13] Reactive oxygen species react with proteins, lipids, nucleic acids, and pigments and cause irreparable damage.[13] Oxidative stress is measured by the concentration of malondialdehyde and reactive oxygen species.[13] Malondialdehyde is a by-product of lipid peroxidation.[13] Oxidative stress reduces growth, disturbs chloroplast ultrastructure, decreases chlorophyll, photosynthesis, relative water content, and nutrient balance in rice.[13]

Actinorhizal plant *Casuarina glauca* can establish nitrogen-fixing root-nodule symbiosis with *Frankia* bacteria which permits it to thrive under extreme environments, such as high salinity.[14]

The effect of biochar on mitigating fluoride toxicity in safflower seedlings has been studied.[15] The growth reduction was caused by an increase in fluoride content in plant tissues, generation of superoxide radicals and hydrogen peroxide, lipid peroxidation, misbalancing potassium and calcium ions, and a decrease in synthesis of photosynthetic pigments including chlorophylls, carotenoids, anthocyanin, flavonoids and xanthophylls, and photochemical efficiency of photosystem II.[15] Biochar is a carbon-rich material that is produced by thermal decomposition of organic material under limited supply of oxygen at temperatures up to 700°C.[15] Biochar was added to the soil for improving organic carbon storage, soil structure, and crop productivity.[15] Biochar decreased the fluoride solubility, the fluoride content of plant tissues, oxidative stress, and antioxidant enzymes activities, leading to an increase in cation exchange capacity of the soil and the pH, calcium and potassium uptakes, maximum efficiency of photosystem II, synthesis of photosynthetic pigments, and plant growth.[15]

Jasmonates are plant oxylipins, such as methyl jasmonate, jasmonic acid, and jasmonyl-isolucine.[16] These growth regulators are involved in physiological and biochemical procedures in plant growth and development, such as seed development, leaf growth, and senescence.[16] Jasmonates are also involved in plant defense mechanism against wounding by pathogens and insects attacks.[16] Jasmonates can modulate aspects of plant growth and resistance to different abiotic stresses such as drought, salinity, thermal stress, light stress, heavy metals, and flooding stress (Figure 4.6).[16]

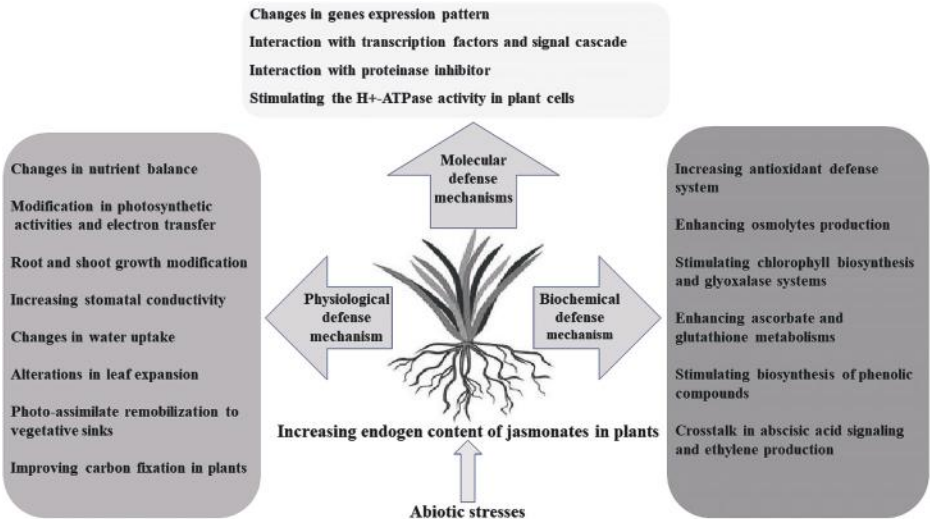


Figure 4.6. Summary of jasmonates mechanisms in increasing abiotic stress tolerance in plants. [Adapted, by permission, from Farhangi-Abriz, S; Ghassemi-Golezani, K, *Biocatal. Agr. Biotechnol.*, **20**, 101210, 2019.]

4.4 FISH

Fish are the most susceptible to the toxic effects of lead exposure.[17] In addition, fish can directly affect humans through food intake; therefore, fish can be used to assess the extent of environmental pollution in an aquatic environment.[17] Pb toxicity is caused by bioaccumulation in specific tissues.[17] The accumulation mechanisms vary depending on water habitat (freshwater or seawater) and pathway (waterborne or dietary exposure).[17] Lead accumulation in fish tissues causes oxidative stress due to excessive production of reactive oxygen species.[17] The oxidative stress mechanisms in fish exposed to metals are shown in Figure 4.7.[17]

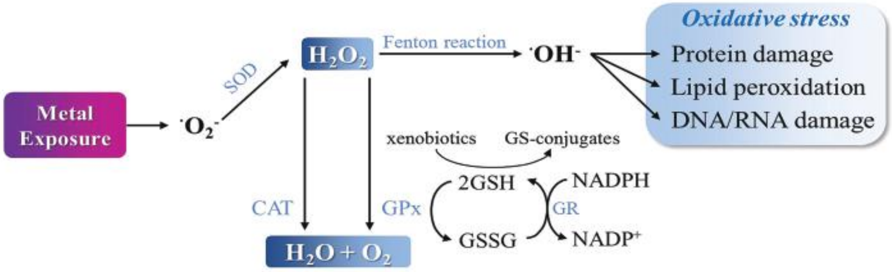


Figure 4.7. Oxidative stress mechanisms in fish exposed to metals. [Adapted, by permission, from Lee, J-W; Choi, HC; Hwang, U-K; Kang, J-C; Kim, J-H, *Environ. Toxic. Pharm.*, **68**, 101-8, 2019.]

Cold stress is a major threat to fish in both nature and aquaculture and can induce oxidative stress in various fish.[18] The acute cold exposure-induced high oxidative stress in zebrafish liver, which may lead to mortality.[18] The zebrafish fed with α-lipoic acid or reduced glutathione had lower cold-caused oxidative stress and tissues damage, showing higher cold tolerance.[18] Increasing oxidative stress by H_2O_2 decreased cellular cold tolerance.[18] The cold tolerance was partly recovered when oxidative stress was reduced by the addition of vitamin C.[18] Increased antioxidant capacity through dietary supplementation of antioxidants could largely promote cold tolerance in zebrafish.[18]

The effect of chronic exposure to Cu on the growth, oxidative stress, immune and biochemical response in the Nile tilapia has been studied.[19] Chronic exposure to Cu did not induce mortality, but growth of fish was affected.[19] Significant reduction in the activities of the antioxidant enzymes and concentrations of non-enzymatic antioxidants in gill and liver tissues were significantly increased.[19]

The effect of increased temperature on thermal and oxidative stress responses was studied in the muscles of several estuarine fish species (*Diplodus vulgaris, Diplodus sargus, Dicentrarchus labrax, Gobius niger,* and *Liza ramada*).[20] Catalase activity significantly increased in *L. ramada, D. labrax* and decreased in *D. vulgaris*.[20] Glutathione S-transferase activity increased in *L. ramada, D. sargus, D. vulgaris*, and *D. labrax*.[20] In *G. niger,* it showed a cycle of increase-decrease. Lipid peroxidation increased in *L. ramada, D. sargus* and *D. labrax*.[20]

Short-term exposure to increased temperature did not affect the oxidative status in Antarctic fish.[21] Long-term exposure to increased temperature affected the antioxidant system in tissues and induced the oxidative damage to lipids in tissues of rock cod.[21]

Autophagy is a bulk subcellular degradation process through which eukaryotic cells maintain health by forming autophagosomes and recycling intracellular substances.[22] This particular process is an important mechanism for cell survival, growth, differentiation, development, and homeostasis.[22] The nutrient deficiency-induced autophagy exerts a protective effect against reactive oxygen species-mediated toxicity, which can be used as a routine tool to monitor environmental toxicity risks.[22]

Cypermethrin is a synthetic pyrethroid insecticide, used in industrial and agricultural environments.[23] It is now one of the most common contaminants in freshwater aquatic systems.[23] An increase in DNA damage of gill cells following a dose- and time-dependent treatment with cypermethrin.[23] Also, superoxide dismutase and catalase activities significantly increased after exposure to 0.6 μg/L cypermethrin, both during six and nine days.[23]

Bacterial diseases cause major problems in freshwater fish culture and have been linked to significant losses and high mortality rate.[24] Nile tilapia *Oreochromis niloticus* was infected by *Providencia rettgeri* to evaluate the oxidative stress and antioxidant responses in the fish tissues.[24] Liver and kidney reactive oxygen species and lipid peroxidation levels were high in infected fish on day 14 post-infection compared to the control group.[24] Superoxide dismutase activity was lower in the liver (days 7 and 14 post-infection) and kidney (day 14 post-infection) compared to their respective control groups.[24] Liver and kidney antioxidant capacities against peroxyl radicals, non-proteic, and proteic thiols levels were lower in infected tilapia on day 14 post-infection compared to the control group.[24]

Toxic effects of graphene oxide on oxidative stress physiology especially at the mitochondrial level and redox modulation in fish in general and in climbing perch *Anabas testudineus* was absent.[25] Liver and gill tissues had shown a stronger response to graphene oxide than muscle.[25] The activity of superoxide dismutase, catalase, and glutathione-S-transferase was augmented in contrast to the lowered level of the reduced glutathione titer.[25] Graphene oxide-induced oxidative stress in cell and mitochondria in fish.[25]

4.5 ANIMALS

Preparation for oxidative stress was observed during oxygen deprivation (anoxia or hypoxia), freezing exposure, severe dehydration, aerial exposure of water-breathing animals, and estivation.[26] The 102 species from 8 phyla were stress-dependent: in estivation and dehydration, it was 91-100%, while in hypoxia it was 37.5-53%, depending on the criteria. In the case of air exposure, anoxia, and freezing the proportions of preparation for oxidative stress-positive species were 54-77%, 64-77%, and 75-86%, respectively.[26] Preparation for oxidative stress was a survival strategy of animals exposed to freezing, dehydration, and estivation, and, to a lesser extent, to oxygen deprivation itself (i.e., hypoxia and anoxia).[26]

Oxidative stress to cell components, caused by excessive reactive oxygen species, is connected to degenerative diseases associated with aging, such as cancer, Parkinson's disease, and cardiovascular disease.[27] Antioxidant defense systems, including enzymatic and non-enzymatic scavengers counteract the stress of reactive oxygen species, but these intracellular antioxidant defenses in older organisms are less able to prevent oxidative stress.[27] Levels of the enzymatic antioxidants superoxide dismutase, glutathione peroxidase, and catalase influence oxidative stress.[27] The antioxidative effects of probiotic products have attracted attention.[27] These probiotic products mainly contain *Lactobacillus* and *Bifidobacterium*, as well as some *Streptococcus* species.[27] In aged model mice, probiotics treatment had beneficial effects on serum catalase activity, glutathione peroxidase activity, and malondialdehyde content, and it reduced oxidative stress.[27]

Cerebral malaria is associated with oxidative stress and inflammatory mediators.[28] The oral administration of CoQ_{10} for 1 month and after malaria infection improves survival and significantly reduced edema.[28] CoQ_{10} reduced cholesterol and triglycerides lipids, levels of matrix metalloproteinases-9, angiopoietin-2 and angiopoietin-1 in the brain.[28] CoQ_{10} supplementation abrogated malondialdehyde, and 8-hydroxy-2-deoxyguanosine, and restored cellular glutathione.[28] The oral supplementation of CoQ_{10} protected mice against malaria-induced oxidative stress and neuro-inflammation.[28]

To oppose reactive species, animals have developed antioxidant defense mechanisms, which are classified according to enzymatic activity, such as catalase and peroxiredoxins, which act on H_2O_2, glutathione peroxidase, which reacts with peroxides in general, glutathione S-transferase, which is involved in the detoxification of xenobiotics, and superoxide dismutase, which catalyzes dismutation of superoxides into H_2O_2 and O_2.[29] Among non-enzymatic antioxidant defenses available to cells, reduced glutathione is the most abundant; also, vitamin C can protect against oxidative stress.[29] Animals with previous reproductive experience had a progressive increase in activity of all antioxidant enzymes until the animals reached 12 months of age; then the activity fell abruptly among older (24 months) animals.[29] In the group of animals without reproductive experience, the antioxidant enzyme activities remained stable from 3 to 12 months of age, but again, the activity also fell abruptly in 24 month-old animals.[29] The decrease in the activity of all enzymes among 24 month-old animals was greater in animals with reproductive experience.[29] At about the same time, the production of testosterone decreased.[29] Testosterone is a pro-oxidant, and increases oxidative stress in other organs by increasing metabolism, and thereby reduces male lifespan.[29] The castrated male rats lived longer than intact male rats.[29]

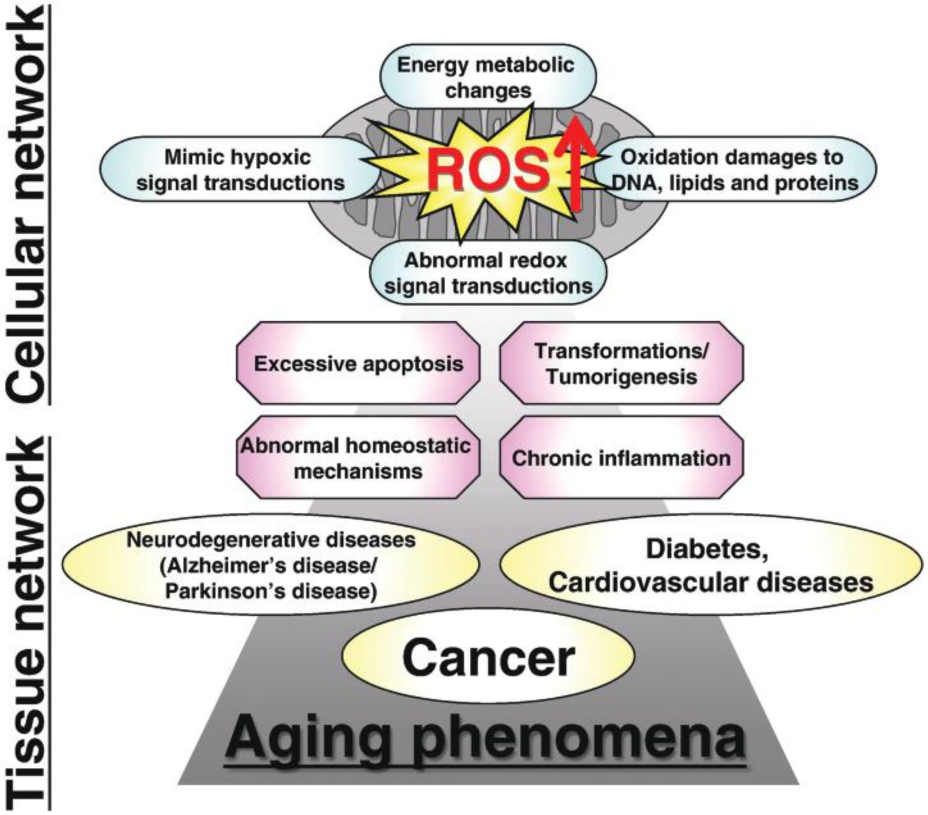


Figure 4.8. Mitochondrial ROS, cellular dysfunctions, organismal dysfunctions, and aging phenomena. This figure summarizes effects of elevated ROS in mitochondria, as it occurs in animal models (mev-1 model systems), and the various consequences of excess ROS on a variety of phenomena that relate to aging. [Adapted, by permission, from Ishii, T; Miyazawa, M; Onouchi, H; Yasuda, K; Ishii, N, *Biochim. Biophys. Acta - Bioenergetics*, **1827**, 588-97, 2013.]

Insulin increased brain oxidative stress through increase in levels of malonedialdehyde and glutathione peroxidase.[30] Also, nitric oxide level in the brain was increased in animals exposed to higher insulin levels. Insulin treatment may have deleterious effects on the brain through increased nitric oxide and oxidative stress levels.[30]

Airway inflammation and oxidative stress are the two major characteristics of asthma pathogenesis.[31] Combination of low doses of ascorbic acid with calcitriol improved mouse asthma because of the decrease of oxidative stress and inflammation.[31]

High-fat diet-induced oxidative stress, and neuronal damage that may have increased susceptibility to seizures.[32] Pentylenetetrazol seizures in rats consuming high-fat diet was prevented by vitamin E supplement, which induced changes in oxidative stress biomarkers and capacity enzymes.[32]

Mitochondria play a role of energy production and produce intracellular reactive oxygen species, especially superoxide anion, as a byproduct of energy metabolism.[33] The superoxide anion is converted from oxygen and is overproduced by excessive electron leakage from the mitochondrial respiratory chain.[33] The overproduction would cause chronic inflammation-related diseases or lifestyle-related diseases such as cardiovascular disease and diabetes as well as excessive apoptosis-related diseases; that is, neurodegenerative diseases such as Alzheimer's disease and Parkinson's disease (Figure 4.8).[33]

Bisphenol A is a widely used industrial compound worldwide, which have been classified as an environmental toxicant.[34] Dietary bisphenol A uptake increased the levels of oxidative stress indicators such as reactive oxygen species, reactive nitrogen species, malondialdehyde, and hydrogen peroxide in mouse serum, colon, and liver tissues.[34] Antioxidant indicators, such as superoxide dismutase, glutathione peroxidase, catalase, and total antioxidant capacity, as well as proinflammatory cytokines (interleukin-1β, interleukin-6, interleukin-8 and tumor necrosis factor-α) were also significantly reduced in the serum, colon, and liver tissues in the bisphenol A group.[34] Dietary bisphenol A induced oxidative stress, inflammatory response, apoptosis and mitochondrial dysfunction in mouse colons and livers.[34]

4.6 HUMANS

Ultra-weak photon emission (biophoton emission) is observed in living organisms, and it is detectable in human skin.[35] Its intensity increases due to external stress such as ultraviolet irradiation.[35] Biophoton emission is caused by the formation of reactive oxygen species-induced lipid peroxidation and protein and nucleic acid oxidation.[35] The emission is suppressed by antioxidants.[35] The efficiency of sunscreen was confirmed by the imaging technique.[35]

Statins (3-hydroxy-3-methylglutaryl-coenzyme A reductase inhibitors) are the most effective lipid-lowering drugs, effectively reducing total cholesterol and low-density lipoprotein, while also decreasing three triacylglycerols and increasing high-density lipoprotein.[36] The long-term use of statins can cause *in vitro* cytotoxicity, *in vivo* liver injury, liver necrosis, kidney damage, and myopathy in both human beings and animals.[36] Various antioxidants may prevent or reduce damage (Figure 4.9).[36]

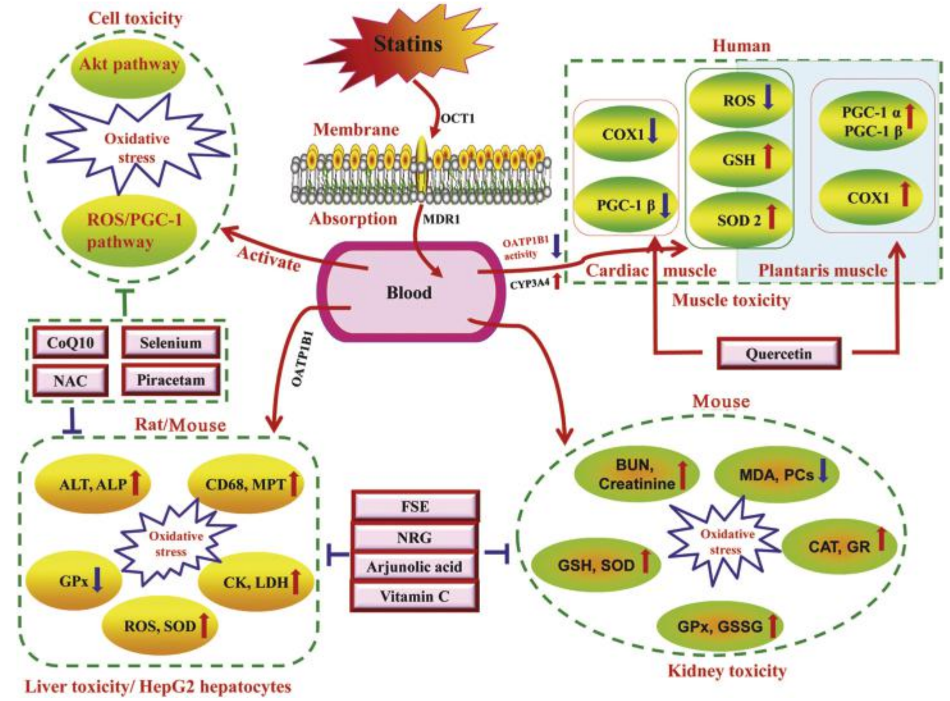


Figure 4.9. Schematic illustration of the preventive effect of different compounds, including antioxidants and free radical scavengers, on statin-induced oxidative stress. The use of different antioxidants, such as quercetin, selenium, piracetam, CoQ10, arjunolic acid, vitamin C, naringenin (NRG), extract from *Fructus schisandrae* (FSE), and N-acetylcysteine (NAC), can suppress statin-induced oxidative stress levels, which improves the total antioxidant status, and thus leads to the prevention of apoptosis. [Adapted, by permission, from Liu, A; Wu, Q; Guo, W; Ares, I; Martínez, M-A, *Pharmacol. Therapeutics*, **195**, 54-84, 2019.]

In heart failure, there is oxidative stress in the heart, leading to structural and functional changes that contribute to disease progression.[37] The oxidative stress results from an imbalance in the production and degradation of reactive species.[37] The cause of increased reactive oxygen species is their increased production because of increased metabolic activity, stimulated production by mechanical strain, neurohormonal activation, inflammatory cytokines, and decreased antioxidant activity.[37]

Bisphenol F and S are increasingly used as alternatives to endocrine-disrupting chemical bisphenol A.[38] Evidence from *in vitro,* and animal studies demonstrates that all of them induce oxidative stress.[38] Repeated urinary specimens are required to characterize bisphenol exposure levels and the oxidative stress status of individuals.[38]

Bisphenol A was implicated in altered human reproductive function.[39] The oxidative stress or change of inflammatory signaling may be a key factor in the biological changes of the human endometrium.[39] Reactive oxygen species generation was the highest upon exposure to 1000 pmol bisphenol A.[39] An elevated estrogen receptor-α expression levels correlated with changes in oxidative stress, inflammatory gene expression, and signal changes in cellular proliferation signaling.[39] The bisphenol A exposure alters cell signaling pathways by reactive oxygen species generation, leading to increased proliferation, up-regulation of pro-survival proteins, and increased migration and invasion in other human cells (Figure 4.10).[39]

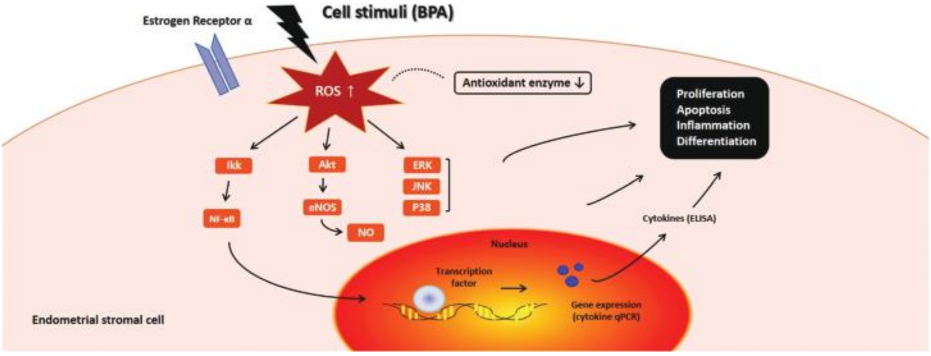


Figure 4.10. Responses to bisphenol A. [Adapted, by permission, from Cho, YJ; Park, SB; Park, JW; Oh, SR; Han, M, *Reproductive Toxicol*., **81**, 41-9, 2018.]

Cinnamon is a dietary supplement and traditional medicine used for the therapy of oxidative stress-related diseases.[40] The preventive functions of cinnamon are attributed to the presence of cinnamaldehyde and its analogs.[40] Cinnamon improved the intracellular antioxidant capacity.[40] Cinnamon contains twenty-two chemical ingredients, including cinnamaldehyde analogues, a lignan pinoresinol and a flavonol (-)-(2R,3R)-5,7-dimethoxy-3′, 4′-methylenedioxy-flavan-3-ol were identified as inhibitors of oxidative stress.[40] The lignan pinoresinol and the flavonoid are two novel Nrf2 activators protecting tissues against oxidative insults.[40]

The amyloid beta peptide is implicated in the development of pathological reactions associated with Alzheimer's disease, such as oxidative stress, neuro-inflammation, and death of brain cells.[41] Exposure to radiofrequency electromagnetic field caused a decrease of beta-amyloid deposition in the brains. Electromagnetic field was able to reduce $A\beta_{42}$- and H_2O_2-induced cellular reactive oxygen species, abrogate $A\beta_{42}$-induced production of mitochondrial reactive oxygen species.[41] Electromagnetic treatment of brain cells with parameters similar to irradiation from an ordinary mobile phone was capable of suppressing oxidative stress triggered by $A\beta_{42}$ and H_2O_2.[41] The beneficial impact of electromagnetic frequency can be employed in the treatment of neurodegenerative disorders such as Alzheimer's disease.[41]

Carcinogenesis is a multistep process involving both the mutation of critical genes, and increased cell proliferation.[42] Overproduction of reactive oxygen species is caused by endogenous and/or exogenous sources.[42] Endogenous sources include intracellular organelles and inflammatory sources.[42] Exogenous sources include xenobiotics, pharmaceuticals, and radiation.[42] The resulting oxidative stress can induce mutations in critical cellular genes under inhibited antioxidant defense pathways and DNA repair mechanisms.[42] Oxidative stress and damage participate in all stages of cancer development (Figure 4.11).[42] Oxidative stress has also been linked to a number of human cancers (causing and modulating factor).[42] The susceptibility to human cancers can be modified by polymorphisms in oxidative DNA repair genes and antioxidant genes.[42]

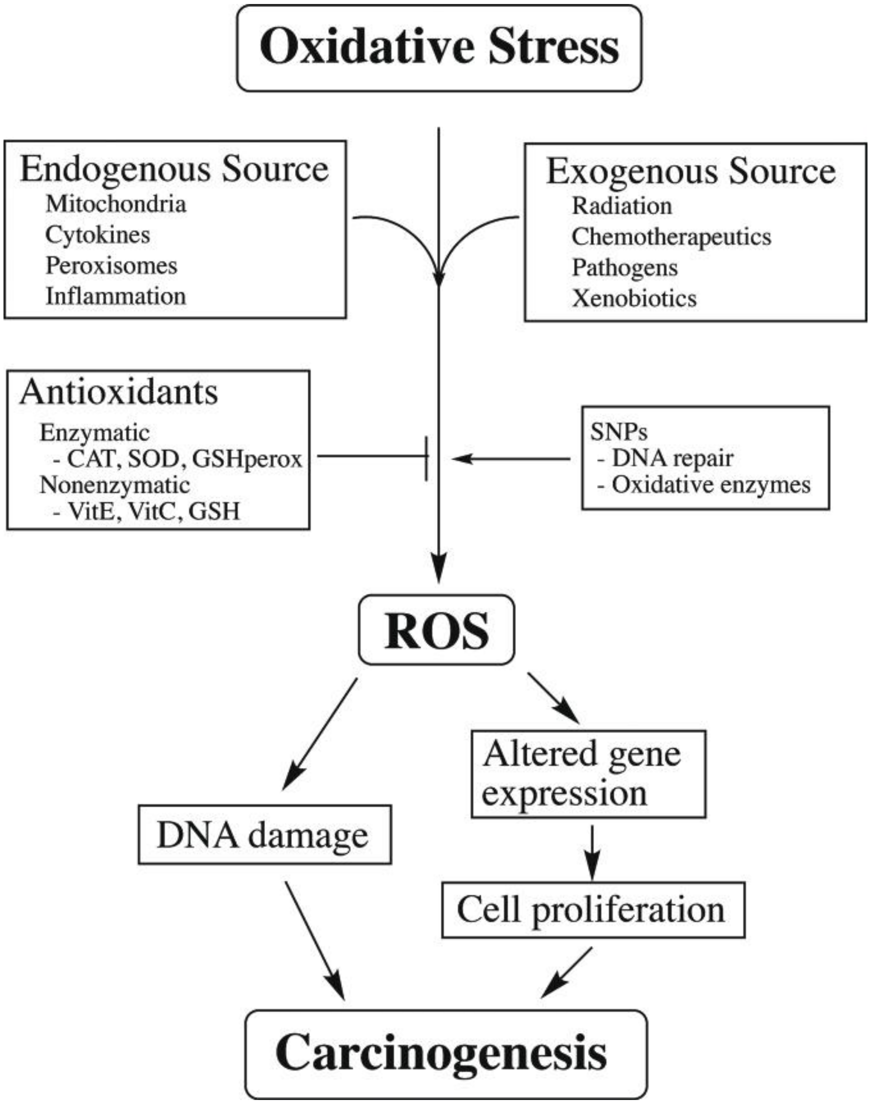


Figure 4.11. Sources of oxidative stress and effects on carcinogenesis endpoints. Diagram showing the influence of endogenous and exogenous sources of oxidative stress on carcinogenesis endpoints. Genetic (SNPs) and nongenetic repair pathways can be overrun by excess oxidative stress resulting in reactive oxygen species that can in turn damage DNA or alter gene expression (in particular cell growth genes) resulting in activity on the carcinogenesis process. [Adapted, by permission. from Klaunig, JE; Wang, Z, *Current Opinion Toxicol*., **7**, 116-21, 2018.]

Curculigoside, a phenolic glycoside, protects against damage induced by oxidative stress.[43] H_2O_2-induced oxidative stress of cell models decreased percentages of cell viability, increased levels of reactive oxygen species, reduced activities in antioxidant enzymes, and inhibited expressions of antioxidant proteins.[43] The pretreatment with curculigoside significantly inhibited the H_2O_2-induced apoptosis and prevented the cytotoxic effects of H_2O_2, suggesting that it protected the cells against H_2O_2-induced oxidative damage.[43]

The effect of ultrasound exposure on human lens epithelial cells was investigated *in vitro* in relation to the generation of oxidative stress.[44] The effect of ultrasound on cell viability and induction of oxidative stress increased with ultrasound intensity.[44] Continuous ultrasound increased the oxidative stress levels.[44]

Pomegranate phenolics have been reported to exert beneficial skin effects.[45] The commercial pomegranate extract and its phenolics, including punicalagin and ellagic acid reduced the production of H_2O_2-induced reactive oxygen species in spontaneously transformed aneuploid immortal keratinocyte cells by 1.03-, 1.37-, and 2.67-fold, respectively.[45]

Overproduction of reactive oxygen species is associated with the pathophysiology of many diseases, including excessive activation of polymorphonuclear neutrophils and macrophages, which leads to reactive oxygen species generation.[46] Antioxidants prevented damage associated with oxidative stress.[46] Antioxidant vitamins exert a protective effect against oxidative stress on human cells.[46] Exercise promotes mechanisms to accumulate antioxidant vitamins into cells sensitive to the effects of reactive oxygen species.[46]

References

1 Forman, HJ; Davies, KJA; Ursini, F, *Free Radical Biol. Med.*, **66**, 24-35, 2014.
2 Gebicka, L; Krych-Madej, J, *J. Inorg. Biochem.*, **197**, art 110699, 2019.
3 Aguilar-Toalá, JE; Estrada-Montoya, MC; Liceaga, AM; Garcia, HS; Hernández-Mendoza, A, *LWT*, **102**, 58-63, 2019.
4 Yoshimoto, N; Kawai, T; Yoshida, M; Izawa, S, *J. Biosci. Bioeng.*, in press, 2019.
5 Arcanjo, NO; Andrade, MJ; Padilla, P; Rodríguez, A; Estévez, M, *Free Radical Biol. Med.*, **135**, 38-45, 2019.
6 Pugazhendhi, A; Radhakrishnan, R; Duc, PA, *Biocat. Agric. Biotech.*, **20**, art. 101274, 2019.
7 Butcher, LD; den Hartog, G; Ernst, PB; Crowe, SE, *Cellular Molec. Gastroenterology Hepatology*, **3**, 316-22, 2017.
8 Fu, H; Yuan, J; Gao, H, *Arch. Biochem. Biophys.*, **584**, 28-35, 2015.
9 Grene Alscher, R; Erturk, N; Heath, LS, *J. Exp. Botany*, **53**, 372, 1331-41, 2002.
10 Spormann, S; Soares, C; Fidalgo, F, *J. Environ. Mng.*, **241**, 226-34, 2019.
11 Morales, M; Munné-Bosch, S, *Trends Plant Sci.*, **21**, 12, 996-9, 2016.
12 Ding, F; Wang, M; Zhang, S, *Scientia Horticulturae*, **214**, 27-33, 2017.
13 Ashraf, AA; Iqbal, M; Rasheed, R; Hussain, I; Riaz, M, **Abiotic Stress-Induced Oxidative Stress in Rice. Advances in Rice Research for Abiotic Stress Tolerance**, *Woodhead Publishing*, 2019, pp. 489-504.
14 Jorge, TF; Tohge, T; Wendenburg, R; Ramalho, JC; António, C, *Environ. Experim. Botany*, **166**, art. 103808, 2019.
15 Ghassemi-Golezani, K; Farhangi-Abriz, S, *Chemosphere*, **223**, 406-15, 2019.
16 Farhangi-Abriz, S; Ghassemi-Golezani, K, *Biocatal. Agr. Biotechnol.*, **20**, 101210, 2019.
17 Lee, J-W; Choi, HC; Hwang, U-K; Kang, J-C; Kim, J-H, *Environ. Toxic. Pharm.*, **68**, 101-8, 2019.
18 Lu, D-L; Ma, Q; Sun, S-X; Zhang, H; Du, Z-Y, *Comparative Biochem. Phys. Part A: Molec. Integrative Physiol.*, **235**, 166-73, 2019.
19 Gopi, N; Vijayakumar, S; Thaya, R; Govindarajan, M; Vaseeharan, B, *J. Trace Elements Med. Biol.*, **55**, 170-9, 2019.
20 Madeira, D; Narciso, L; Cabral, HN; Vinagre, C; Diniz, MS, *Comparative Biochem. Phys. Part A: Molec. Integrative Physiol.*, **166**, 2, 237-43, 2013.

21 Klein, RD; Borges, VD; Rosa, CE; Colares, EP; Bianchini, A, *J. Thermal Biol.*, **68A**, 110-8, 2017.

22 Xia, X; Wang, X; Qin, W; Jiang, J; Cheng, L, *Aquaculture*, **511**, art. 734212, 2019.

23 Paravani, EV; Simoniello, MF; Poletta, GL; Casco, VH, *Ecotoxicol. Environ. Safety*, **173**, 1-7, 2019.

24 De Freitas Souza, C; Baldissera, MD; Verdi, CM; Santos, RCV; Baldisserotto, B, *Microbial Pathogenesis*, **131**, 164-9, 2019.

25 Paital, B; Guru, D; Mohapatra, P; Panda, B; Srivastava, A, *Chemosphere*, **224**, 796-804, 2019.

26 Moreira, DC; Venancio, LPR; Sabino, MACT; Hermes-Lima, M, *Comparative Biochem. Phys. Part A: Molec. Integrative Physiol.*, **200**, 64-78, 2016.

27 Zhao, J; Tian, F; Zhao, N; Zhai, O; Chen, W, *J. Funct. Foods*, **39**, 44-49, 2017.

28 Nyariki, JN; Ochola, LA; Jillani, NE; Nyamweya, NO; Isaac, AO, *Parasitology Int.*, **71**, 106-20, 2019.

29 Salomon, TB; Schäfer Hackenhaar, F; Almeida, AC; Krumberg Schüller, A; Silveira Benfato, M, *Exp. Gerontology*, **48**, 9, 940-6, 2013.

30 Yarube, I; Ayo, J; Magaji, R; Umar, I, *Respiratory Phys. Neurobiol.*, in press, art. 112640, 2019.

31 Sadeghipour, HR, *Respiratory Phys. Neurobiol.*, in press, art. 103265, 2019.

32 Alzoubi, KH; Hasan, ZA; Khabour, OF; Mayyas, FA; Alrabadi, NNS, *Phys. Behavior*, **206**, 200-5, 2019.

33 Ishii, T; Miyazawa, M; Onouchi, H; Yasuda, K; Ishii, N, *Biochim. Biophys. Acta - Bioenergetics*, **1827**, 588-97, 2013.

34 Wang, K; Zhao, Z; Ji, W, *Biomed. Pharmacotherapy*, **117**, art. 109182, 2019.

35 Tsuchida, K; Iwasa, T; Kobayashi, M, *J. Photochem. Photobiol B: Biol.*, **198**, 111562, 2019.

36 Liu, A; Wu, Q; Guo, W; Ares, I; Martínez, M-A, *Pharmacol. Therapeutics*, **195**, 54-84, 2019.

37 Sverdlov, AL; Ngo, DTM; Colucci, WS, **Oxidative Stress in Heart Failure, Heart Failure: a Companion to Braunwald's Heart Disease**, 4th Ed, *Elsevier*, 2020, pp. 115-26.

38 Wang, Y-X; Liu, C; Shen, Y; Wang, Q; Zeng, Q, *Environ. Int.*, **123**, 301-9, 2019.

39 Cho, YJ; Park, SB; Park, JW; Oh, SR; Han, M, *Reproductive Toxicol.*, **81**, 41-9, 2018.

40 Li, A-L; Li, G-H; Li, Y-R; Wu, X-Y; Shen, T, *Phytomedicine*, **53**, 143-53, 2019.

41 Tsoy, A; Saliev, T; Abzhanova, E; Turgambayeva, A; Askarova, S, *Neuroscience*, **408**, 46-57, 2019.

42 Klaunig, JE; Wang, Z, *Current Opinion Toxicol.*, **7**, 116-21, 2018.

43 Chang, H-T Jan, C-R; Liang, W-Z, *J. Functional Foods*, **41**, 171-82, 2018.

44 Rwei, P; Gong, C-SA; Luo, L-J; Lin, M-B; Liu, H-L, *Biochem. Biophys. Res. Commun.*, **482**, 4, 954-60, 2017.

45 Liu, C; Guo, H; DaSilva, NA; Li, D; Ma, H, *J. Functional Foods*, **54**, 559-67, 2019.

46 Tur, JA; Sureda, A; Pons, A, **Evaluation of Oxidative Stress in Humans: A Critical Point of View Obesity**, *Academic Press*, 2018, pp. 191-6.

5

PREVENTION OF OXIDATION OF SELECTED POLYMERS AND RUBBERS

5.1 ABS (ACRYLONITRILE-BUTADIENE-STYRENE)

β-Carotene decreased the number of carbonyl and hydroxyl functional groups as compared to the non-stabilized samples.[1] The reaction of carotenoid biradicals with molecular oxygen hindered the formation of peroxy and alkoxy radicals in the propagating step of the thermooxidation of acrylonitrile-butadiene-styrene.[1]

Polymeric antioxidant for acrylonitrile-butadiene-styrene was prepared by reacting oligo(styrene-co-chloromethylstyrene) and 2,6-di-tert-butylphenol, in which the 2,6-di-tert-butylphenol moiety acted as an antioxidant and the polystyrene portion improved the solubility of this antioxidant in ABS.[2]

Blend of phosphites comprising bis-(2,4-dicumylphenyl) pentaerythritol diphosphite and hindered phenol antioxidant (tetrakis [methylene(3,5-di-t-butyl hydroxyhydrocinnamate)]methane) was used as a stabilizer against thermooxidative degradation of several polymers including ABS.[3]

References

1 Abdel-Razik, EA, *J. Polym. Sci. Part A Polym. Chem.*, **27**, 1, 343-355, 1989.
2 Tseng, T-w; Tsai, Y; Lee, J-s, *Polym. Deg. Stab.*, **58**, 3, 241-5, 1997.
3 Stein, D; Stevenson, DR; Kodali, SR; Nolen, M, **US6770693B2**, *Dover Chemical Corp.*, Aug. 3, 2004.

5.2 AK (ALKYD RESIN)

The autoxidation of fatty acid methyl esters derived from colza, sunflower, linseed, and tung oils and the oxidation of sunflower fatty acid methyl esters in the presence of several commercial driers based on Co(II), Mn(II), Fe(II), V(IV), Sr(II), Zr(IV), Ca(II), Zn(II) have been investigated.[1] Only Co(II), Mn(II) and Fe(II) had catalytic effects on the oxidation and the ROOH decomposition steps. Co-based drier had a higher oxidation rate while the Fe-based drier had a greater ROOH decomposition rate.[1]

Alkyd resins are used in both air-drying and baking varnishes and enamels.[2] Baked films of tung oil-unsaturated alkyd resin compositions do not require use of driers as ordinary varnishes since the hardening process takes place as a result of a Diels-Alder addition reaction between the unsaturated alkyd resin and the conjugated double bond system of the eleostearic acid which comprises from about 75 to 80% of the tung oil.[2] It is desirable to add an antioxidant to such varnishes to suppress air drying. It is desirable to add 0.01 to 0.5% of an antioxidant to the mixture of tung oil and the rosin-modified unsaturated alkyd resin to prevent the frosting or wrinkling of the surfaces exposed to the air during curing or baking.[2] The antioxidant may be copper naphthenate, hydroquinone, resorcinol, or tertiary butyl catechol.[2]

The thermal aging of alkyd resins and of their formulations shows unacceptably high variations in melt viscosity upon thermal aging when the protection system is based on phenolic antioxidants, which are most frequently used for traditional hotmelt adhesives (such as Hostanox 245).[3] Butylated hydroxytoluene was more effective stabilizing antioxidant for alkyd resins than traditional antioxidants.[3]

References

1 Dubrulle, L; Lebeuf, R; Thomas, L; Fressancourt-Collinet, M; Nardello-Rataj, V, *Prog. Org. Coat.*, **104**, 141-51, 2017.
2 Root, FB, **US3092596A**, *USA Agriculture*, Jun. 4, 1963.
3 Corzani, I; Lunetto, P, **US20140094762A1**, *Procter and Gamble Co*, Apr. 3, 2014.

5.3 C (CELLULOSE)

Quercetin offers promising applications in the healthcare, food, and pharmaceutical industries.[1] But, its instability, low water solubility, and low bioavailability remain to be solved.[1] Cellulose nanofiber was used as an effective nanoscale carrier to alleviate these problems.[1] High loading capacity of 78.91% and an encapsulation efficiency of 88.77% were achieved.[1] The nano-formulation had better dietary performance and antioxidant activity than raw quercetin.[1] Moreover, the sustained release of quercetin was demonstrated *in vitro*.[1] Figure 5.1 illustrates the method of preparation.[1]

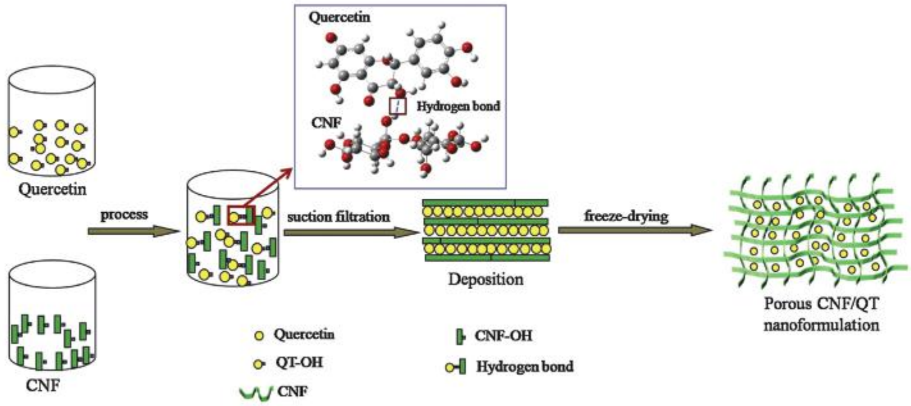


Figure 5.1. Illustration of the formation of the cellulose nanofiber/quercetin nano-formulation. [Adapted, by permission, from Li, X; Liu, Y; Yu, Y; Chen, W; Yu, H, *Carbohydrate Polym*., **207**, 160-8, 2019.]

A self-healing composite hydrogel having antioxidant and antibacterial activities is based on cellulose nanofibrils and tannic acid (Figure 5.2).[2]

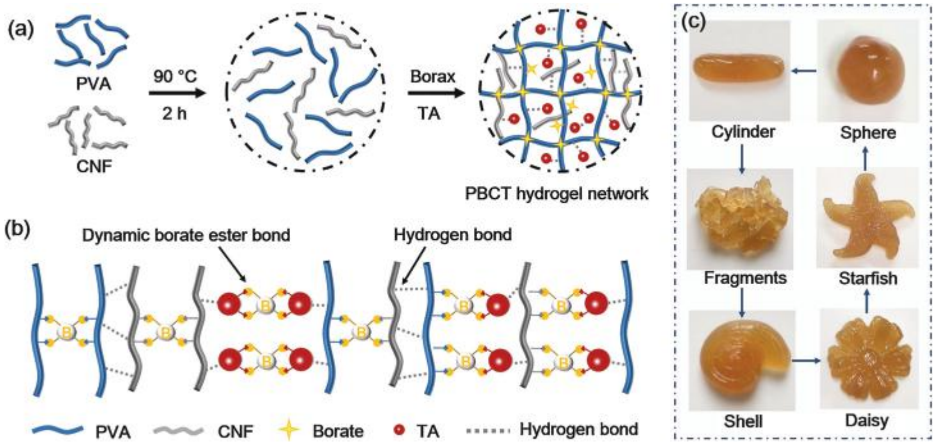


Figure 5.2. Illustration of the preparation of PBCT hydrogel (a). Formation mechanism of the 3D network within PBCT hydrogel (b). PBCT hydrogels molded into various shapes (c). [Adapted, by permission, from Ge, W; Cao, S; Shen, F; Wang, Y; Wang, X, *Carbohydrate Polym*., **224**, 115147, 2019.]

Chain entanglements, inter- and intramolecular hydrogen bonding between the different components contributed to the formation of 3D network within the PBCT hydrogels.[2]

Phenolic antioxidants were immobilized on cellulose nanocrystals and microcrystalline cellulose to reduce their loss.[3] The products were synthesized with antioxidant acid chlorides forming ester bonds, and some were grafted with aliphatic acid chlorides to improve their solubility in non-polar polymeric matrices.[3]

Bacterial cellulose and poly(vinyl alcohol) were used for the preparation of hydrogel, and gallic acid/cyclodextrin was loaded into hydrogel composite.[4] The release profile of the composite was slow compared with that of pristine gallic acid.[4] The antioxidant properties of composite and gallic acid were similar, according to DPPH• and ABTS•^+ assays.[4]

Antibacterial and antioxidant chitosan-xylan/cellulose nanowhiskers nanocomposite films were successfully prepared.[5] The inhibitory effects against *S. aureus* and *E. coli* and the ABTS^+ scavenging activity indicated antibacterial and antioxidant functions of the nanocomposite films.[5]

The lemongrass oil exhibited excellent antioxidant and antibacterial properties, but its low aqueous solubility and instability of its major constituents reduced the retention of these properties.[6] Its composites with cellulose nanofibers-polyethylene glycol were fabricated by the melt mixing process.[6] The composite system retained major compounds of lemongrass essential oil (geranial, neral, and geranyl acetate) up to 120 days and followed pseudo-Fickian diffusion of aroma molecules.[6]

References

1 Li, X; Liu, Y; Yu, Y; Chen, W; Yu, H, *Carbohydrate Polym.*, **207**, 160-8, 2019.
2 Ge, W; Cao, S; Shen, F; Wang, Y; Wang, X, *Carbohydrate Polym.*, **224**, 115147, 2019.
3 Weigl, S; Raffetzeder, S; Paulik, C, *Polym. Deg. Stab.*, **134**, 41-8, 2016.
4 Chunshom, N; Chuysinuan, P; Thanyacharoen, T; Techasakul, S; Ummartyotin, S, *Mater. Chem. Phys.*, **232**, 294-300, 2019.
5 Bao, Y; Zhang, H; Luan, Q; Zheng, M; Huang, F, *Carbohydrate Polym.*, **184**, 66-73, 2018.
6 Mishra, D; Khare, P; Singh, DK; Luqman, S; Saikia, BK, *Ind. Crops Products*, **114**, 68-80, 2018.

5.4 CA (CELLULOSE ACETATE)

Nano-biocomposite films based on plasticized cellulose acetate/triethyl citrate were prepared with silver nanoparticles/gelatin-modified montmorillonite nanofiller and thymol.[1] The glass transition temperature of polymer increased slightly after the addition of clay but decreased because of the presence of thymol due to its plasticizing effect.[1] The radical 2,2-diphenyl-1-picrylhydrazyl tests confirmed the antioxidant properties of thymol-containing films.[1] The material with antimicrobial/antioxidant properties is promising for active packaging.[1]

Encapsulation matrix was fabricated by electrospinning of cellulose acetate and gum arabic blend for encapsulation of *Viburnum opulus* L. fruit extract.[2] Encapsulation efficiency of the extract was between 83 and 87%.[2] The 2,2-diphenyl-1-picrylhydrazyl scavenging assay showed that after 14 days of storage at 4 and 25°C, antioxidant activity of free extract was 40 and 34%, respectively.[2] Antioxidant activities of extract loaded into fibers were significantly higher ranging from 56-59% and 55-58% at 4 and 25°C, respectively.[2] More information about the use of cellulose acetate electrospun nanofibers for drug delivery systems can be found in a review paper.[3]

Clove essential oil or eugenol in cellulose acetate or acrylic component/hydrophobically modified starch coatings on corona treated oriented polypropylene film were investigated for their possible applications as antioxidant packaging materials for fresh meat.[4] The cellulose acetate coatings containing clove essential oil or eugenol showed 43-92% and 43-94% inhibition against DPPH free radicals.[4] After 14 days, the lipid oxidation in beef steaks was kept in control.[4]

Ascorbic acid used to reduce oxidation of powders, tablets, gels, and emulsions obtained from cellulose acetate comprising high doses of omega-3 fatty acids.[5] Biodegradable plastic material based on cellulose acetate contained Irganox 1076 or its mixture with organic phosphite.[6] The proliposomal composition that was used to deliver nutraceuticals contained quercetin.[7]

References

1 Dairi, N; Ferfera-Harrar, H; Ramos, M; Garrigós, MC, *Int. J. Biol. Macromol.*, **121**, 508-23, 2019.
2 Çanga, EM; Dudak, FC, *LWT*, **110**, 247-54, 2019.
3 Khoshnevisan, K; Maleki, H; Samadian, H; Shahsavari, S; Khorramizadeh, MR, *Carbohydrate Polym.*, **198**, 131-41, 2018.
4 Navikaite-Snipaitiene, V; Ivanauskas, L; Jakstas, V; Rüegg, N; Yildirim, S, *Meat Sci.*, **145**, 9-15, 2018.
5 Torgersen, T-L; Klaveness, J; Myrset, AH, **US20120156296A1**, *Omegatri AG*, Jun. 21, 2012.
6 Conterno, C, **EP2599827A1**, *ES Laminati Estrusi Termoplastici SpA*, Jun. 5, 2013.
7 Yatvin, MB, **WO2006062544A1**, *Oradel Medical Ltd.*, Jun. 15, 2006.

5.5 CAR (CARRAGEENAN)

Antioxidant and pH-sensitive κ-carrageenan-based films were developed by incorporating different amounts of mulberry polyphenolic extract.[1] Due to abundant anthocyanin content, the extract showed pH-sensitive property with solution color changed from red to purple and final gray when pH value increased from 2 to 13.[1] Extract and κ-carrageenan interacted *via* hydrogen bonds.[1] κ-Carrageenan-mulberry polyphenolic extract films could be used to monitor the freshness of milk.[1]

The antioxidant capacity of irradiated κ-, ι-, λ-carrageenans were investigated using the hydroxyl radical scavenging assay, reducing power assay and DPPH radical scavenging capacity assay.[2] The degree of oxidative inhibition increased with increasing concentration and dose.[2] The type of carrageenan had also an influence on its antioxidant activity which followed the order of lambda<iota<kappa.[2] Increase in oxidative property with radiation dose can be attributed mainly to the depolymerization of the carrageenans with a corresponding increase in reducing sugar.[2]

Pharmacological properties of native carrageenan (κ) extracted from *Kappaphycus alvarezii* and commercial carrageenan were evaluated using *in vitro* antioxidant, anticancer, and antidiabetic studies.[3] The native carrageenan from *K. alvarezii* possessed better antioxidant potential than commercial carrageenan.[3] The native carrageenan had anticancer agents because of free radical scavenging ability.[3]

References

1 Liu, Y; Qin, Y; Bai, R; Zhang, X, Liu, J, *Int. J. Biol. Macromol.*, **134**, 993-1001, 2019.
2 Abad, LV; Relleve, LS; Racadio, CDT; Aranilla, CT; De la Rosa, AM, *Appl. Radiat. Isotopes*, **79**, 73-9, 2013.
3 Suganya, AM; Sanjivkumar, M; Chandran, MN; Palavesam, A; Immanuel, G, *Biomed. Pharmacotherapy*, **84**, 1300-12, 2016.

5.6 CHI (CHITOSAN)

Water-soluble chitosan derivatives were synthesized by the Maillard reaction with lactose (Figure 5.3).[1] The Maillard reaction derivatives with a lower molecular weight, degree of deacetylation, and greater solubility were obtained.[1]

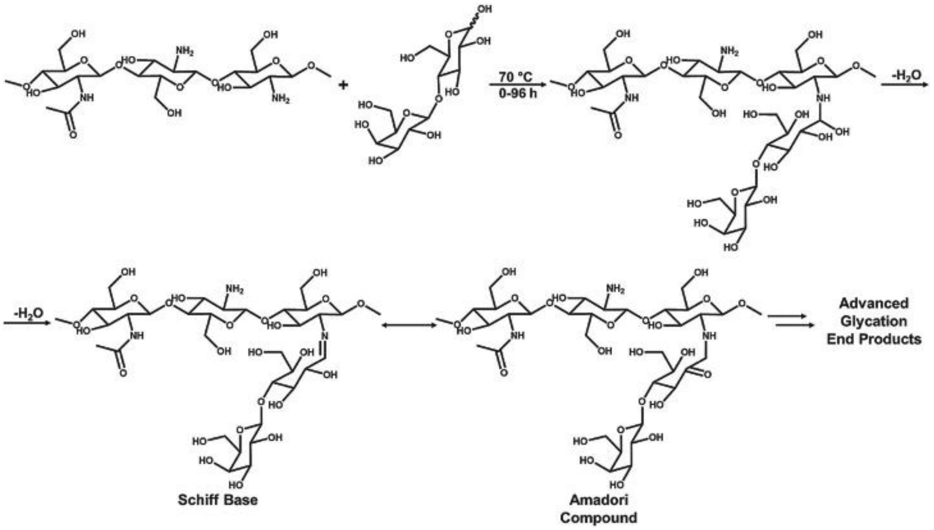


Figure 5.3. Synthesis routes for chitosan derivatives by the Maillard reaction between chitosan and lactose. [Adapted, by permission, from Badano, JA; Vanden Braber, N; Rossi, Y; Díaz Vergara, L; Montenegro, M, *Carbohydrate Polym*., **224**, 115158, 2019.]

The solubility of the derivatives obtained was up to 37 times higher than that of chitosan.[1] The antioxidant activity of the derivatives towards ABTS•$^+$ and O2•$^-$ was increased, and the activity towards HO• remained the same.[1]

Chitosan is used for edible coatings.[2] Chitosan was grafted with procyanidin (grafting degree of 340.9 g kg^{-1}), a potent natural antioxidant, by a free radical-mediated procedure to improve the protective effect on the antioxidant capacity of fresh-cut pineapple.[2] The coating of pineapple containing chitosan derivative prevented its weight loss, inhibited microbial growth on the fruit, and preserved its vitamin C content.[2]

Films of chitosan and reacetylated chitosan having different degrees of acetylation (13.3 and 33.9%, respectively) were produced and used to incorporate antioxidant active compounds such as annatto (*Bixa Orellana L.*) and vitamin C with potential application as an anti-aging skin mask treatment.[3] The antioxidant compounds (annatto and vitamin C) were released faster from reacetylated chitosan films and were more suitable for cosmetics applications.[3] They released 52% of the anti-aging compounds in about 15 min.[3]

Zein nanoparticles coated with chitosan for use as resveratrol were obtained by the liquid-liquid dispersion method.[4] Particles had a mean diameter of 295 nm, low polydispersity index, and spherical shape.[4] Zeta potential after coating was +29 mV and the encapsulation efficiency was 51%.[4] Chitosan coating improved the nanoparticles protection against the premature resveratrol release in simulated gastrointestinal fluids.[4] The antioxidant activity of resveratrol-loaded chitosan-coated zein nanoparticles was due to the additive effect of resveratrol, chitosan, and amino acids present in the zein structure.[4] Figure 5.4 illustrates the method of production and properties of coated particles.[4]

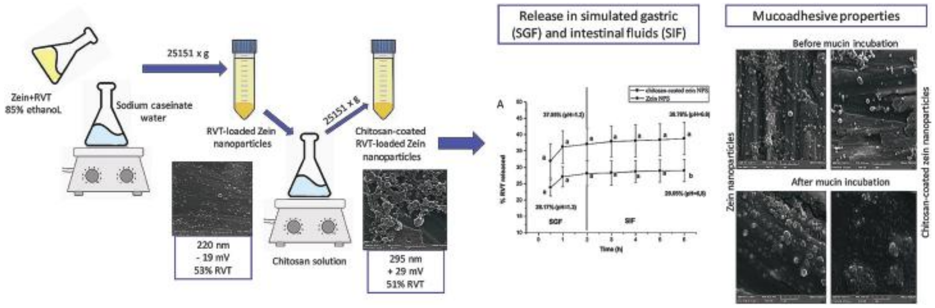


Figure 5.4. Protection and properties of coated particles. [Adapted, by permission, from Pauluk, D; Krause Padilha, A; Khalil, NM; Mainardes, RM, *Food Hydrocolloids*, **94**, 411-7, 2019.]

In *in vitro* studies, low molecular weight chitosan with high degrees of deacetylation had more potent antioxidant properties than the high molecular weight chitosan.[5] Chitosan having moderate molecular weight and degree of acetylation caused a significant reduction of oxidative stress in several chronic oxidative stress-related diseases, such as metabolic syndrome and renal failure.[5]

Chitosan-coated liposome drug delivery of antioxidant was developed for administering nutraceuticals, including polycyclic, aromatic antioxidant or anti-inflammatory compounds to the gastrointestinal tract after oral administration.[6]

A stable emulsion of chitosan in krill oil was developed to be used as a food supplement for carnivorous animals.[7]

A coating composition for fruits contains 0.5-1.5 wt% chitosan in the gelatin matrix.[8] The coating composition increased the shelf-life of fruits, especially apples and pears.[8] These effects are due to the semipermeable barrier and antioxidant properties.[8]

References

1 Badano, JA; Vanden Braber, N; Rossi, Y; Díaz Vergara, L; Montenegro, M, *Carbohydrate Polym.*, in press, 2019, article 115158.
2 Jing, Y; Huang, J; Yu, X, *Postharvest Biol. Technol.*, **154**, 79-86, 2019.
3 Afonso, CR; Hirano, RS; Gaspar, AL; Chagas, EGL; Yoshida, CMP, *Int. J. Biol. Macromol.*, **132**, 1262-73, 2019.
4 Pauluk, D; Krause Padilha, A; Khalil, NM; Mainardes, RM, *Food Hydrocolloids*, **94**, 411-7, 2019.
5 Anraku, M; Gebicki, JM; Iohara, D; Tomida, H; Otagiri, M, *Carbohydrate Polym.*, **199**, 141-9, 2018.
6 Yatvin, MB, **WO2006062544A1**, Jun. 7, 2005.
7 **DE202010011127U1**, *MBP Marine Bio Products GmbH*, Aug. 6, 2010.
8 Rodie, JU; Bordonaba, JG; Larrigaudiere, CEGM, **WO2016166389A1**, *Desarrollos Sanitarios Hortofruticolas*, Mar. 14, 2016.

5.7 CMC (CARBOXYMETHYL CELLULOSE)

Carboxymethyl cellulose films are eco friendly biodegradable biopolymers possessing suitable gas barrier and mechanical properties to be used to deliver bioactive compounds to targets.[1] Nanoencapsulation is used to entrap active compounds or ingredients in capsules with nanometer sizes to increase their stability and protect them against chemical reactions.[1] These capsules increase the bioactivity of materials. Polycaprolactone was used as encapsulating material for α-tocopherol, and capsules were used in carboxymethyl cellulose films.[1] The encapsulation efficiency of films containing 30-70% α-tocopherol nanocapsules was varied between 88.43 and 99.66%.[1] Antioxidant potential of carboxymethyl cellulose films had a linear relationship with the concentration of α-tocopherol nanocapsules.[1] Films containing 70% nanocapsules showed the highest radical scavenging activity of 68.85%.[1]

Traditional polymer packaging materials are being replaced by edible films because they pollute the environment and are non-degradable.[2] Antioxidants or antimicrobial agents are added to packaging films to expand the functional properties of edible films.[2] The active edible films were prepared by incorporating epigallocatechin gallate into sodium alginate and carboxymethyl cellulose.[2] The films with high epigallocatechin gallate content slowly released antioxidant and had suitable antioxidant activity in fatty foods.[2]

Carboxymethyl cellulose used in wound dressing has little antioxidant capacity.[3] It has good adhesion to the wound bed, high fluid absorbency, and, when kept for a long time, it does not damage the newly formed tissues when it is being removed.[3] Carboxymethyl cellulose was grafted with collagen peptide.[3] The scavenging effects of carboxymethyl cellulose increased with the increasing the degree of substitution and concentration.[3]

Antioxidants were microencapsulated using sodium carboxymethyl cellulose.[4] The encapsulation efficiency values were higher than 90%.[4] Spherical microparticles with a smooth surface with mean diameter below 11 μm were prepared by spray-drying.[4] Microparticles loaded with caffeic acid, chlorogenic acid, and rosmarinic acid were fully released after 45 min, 2 h and 4 h, respectively.[4]

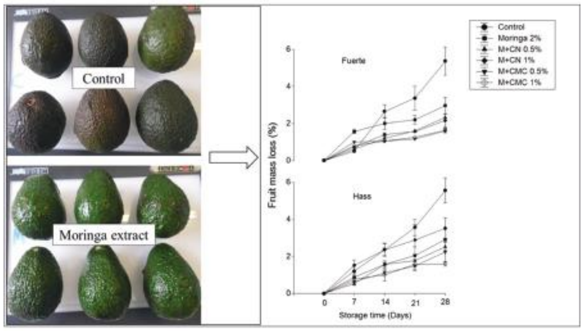


Figure 5.5. Results of avocado treatment. [Adapted, by permission, from Tesfay, SZ; Magwaza, LS, *Food Packaging Shelf Life*, **11**, 40-8, 2017.]

Postharvest treatment of avocado included edible coating containing 2% moringa extract with an emulsifier, two levels of chitosan (0.5, 1%), and carboxymethyl cellulose (0.5, 1%).[5] Fuerte fruit treated with the combination of carboxymethyl cellulose (1%) and 2% moringa had significantly lower mass loss (1.78±0.08%), electrical conductivity (192.0±3.0 μS/m), and respiration rate (167.4±40.8 mg/kg/h) compared to the untreated control with respective values of 4.7±0.7%, 290.0±5.0 μS/m, and 290.0±62.0 mg/kg/h (Figure 5,5).[5]

A medical device (drug delivery stent) uses a coating which contains antioxidant selected from natural antioxidants (ascorbic acid, folic acid, beta carotene, flavonoids, superoxide dismutase mimetic, polyphenol antioxidants, or apigenin), synthetic antioxidants (synthetic antioxidant should not be butylated hydroxytoluene or butylated hydroxyanisole), or their combinations.[6]

Solid, semisolid, or liquid formulations comprising water-soluble antioxidants (ascorbic acid, propyl gallate, sodium sulfite, sodium metabisulfite, sodium bisulfite, thioglycerol, or thioglycolic acid) that prevent or reduce formic acid and/or formyl species generation in the dosage form during the manufacturing process and/or during shelf-life storage.[7]

References

1 Mirzaei-Mohkam, A; Garavand, F; Dehnad, D; Keramat, J; Nasirpour, A, *Prog. Org. Coat.*, **134**, 333-41, 2019.
2 Ruan, C; Zhang, Y; Wang, J; Sun, Y; Liang, J, *Int. J. Biol. Macromol.*, **134**, 1038-44, 2019.
3 Fan, L; Peng, M; Zhou, X; Wu, H; Liu, S, *Carbohydrate Polym.*, **112**, 32-38, 2014.
4 Aguiar, J; Costa, R; Rocha, F; Estevinho, BN; Santos, L, *Powder Tech.*, **313**, 287-92, 2017.
5 Tesfay, SZ; Magwaza, LS, *Food Packaging Shelf Life*, **11**, 40-8, 2017.
6 Ding, N; Coleman, L, **US20070198080A1**, *Abbott Cardiovascular Systems Inc*, Apr. 26, 2007.
7 Narang, A; Rao, VM; Desai, DS, **EP2611442A2**, *AstraZeneca UK Ltd Bristol Myers Squibb Co*, Jul. 4, 2018.

5.8 CN (CELLULOSE NITRATE)

Lutein is a well-known antioxidant and free radical scavenger, able to protect the human body from different types of free radicals.[1] Lutein also filtrates the blue light, which generates reactive oxygen species.[1] Lutein provides protection for skin or eye from photodamage.[1] After 1 h, just 0.57% of lutein powder penetrated cellulose membrane which was used as *in vitro* model of skin and 14 times more (8.16%) in the case of the lutein nanocrystals.[1]

Cellulose nitrate is a material of choice for the filtration of antioxidants of natural and synthetic origins.

References

1. Mitri, K; Shegokar, R; Gohla, S; Anselmi, C; Müller, RH, *Int. J. Pharm.*, **420**, 1, 141-6, 2011.

5.9 COC (CYCLIC OLEFIN COPOLYMER)

Antioxidant stabilizers commonly used in commercial polymers are physically lost by migration from the polymeric matrix during compounding and during storage and final use.[1] When plastics are used as packaging materials in contact with foodstuff or biomedical products, such a migration poses serious concerns since it represents a risk of contamination and may have unpredictable allergenic effects on consumers.[1] Ethylene-based terpolymers containing 0.3-0.7 mol% of a norbornene comonomer bearing an antioxidant phenolic functionality were synthesized (Figure 5.6).[1] Due to the microstructural similarity, the terpolymeric additives are easily dispersed by melt blending to give materials with long-term thermal and thermooxidative stability.[1]

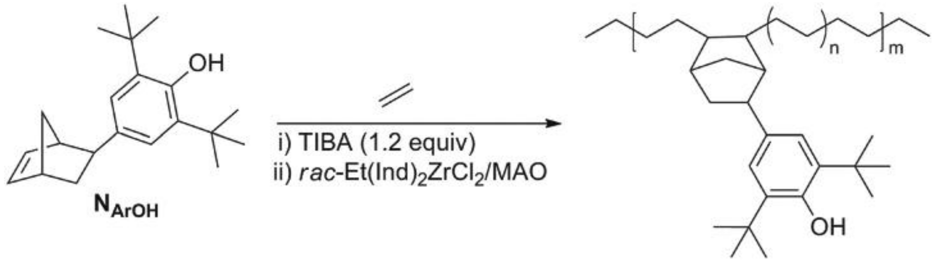


Figure 5.6. Synthesis of ethylene polymer with antioxidant functionality. [Adapted, by permission, from Losio, S; Tritto, I; Boggioni, L; Mancini, G; Stagnaro, P, *Polym. Deg. Stab.*, **144**, 167-75, 2017.]

This method of stabilization of polymers in the polymerization phase without any post-treatment is a cost-efficient way and provides an intimate distribution of the stabilizer in the polymer matrix, which permits lowering the amount of stabilizing moiety.[1]

The effect of radio-sterilization on cycloolefin copolymers that can be used as pharmaceutical storage materials has been studied.[2] The oxidation products were formed and crosslinking of chains occurred.[2] After irradiation, a remarkable decrease of the extractable amount of polyphenolic antioxidant (Irganox 1010®) initially present in the matrix, and a generation of an important number of degradation products that represent potential migrants for pharmaceutical formulations has been noted.[2]

Photooxidation processes of high-density polyethylene and cyclic olefin copolymer poly(ethylene-co-norbornene), both stabilized with biological antioxidant α-tocopherol, has been investigated.[3] The heterogeneity of the oxidation process and the pro-oxidative activity of α-tocopherol were confirmed.[3] The increased concentration of products of polymer oxidation was found in the surface layers of polymers stabilized with α-tocopherol unlike in control experiments with polymers stabilized with HAS Tinuvin® 770, where no oxidation products were observed after the same treatment before HAS depletion.[3] It was confirmed that α-tocopherol exhibits antioxidant activity during thermooxidation, but it acts as a pro-oxidant agent during photooxidation.[3]

A masterbatch of additives, useful for maintaining a constant and reduced coefficient of friction in polyethylene-based films, is a compounded blend of siloxane additive in conjunction with a mineral, a cyclic olefin copolymer, and an antioxidant (antioxidants comprise phenols, phosphites, or their combinations).[4] These additives are different from the polar additives used in the past to reduce the coefficient of friction of polyethylene films and do not have an inherent incompatibility with the non-polar polyethylene matrix.[4]

Suitable antioxidants for cycloolefin copolymers include phenolic antioxidants (such as pentaerythritol tetrakis(3-(3,5-di-tert-butyl-4-hydroxyphenyl)propionate, Irganox® 1010), phosphite antioxidants (such as tris(2,4-ditert-butylphenyl)phosphite, Irgafos® 168), phosphonite antioxidants (such as tetrakis(2,4-di-tert-butylphenyl)[1,1-biphenyl]-4,4'-diylbisphosphonite, Irganox® P-EPQ),[5]

References

1 Losio, S; Tritto, I; Boggioni, L; Mancini, G; Stagnaro, P, *Polym. Deg. Stab.*, **144**, 167-75, 2017.
2 Barakat, H; Aymes-Chodur, C; Saunier, J; Yagoubi, N, *Radiat. Phys. Chem.*, **84**, 223-31, 2013.
3 Pilař, J; Šlouf, M; Michálková, D; Šloufová, I; Dybal, J, *Polym. Deg. Stab.*, **138**, 55-71, 2017.
4 Roy, SD; Hindy, EG, **US9422424B2**, *Ingenia Polymers Inc*, Aug, 23, 2016.
5 Hong, W; Bai, D; Flaim, TD; Puligadda, R, **US20120291938A1**, *Brewer Science Inc,* Nov., 22, 2012.

5.10 CPE (CHLORINATED POLYETHYLENE)

Chlorinated polyethylene elastomer has been produced by the introduction of chlorine atoms into the polyethylene backbone to reduce the ability of crystallization of polyethylene.[1] A phenol-based antioxidant, namely, 2,2′-dicyclopentyl-bis (4-methyl-6-tert-butyl-phenol), has been used to improve thermal aging resistance in chlorinated polyethylene/natural rubber blends.[1]

An intumescent thermoplastic elastomer molding composition contains high-density polyethylene, chlorinated polyethylene, silicone rubber, a heat stabilizer, and an intumescent and fire-resistant additive.[2] A system consisting of distearylthiodipropionate and a butylated reaction product of p-cresol and dicyclopentadiene (Wingstay L) is very effective as an antioxidant.[2] MgO is used in the formulation to absorb evolved HCl produced during aging of chlorinated polyethylene, acting as an effective dehydrochlorination stabilizer.[2]

The waterproofing membrane consists of chlorinated polyethylene 22-25 wt%, rubber 22-25 wt%, reinforcing agent 2 wt%, filler 40-45 wt%, softening agent 5 wt%, antioxidant 0.5-1.5 wt%.[3] The most suitable antioxidants include N-isopropyl-N'-phenyl-P-phenylenediamine or 2,2,4-trimethyl-1,2-dihydroquinoline.[3]

Chlorinated polyethylene composition for hose production contain chlorinated rubber, metal deactivators (decamethylene dicarboxylic acid disalicyloylhydrazide, N, N'-bis [3- (3,5-di -t- butyl-4-hydroxyphenyl) propionyl] hydrazine, or a oxalic acid bisbenzylidene hydrazide, an acid acceptor (Ca-Mg-Zn based complex stabilizer, or a hydrotalcite), and antioxidant (tetrakis (methylene-3 (3',5'-di-t-butyl-4-hydroxyphenyl) propionate)methane).[4]

References

1 Sirisinha, C; Saeoui, P; Guaysomboon, J, *Polymer*, **45**, 14, 4909-16, 2004.
2 Abu-Isa, IA; Jaynes, CB, **US5834535A**, *Motors Liquidation Co, General Motors Corp.*, Dec. 22, 1996.
3 **CN1986719A**, Feb. 10, 2010.
4 **JP4176825B1**, May 23, 2011.

5.11 CPVC (CHLORINATED POLY(VINYL CHLORIDE))

Poly(vinyl chloride)/chlorinated poly(vinyl chloride) foamed sheet comprises the following materials in parts by weight: 60-90 parts of poly(vinyl chloride), 10-40 parts of chlorinated poly(vinyl chloride), 2.8-7 parts of stabilizer, 3-5 parts of foam regulator, 1-3 parts of foam nucleating agent, 0.5-2 parts of foaming agent, 0.6-1.5 parts of external lubricant, 0.5-1 part of internal lubricant, 0.5-2 parts of processing aid, 0.05-0.5 part of antioxidant (butylated hydroxytoluene) and no more than 30 parts of filler.[1]

The chlorinated poly(vinyl chloride) pipe is composed of chlorinated poly(vinyl chloride) resin, lubricating agent, stabilizer, processing agent, acrylic acid composite resin, nanofiller, filler, ultraviolet light absorber, antioxidant, and impact modifier.[2] The advantages include fire and corrosion protection, high-temperature resistance, and long aging resistance time.[2]

Tetrakis[methylene(3,5-di-tert-butyl-4-hydroxy-hydrocinnamate)]methane) in the amount from 0.1 to 1 wt% of the CPVC resin were used in chlorinated poly(vinyl chloride) compounds having excellent combustion characteristics,[3]

References

1 **CN102040785B**, Jun, 13, 2012.
2 **CN107141670A**, Jun. 26, 2017.
3 Dalal, GT; Olah, AM; Schmitz, TJ; Townley, DR, **WO1999067332A2**, *BF Goodrich*, Aug. 24, 2000.

5.12 CR (POLYCHLOROPRENE)

In polychloroprene excellent protection against ozone attack is available. Vulcanox 3100 (mixture of N,N'-diaryl-p-phenylene diamines) is advantageously used in conjunction with Vulcanox 4010 NA (p-isopropylaminodiphenylamine) or Vulkanox 4020 (4-N-(4-methylpentyl-2-amino)-diphenylamine) antidegradants.[1]

The rubber bearing used in structures such as bridges and buildings, which are earthquake-resistant, are made from polychloroprene compositions containing antiozonant selected from a group including N- phenyl-N'-isopropyl-p-phenylenediamine, N-phenyl-N'-(1,3-dimethylbutyl)-p-phenylenediamine, N-phenyl-N'-(3-methacryloyloxy-2-hydroxypropyl)-p-phenylenediamine, N,N'-bis-(1,4-dimethylphenyl)-p-phenylenediamine, 6-ethoxy-1,2-dihydro-2, 2,4-trimethyl quinoline, diethyldithiocarbamate nickel, nickel dibutyldithiocarbamate, and 1,3-bis (dimethyl rutile-aminopropyl) -2-thiourea.[2]

Invention provides method of packaging and sterilizing elastomeric articles in a manner that prevents and/or reduces degradation of articles, particularly degradation that may be caused and/or accelerated by sterilization techniques such as gamma irradiation, x-ray irradiation, and electron-beam processing.[3] Packaged elastomeric articles contain antidegradant(s), such as antioxidant and/or antiozonant compounds. One particularly preferred antioxidant is butylated reaction products of p-cresol and dicyclopentadiene (e.g., Wingstay L).[3]

References

1 Flick, EW, **Antioxidants, Plastic Additives**, 3rd Ed., *William Andrew*, 2001, pp. 31, 33-75.

2 **WO2016052458A1**, Apr. 7, 2016.

3 Chen, SF; Wong, WC, **WO2011090942A1**, *Allegiance Corporation*, May 4, 2010.

5.13 CY (CYANOACRYLATE)

Poly(butyl cyanoacrylate) nanoparticles have been used for curcumin loading. *In vitro* they gave controlled drug release over a prolonged period, with the higher release in acidic media, suggesting their usefulness to specifically target acidic intracellular compartments.[1]

Phenolic antioxidants, such as quercetin, curcumin, catechin were encapsulated using poly(butyl cyanoacrylate).[2]

Curcumin activity was enhanced in apolipoprotein E3-mediated poly(butyl cyanoacrylate) nanoparticles compared to plain curcumin.[3] Apolipoprotein E3 also possessed both antioxidant and anti-amyloidogenic activity; therefore apolipoprotein E3 itself had activity against β-amyloid-induced cytotoxicity along with curcumin, suggesting that apolipoprotein E3-poly(butyl) cyanoacrylate offered a great advantage in the treatment of β-amyloid-induced cytotoxicity in Alzheimer disease.[3]

An adhesive composition includes a polymerizable adhesive monomer (cyanoacrylate) and antioxidant stabilizer (vitamin E, octyl gallate, or pentamethylbenzofuranol).[4] The antioxidant stabilizer provides superior stabilization and shelf-life of the composition.[4]

Mixtures of N-butyl cyanoacrylate and 2-octyl-cyanoacrylate monomers contained free radical inhibitor/antioxidant stabilizer (butyl hydroxytoluene).[5] The cyanoacrylate composition can withstand radiation such as E-beam and gamma radiation at any desired level and not be adversely affected.[5]

Cyanoacrylate composition suitable for repairing and filling depressions, cracks, or holes in a substrate or between substrates to be bonded contains antioxidant (methylene-bis(4- methyl-6-t-butyl phenol)).[6]

References

1 Leonarduzzi, G; Sottero, B; Poli, G, *Pharm. Therapeutics*, **128**, 2, 336-74, 2010.
2 Shinwari, KJ; Rao, PS, *Trends Food Sci. Technol.*, **75**, 181-93, 2018.
3 Farooqui, T; Farooqui, AA, **Curcumin: Historical Background, Chemistry, Pharmacological Action, and Potential Therapeutic Value, Curcumin Neurological Psychiatric Disorders**, *Academic Press*, 2019, pp. 23-44.
4 Badejo, IT; AyarzaJ; Voiers, AS; Thompson, RF;. Szabo, GN; Toni, RV; Nicholson, WSC, **WO2002020069A2**, *Closure Medical Corporation*, Mar. 14, 2002.
5 Blacklock, DS; Berger, TJ, **US7772306B2**, *Glustitch, Inc.*, Aug. 10, 2010.
6 Mcardle, C; Jiménez, AP; López Maeso, JA; Gherardi. S, **EP3071638A1**, *Afinitica Technologies S L*, May 3, 2017.

5.14 EC (ETHYL CELLULOSE)

Supercritical emulsions extraction technology was used to encapsulate astaxanthin in ethyl cellulose.[1] The best emulsion formulation was obtained using 1.0 wt% of ethyl cellulose in the oily phase and 0.1 wt% of surfactant in the water phase. Encapsulation efficiency was 84%.[1] The carrier was loaded with 21 mg/g of astaxanthin and showed an excellent antioxidant capacity.[1] A release of 70% of the total encapsulated astaxanthin was achieved after 10 h.[1] Figure 5.7 shows equipment and information about resulting particles.[1]

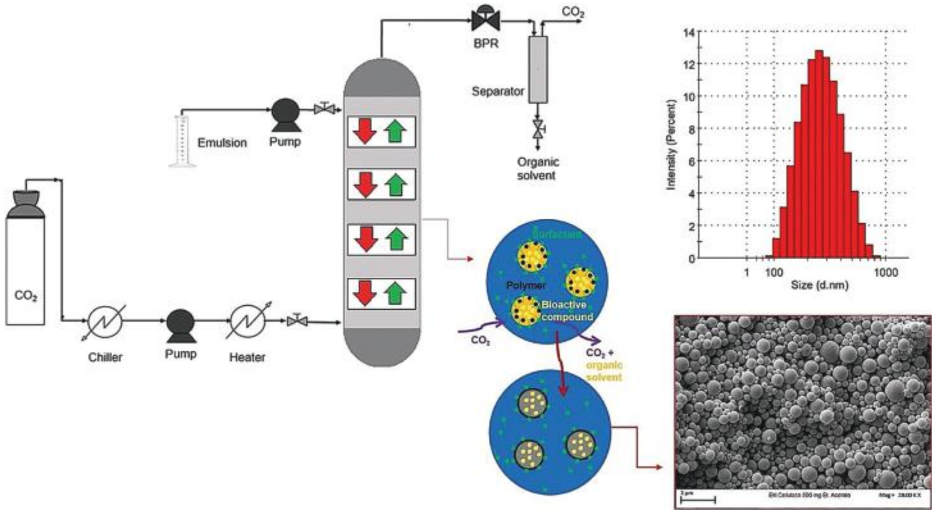


Figure 5.7. Supercritical emulsions extraction technology. [Adapted, by permission, from Tirado, DF; Palazzo, D; Scognamiglio, M; Calvo, L; Reverchon, E, *J. Supercritical Fluids*, **150**, 128-36, 2019.]

Ethyl cellulose/polydimethylsiloxane composite films were prepared at various concentrations of PDMS in the films.[2] A small amount of clove essential oil was added to the best waterproofing composite (80 wt% ethyl cellulose and 20 wt% PDMS).[2] The essential oil increased the flexibility and the antioxidant capacity of the composite, as tested against common pathogens such as *Escherichia coli, Staphylococcus aureus*, and *Pseudomonas aeruginosa*. The presence of clove essential oil reduced the biofilm formation.[2]

Ethyl cellulose films containing up to 17% polyaniline were prepared from ethanol solution.[3] The films demonstrated very efficient peroxyl free radical scavenging activity.[3] Reduced PANI presented more significant peroxyl radical scavenging activity than more oxidized as-prepared forms. Oil stored in the presence of a PANI-containing ethyl acetate film exhibited a lower peroxide value than in the absence of PANI.[3] The inclusion of an insoluble antioxidant polymer can be considered for active packaging applications.[3]

Hydroxytyrosol (high concentrations in olive oil) presents remarkable health benefits, mainly due to its antioxidant properties.[4] The inclusion of hydroxytyrosol in functional foods and pharmaceutical compounds is restricted due to its high hydrophilicity.[4]

Hydroxytyrosol-loaded microparticles of ethyl cellulose used as a carrier were produced by double emulsion solvent evaporation technique with loadings (5 and 10 wt%).[4] The maximum encapsulation efficiency and product yield were 88.1±0.1% and 82.4±2.1%, respectively, using the formulation with the lower loading.[4] The performance characteristics of microparticles indicated suitability for application of microencapsulated hydroxytyrosol in foods, drugs, and nutraceuticals.[4] Figure 5.8 illustrates encapsulation and release properties.[4]

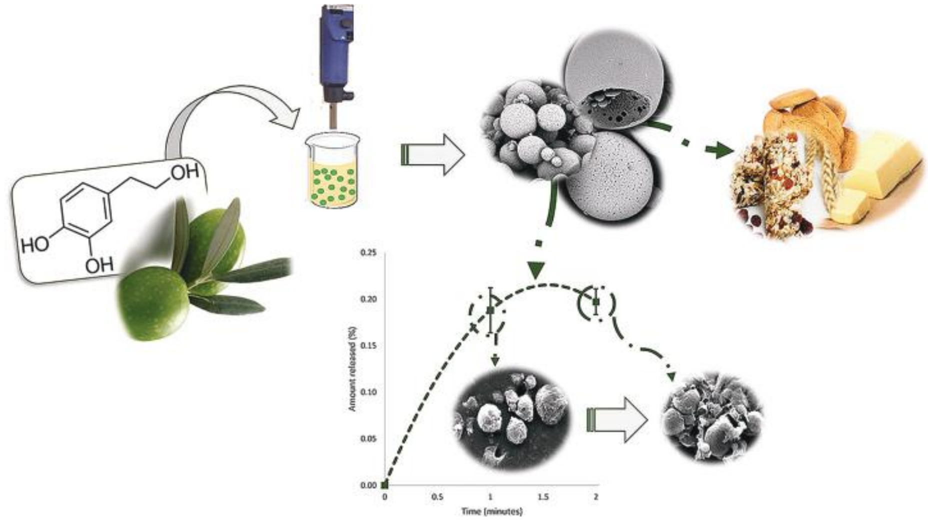


Figure 5.8. Microencapsulation of hydroxytyrosol in ethyl cellulose and its release. [Adapted, by permission, from Paulo, F; Santos, L, *Food Hydrocolloids*, **84**, 104-16, 2018.]

References

1 Tirado, DF; Palazzo, D; Scognamiglio, M; Calvo, L; Reverchon, E, *J. Supercritical Fluids*, **150**, 128-36, 2019.

2 Heredia-Guerrero, JA; Ceseracciu, L; Guzman-Puyol, S; Paul, UC; Bayer, IS, *Carbohydrate Polym*., **192**, 150-8, 2018.

3 Hsu, CF; Kilmartin, PA, *Reactive Functional Polym*., **72**, 11, 814-22, 2012.

4 Paulo, F; Santos, L, *Food Hydrocolloids*, **84**, 104-16, 2018.

5.15 ECTFE (POLY(ETHYLENE-CO-CHLOROTRIFLUOROETHYLENE))

Fluoropolymer composition comprising a copolymer of ethylene with chlorotrifluoroethylene and polyelectrolytes has improved thermal resistance due to application of antioxidant (alkyl (C12-C15) bisphenol A phosphite or butylidene-bis[2-tert-butyl-5-methyl-p-phenylene]-P,P,P',P'-tetratridecylbis(phosphine)).[1]

References

1 Carella, S; Besana, Suneel, G; Bandi, S; Kent, BL, **WO2014187758A1**, *Solvay Specialty Polymers Italy S.P.A.*, Nov. 27, 2014.

5.16 EP (EPOXY RESIN)

Bio-based epoxy resin derived from tannic acid was synthesized *via* glycidylation by epichlorohydrin.[1] The bio-resin exhibited good thermal stability and properties of effective antioxidant material.[1] Figure 5.9 shows the origin and some properties of the bio-epoxy resin.[1]

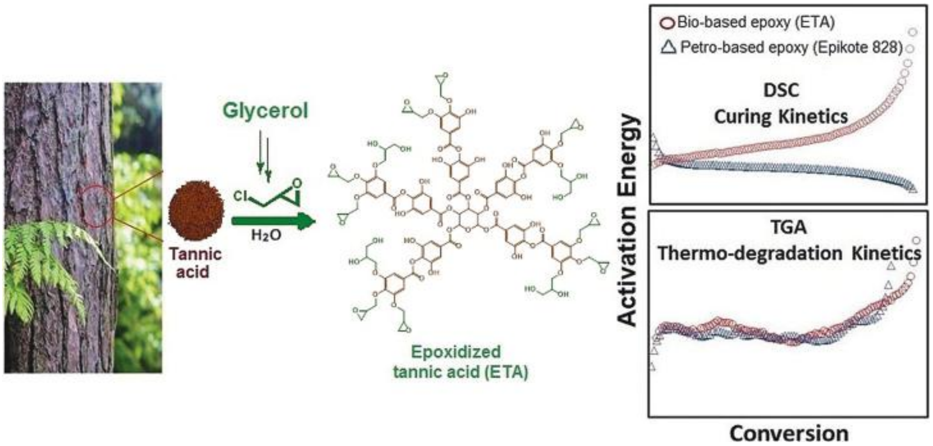


Figure 5.9. Tannic acid based epoxy resin. [Adapted, by permission, from Esmaeili, N; Vafayan, M; Salimi, A; Zohuriaan-Mehr, MJ, *Thermochim. Acta*, **655**, 21-33, 2017.]

A curable epoxy resin composition comprises cycloaliphatic diglycidyl compound as epoxy resin, antioxidant(s), and UV absorber.[2] This combination gave cast resin resistant to storage, especially suitable for the preparation of electric insulation parts[2] and outdoor articles.[3]

The molding compound included a partially cured epoxy composition, an antioxidant (thiodialkylpropionate, thiodiethylenepropionate, or thiodiethylene bis[3-(3,5-di-tert-butyl-4-hydroxyphenyl) propionate), and, optionally, a phosphor material substantially uniformly distributed throughout the epoxy composition.[4]

References

1 Esmaeili, N; Vafayan, M; Salimi, A; Zohuriaan-Mehr, MJ, *Thermochim. Acta*, **655**, 21-33, 2017.
2 Beisele, C, **US20090023843A1**, *Huntsman International LLC*, May 7, 2013.
3 Beisele, C; Liu, Z; Chen, H; Hishikawa, S, **WO2016150724A1**, *Huntsman Advanced Materials (Switzerland) GmbH*, Mar. 10, 2016.
4 Starkey, D, **US7622516B1**, *Henkel Corp*, Nov. 24, 2009.

5.17 EPDM (ETHYLENE-PROPYLENE DIENE TERPOLYMER)

Zinc dimethacrylate and 2-sulfur-benzimidazole/N-4(phenyl–phenyl)-maleimide were used as synergistic antioxidants to improve the thermo-oxidative aging resistance of peroxide vulcanized ethylene-propylene-diene monomer for its application at high temperature.[1] The crosslink density of EPDM was only slightly decreased by the synergistic antioxidant.[1] The degree of oxidation of stabilized EPDM was much lower than control after aging at 180°C for 216 h.[1]

The doped lead titanate ($PbTiO_3$) with several atoms (Ce, Pr, In, Gd and Nb) was used as antioxidant.[2] The most evident effect was achieved when the filler was doped with gadolinium and dysprosium.[2] The highest stabilization efficiencies were found for the sample containing 5 and 10 phr of the inorganic phase.[2]

To improve adhesion of EPDM rubber to polyester fabric, antioxidant prepared by graft copolymerization of 1, 5-diaminonaphthalene onto natural rubber was used.[3] The obtained adhesion in the presence of this antioxidant was substantially improved as compared with commercial antioxidants.[3]

Oxidation of γ-ray vulcanized ethylene–propylene diene rubber in the presence of pentaerythrityl tetrakis(3,5-di-tert-butyl(-4-hydroxyphenyl))propionate (Irganox 1010), Irganox 1035, Irganox 1520D, as primary antioxidants; Irganox B561 and Irganox B900, as synergistic blends; hindered amine light stabilizer (Tinuvin 622 LD); N-isopropyl-N-phenyl-p-phenylenediamine, and trimethyl quinoline and their mixtures have been studied.[4] The resistance to thermooxidative degradation of irradiated EPDM rubber was greatly improved by addition of 0.5 phr of either Irganox B900 blend or a mixture of N-isopropyl-N-phenyl-p-phenylenediamine, and trimethyl quinoline.[4]

Ethylene-propylene-diene terpolymer was efficiently stabilized against γ-radiation with naringenin and caffeic acid combined with selenium.[5] Both antioxidants delayed the oxidation of the polymer even under irradiation with a sterilization dose.[5] The oxidation induction time of EPDM samples increased significantly with increased amounts of antioxidants, and the addition of selenium further improved their efficiency.[5]

No stabilizing effect was noted for EPDM composition containing 0.1% Irganox 1035 whereas complete stability with 1% Vulcanox 4010 was observed up to the highest dose of 450 kGy.[6]

Electrically insulating elastomeric compound of submersible power cable included ethylene-propylene diene monomer (M-class) rubber and an alkane-based peroxide that generated radicals, crosslinking the EPDM *via* radical polymerization to form an electrically insulating layer around the conductor and heating the crosslinked EPDM to at least 55°C to reduce the concentration of the decomposition products in the electrically insulating layer.[7] An antioxidant package included primary and secondary antioxidants to slow down the degradation of elastomer due to oxygen aging.[7] Primary antioxidant was ethylenediaminetetraacetic acid.[7] Synergistic effects were observed when the primary antioxidant was combined with a secondary antioxidant (e.g., Vanox™ ZMTI and MTI).[7]

Composition and method for providing insulation for solid propellant rocket motors were based on EPDM composition containing antioxidant, plasticizer, tackifier, cure additive, and adhesion promoter.[8] Preferred antioxidants included polymerized 1,2-dihydro-

2,2,4-trimethylquinoline (Agerite® Resin D) and mixed octylated diphenylamines (Agerite® Stalite S).[8]

Timing belts having improved fabric adhesion are produced from EPDM formulation containing additives such as extender oils, antioxidants, waxes, pigments, and plasticizers.[9] The formulation contains 0.5 to 1.5 phr of antioxidant (Aquanox 29).[9]

References

1 Ning, N; Ma, Q; Zhang, Y; Zhang, L; Tian, M, *Polym. Deg. Stab*., **102**, 1-8, 2014.
2 Zaharescu, T, *Mater. Chem. Phys*., **234**, 102-9, 2019.
3 Darwish, NA; El-Wakil, Ahmed AA; Abou-Kandil, I, *Int. J. Adhesion Adhesives*, **29**, 7, 745-9, 2009.
4 Abdel-Aziz, MM; Basfar, AA, *Nucl. Instrum. Methods Phys. Res. Sect. B: Beam Interactions Mater. Atoms*, **185**, 1-4, 346-50, 2001.
5 Kirschweng, B; Tátraaljai, D; Földes, E; Pukánszky, B, *Polym. Deg. Stab*., **145**, 25-40, 2017.
6 Palmas, P; Colsenet, R; Lemarié, L; Sebban, M, *Polymer*, **44**, 17, 4889-97, 2003.
7 Holzmueller, J; Xiang, J, **WO2017058647A1**, *Schlumberger Technology Corporation*, Sep. 23, 2016.
8 Guillot, DG; Harvey. AR, **US7371784B2**, *Northrop Grumman Innovation Systems Inc*, May 5, 2008.
9 Burrowes, TG; Gregg, MJW, **US8795456B2**, *ContiTech USA Inc*, Aug. 5, 2014.

5.18 EPR (ETHYLENE-PROPYLENE RUBBER)

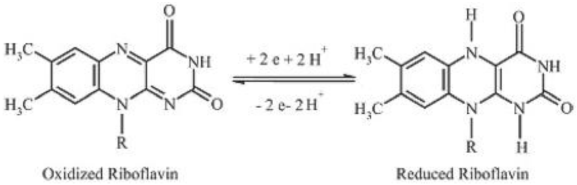


Figure 5.10. Reduction and oxidation of riboflavin. [Adapted, by permission, from Masek, A; Chrzescijanska, A; Zaborski, M; Maciejewska, M, *Comptes Rendus Chimie*, **15**, 6, 524-9, 2012.]

Riboflavin was added to ethylene-propylene rubber in order to improve aging stability.[1] Riboflavin is activated by UV and, as a result, has the properties of a strong reducing agent that provides high degradation protection.[1] Figure 5.10 shows the redox reaction of riboflavin.[1] The oxidation time of EPR with riboflavin was about three times longer than that of ethylene-propylene elastomer which did not contain riboflavin.[1]

The thermal stability of ethylene-propylene copolymers (EPDM and EPR) was evaluated by isothermal and isobaric measurements of oxygen uptake.[2] The presence of ethylidene norbornene in EPDM increased the rate of oxidation.[2] Addition of low amount (0.1%) of antioxidant (Irganox 1076) to the unpurified materials extended their shelf life.[2]

Radiation and thermal degradation of ethylene–propylene rubber used for cable insulation have been studied.[3] The activation energy of thermooxidative degradation changed over the range of 100-120°C, which was attributed to the change in antioxidant concentration due to evaporation during thermal aging at high temperatures.[3] The role of the antioxidant was a reduction of free radical formation during the initiation step in thermal oxidation.[3] Irradiation decomposed the antioxidant.[3] When the antioxidant content decreased to a limiting content, the acceleration in the thermal oxidation occurred.[3]

Several flavonoids (hesperidin, hydroxymorin, hydroxyrutin, xanthone, flavon) were incorporated into ethylene-propylene rubbers.[4] Hesperidin gave the best protection.[4] Xanthone and flavone were oxidized most rapidly.[4]

The radiation-resistant composition for cable insulator and/or a sheath material for nuclear power plants contained antioxidants.[5] A combination of first antioxidant (amine) for trapping/stabilizing radicals generated in a polymer with a second antioxidant (sulfur) which was peroxide-decomposing type for decomposing peroxide into alcohol was used.[5]

References

1 Masek, A; Chrzescijanska, A; Zaborski, M; Maciejewska, M, *Comptes Rendus Chimie*, **15**, 6, 524-9, 2012.
2 Zaharescu, T; Wurm, C; Podina, C, *Polym. Testing*, **17**, 1, 25-34, 1998.
3 Seguchi, T; Tamura, K; Ohshima, T; Shimada, A; Kudoh, H, *Radiat. Phys. Chem.*, **80**, 2, 268-73, 2011.
4 Masek, A; Zaborski, M; Kosmalska, A, *Comptes Rendus Chimie*, **14**, 5, 483-8, 2011.
5 Nakamura, Y; Sorimachi, M; Kimura, H; Matsuyama, S, **US8076408B2**, *Hitachi Metals Ltd*, Dec. 13, 2011.

5.19 EVAC (ETHYLENE-VINYL ACETATE COPOLYMER)

Thermal analysis indicated that the initial loss of acetic acid followed by oxidation and breakdown of the main chain occurred on the exposure of ethylene-vinyl acetate copolymer to elevated temperature.[1] The degradation rate was greater in an oxygen atmosphere, as was the formation of colored products.[1] Hydroperoxide evolution followed typical autooxidation kinetics in which ketonic species were formed, leading to the formation of anhydride groups in severely oxidized EVAc.[1] Primary phenolic antioxidants exhibited variable activity in inhibiting the yellowing of EVAc while combinations with phosphites generally displayed powerful synergism.[1]

Antioxidant was synthesized using esterification of 3-(3, 5-di-tert-butyl-4-hydroxyphenyl) propionic acid with hydrolyzed ethylene-vinyl acetate and ethylene-1-octene copolymer grafted with long-chain monomers bearing hydroxyl groups.[2] The macromolecular stabilizers exhibited outstanding thermal degradation and oxidation stability in comparison with commercial corresponding copolymers and gave excellent performance in the stabilization of polypropylene.[2]

Active packaging films containing bioactive nanocomposites were developed from the natural extract obtained from the brewery residual stream incorporated into ethylene-vinyl acetate copolymer.[3] The films containing 6% of the extract or functionalized nanoclays provided the best results by retarding both the oxidation of beef samples by around 60% and *S. aureus* growth.[3]

A solar cell encapsulant, which has stability against yellowing after a crosslinking process, contains EVAc resin, antioxidant (phenolic, phosphite, and sulfur antioxidant), UV absorber, and light stabilizer.[4]

Heat resistant ethylene-vinyl acetate copolymer compositions comprised a blend of ethylene-vinyl acetate copolymer, peroxide curable polyacrylate elastomer, and polyamide.[5] Useful antioxidants included aryl amines, phenolics, imidazoles, and phosphites.[5]

References

1 Allen, NS; Edge, M; Rodriguez, M; Liauw, CM; Fontan, E, *Polym. Deg. Stab.*, **68**, 3, 363-71, 2000.
2 Manteghi, A; Ahmadi, S; Arabi, H, *Polymer*, **104**, 31-9, 2016.
3 Barbosa-Pereira, L; Angulo, I; Lagarón, JM; Paseiro-Losada, P; Cruz, JM, *Innovative Food Sci. Emerging Technol.*, **26**, 310-8, 2014.
4 Cho, JW; Han, JH; Lee, GH; Kim, KH, **US20120168982A1**, *Hanwha Total Petrochemicals Co Ltd*, May 19, 2015.
5 Oriani, SR, **WO2014089136A1**, *E. I. Du Pont De Nemours and Company*, Jun. 12, 2014.

5.20 EVOH (ETHYLENE-VINYL ALCOHOL COPOLYMER)

Polymer films with antioxidant and antimicrobial properties were manufactured for the active packaging of food products.[1] Green tea extract and oregano essential oil were incorporated in an ethylene-vinyl alcohol copolymer.[1] The release kinetics depended on the affinity between the active agents and the food simulants.[1] In general, the fastest diffusion was obtained when films were exposed to 50% ethanol, and that effect was concurrent with greater antioxidant efficiencies.[1] The antioxidant activity of the films containing green tea extract was the most effective, and films containing oregano essential oil showed strong antimicrobial activity.[1] Industrial printing equipment can be used to coat different polymers films such as polypropylene with the active EVOH layer.[1]

The lipoperoxidation and the oxidation of pigments and proteins reduced the quality and nutritional value of meat products.[2] The use of antioxidants slows down this reaction. Figure 5.11 shows the effect of meat oxidation.[2]

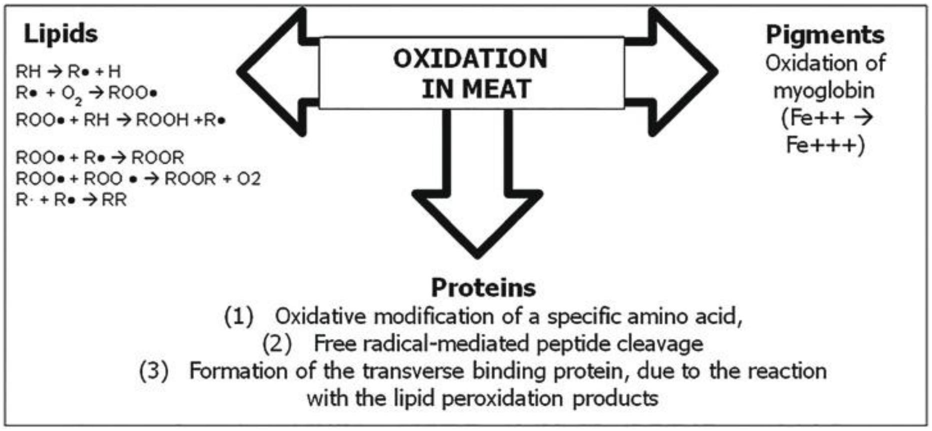


Figure 5.11. Results of meat oxidation. [Adapted, by permission, from Souza Ribeiro, J; Cordeiro Santos, MJM; Silva, LKR; Lavinscky Pereira, LC; da Silva, MN, *Meat Sci.*, **148**, 181-8, 2019.]

Ascorbic acid, ferulic acid, quercetin, and green tea extract were used as natural antioxidants in ethylene-vinyl alcohol copolymer film to protect meat products.[2] The films showed an improvement in the stability of sardines, due to the reduction of the peroxide index and the content of malondialdehyde, and the film with green tea extract offered the best protection against lipid oxidation.[2] Regarding the properties of the polymer, the incorporation of antioxidants did not affect it significantly.[2] Films containing green tea extract and quercetin showed a decrease in permeability values.[2]

Films of ethylene-vinyl alcohol copolymer containing flavonoid-rich cocoa were used as active films in the protection of food products.[3] Exposure of the films to aqueous food simulant showed antioxidant capacity.[3] The release of cocoa extract components depended on the antioxidant concentration and temperature.[3]

Exhaustive review on the application of antioxidant polymers in food packaging can be found in a book chapter.[4]

The presence of anhydride-modified olefin polymer in a melt blend of ethylene-vinyl alcohol copolymer which contains hindered phenol antioxidant (1,3.5-trimethyl-2,4,6-tris(3,5-di-tert-butyl-4-hydroxybenzyl) benzene) and metal salt of an aliphatic carboxylic acid for stabilization against oxidative and thermal degradation, respectively, of the molten EVOH, causes gelation of the EVOH, which can be counteracted by a basic organic metal salt or oxide addition.[5]

Modified ethylene-vinyl alcohol copolymer, used as an oxygen barrier for food and beverage packaging applications, contains oxygen scavenging functional groups and antioxidant selected from 2,6-di(t-butyl)-4-methylphenol(BHT), 2,2′-methylene-bis(6-t-butyl-p-cresol), triphenylphosphite, tris-(nonylphenyl)phosphite, vitamin E, tetra-bismethylene 3-(3,5-ditertbutyl-4-hydroxyphenyl)-propionate methane, or dilaurylthiodipropionate.[6]

References

1 Muriel-Galet, V; Cran, MJ; Bigger, SW; Hernández-Muñoz, P; Gavara, R, *J. Food Eng*., **149**, 9-16, 2015.
2 Souza Ribeiro, J; Cordeiro Santos, MJM; Silva, LKR; Lavinscky Pereira, LC; da Silva, MN, *Meat Sci.*, **148**, 181-8, 2019.
3 Calatayud, M; López-de-Dicastillo, C; López-Carballo, G; Vélez, D; Gavara, R, *Food Chem*., **139**, 1-4, 51-8, 2013.
4 Cirillo, G; Curcio, M; Spataro, T; Picci, N; Spizzirri, UG, **Antioxidant Polymers for Food Packaging. Food Packaging and Preservation**, *Academic Press*, 2018, pp. 213-38.
5 Chen, JC, **EP0595992B1**, *E I du Pont de Nemours and Co*, May, 8, 1996.
6 Yang, H; Ching, YT; Cai, G, **US7288593B2**, *Cryovac LLC*, Oct, 30, 2007.

5.21 GEL (GELATIN)

The fresh orange peel extract exhibited a stronger antioxidant effect in gelatin film than the thermally-dried orange peel extract.[1] The quinic acid was the primary compound among the total poly-phenols followed by rutin, *trans*-ferulic acid, naringenin, and 4,5-di-O-caffeoylquinate.[1]

The effect of Maillard reactions on the physicochemical and biological properties of fish gelatin-based edible films has been studied.[2] Barrier properties against UV light, and water resistance increased due to the gelatin-glucose interactions generated at high temperature.[2] The antioxidant activity was significantly enhanced with glucose content and, to a lesser extent, with the reaction time.[2]

Curcumin is a polyphenol with a wide range of biological properties, including antioxidant and antimicrobial activity; however, its use as a food preservative is limited because of its insolubility in water.[3] This research seeks to overcome this problem by means of matrix encapsulation of curcumin in gelatin through electrohydrodynamic atomization.[3] Compact spherical gelatin particles ranging from few nanometers to more than 1 μm in diameter loaded with 10 wt% curcumin were encapsulated with efficiency close to 100%.[3] The water solubility of curcumin increased 38.6-fold after it had been encapsulated in gelatin microparticles, and its antioxidant activity was greatly improved.[3]

Anthocyanins nanocomplexes fabricated using chitosan hydrochloride and carboxymethyl chitosan were incorporated into gelatin film as a base formulation for the preparation of packaging films.[4] Thermal stability and antioxidant capacity of the films was improved, and visible light transmission was decreased.[4] The film with antioxidant significantly delayed olive oil oxidative deterioration (21.2 meq O_2/kg of peroxide value at the 56th day) when compared with the films composed of gelatin only (28.4 meq O_2/kg of peroxide value at the 56th day).[4]

There is growing evidence that reactive oxygen species are directly involved in bone diseases and the failure of implants.[5] The antioxidant property of tannic acid and biocompatibility of gelatin was used in the multilayer film, which was fabricated by the layer-by-layer method to be used in implants.[5] The multilayer film provided good antioxidant properties in reactive oxygen species stress environment.[5] The antioxidant coating played a critical role in the successful application of bone implants.[5]

Multilayer edible films were fabricated with the stacking order of hydrophobic zein outer layer, hybrid zein/gelatin middle layer, and the hydrophilic gelatin inner layer.[6] Tea polyphenol with a concentration gradient was then loaded into the middle and inner layer of the optimized multilayer film to achieve prolonged release property.[6] When applied on freshly cut fruits, the tea polyphenol-loaded multilayer film exhibited preservation effects, such as controlling weight loss, preventing rapid browning, and inhibiting bacterial deterioration.[6] Figure 5.12 shows the structure and effects of multilayer films.[6]

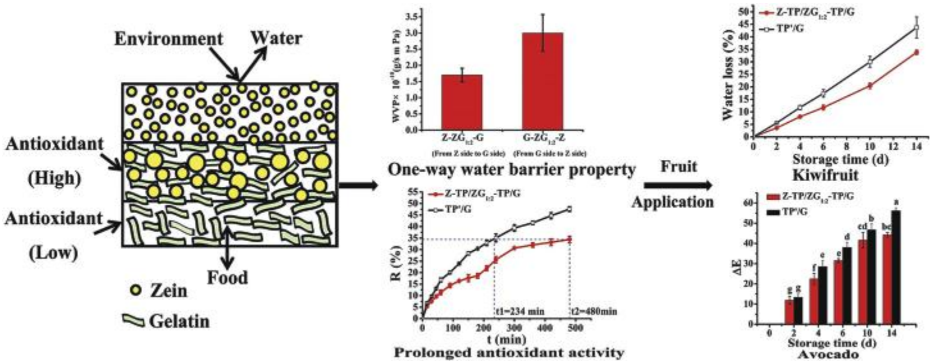


Figure 5.12. Structure and properties of multilayered films. [Adapted, by permission, from Xia, C; Wang, W; Wang, L; Liu, H; Xiao, J, *Food Packaging Shelf Life*, **19**, 76-85, 2019.]

Food packaging material was composed of a polymeric material and a natural antioxidant.[7] The natural antioxidant was extracted and isolated from plant material.[7] The natural antioxidant was selected from caffeic acid, rosmarinic acid, carnosol, and carnosic acid. The natural antioxidant was a rosemary extract comprising phenolic diterpenes.[7]

A soft nicotine pill included nicotine or a nicotine derivative, gelatin, a flavoring agent, and an antioxidant, which were invented as a tobacco substitute product. The antioxidant agent was butyl hydroxy anisole in the concentration of 0.025-0.2% of the total weight of the soft tablet.

References

1 Jridi, M; Boughriba, S; Abdelhedi, O; Nciri, H; Nasri, N, *Food Packaging Shelf Life,* **21**, 100342, 2019.
2 Kchaou, H; Benbettaïeb, N; Jridi, M; Abdelhedi, O; Nasri, M, *Food Hydrocolloids*, **83**, 326-9, 2018.
3 Gómez-Estaca, J; Balaguer, MP; López-Carballo, G; Gavara, R; Hernández-Muñoz, P, *Food Hydrocolloids*, **70**, 313-20, 2017.
4 Wang, S; Xia, P; Wang, S; Liang, J; Gao, X, *Food Hydrocolloids*, **96**, 617-24, 2019.
5 Yang, S; Wang, Y; Luo, S; Shan, C; Zan, X, *Colloids Surf. B: Biointerfaces*, **181**, 549-60, 2019.
6 Xia, C; Wang, W; Wang, L; Liu, H; Xiao, J, *Food Packaging Shelf Life*, **19**, 76-85, 2019.
7 Whithers, P, **WO2017049364A1**, *International Consolidated Business Group Pty Ltd,* Sep. 23, 2016.
8 Sanz Menedez, N; Rizo Martinez, JM; Buxade Viñas, A; Gomez Calvo, A; Prat, RJ, **WO2015136124A1**, *Farmalider, S.A., Laboratorios Viñas, S.A.*, Sep. 17, 2015.

5.22 HDPE (HIGH-DENSITY POLYETHYLENE)

Joined use of antioxidants and prodegradants in high-density polyethylene was correlated with the performance during service life and after disposal.[1] The primary antioxidant significantly increased the induction time of HDPE oxidative degradation processes.[1] Primary antioxidants stabilize free radicals, especially peroxyl radicals (POO•), by donating hydrogen, preventing the formation of alkyl radicals (P•) *via* abstraction of hydrogen from a nearby polymer chain.[1] The deactivation of alkoxyl radicals (PO•) through the formation of aldehydes is also possible, but the deactivation reaction of alkyl radicals (P•) is unlikely to occur since its reaction with oxygen is practically instantaneous.[1] So, the action of the primary antioxidant reduces but does not prevent degradation.[1] Secondary antioxidants act *via* redox reaction, where phosphites oxidize to form phosphates, and the hydroperoxide is reduced to less reactive and thermally stable alcohol.[1] This redox reaction occurs preferentially at processing temperatures.[1] An increase in thermooxidation temperature significantly reduced induction time. In the presence of the prodegradant Mn and the primary and secondary antioxidants, the following reactions occur (Figure 5.13)[1]

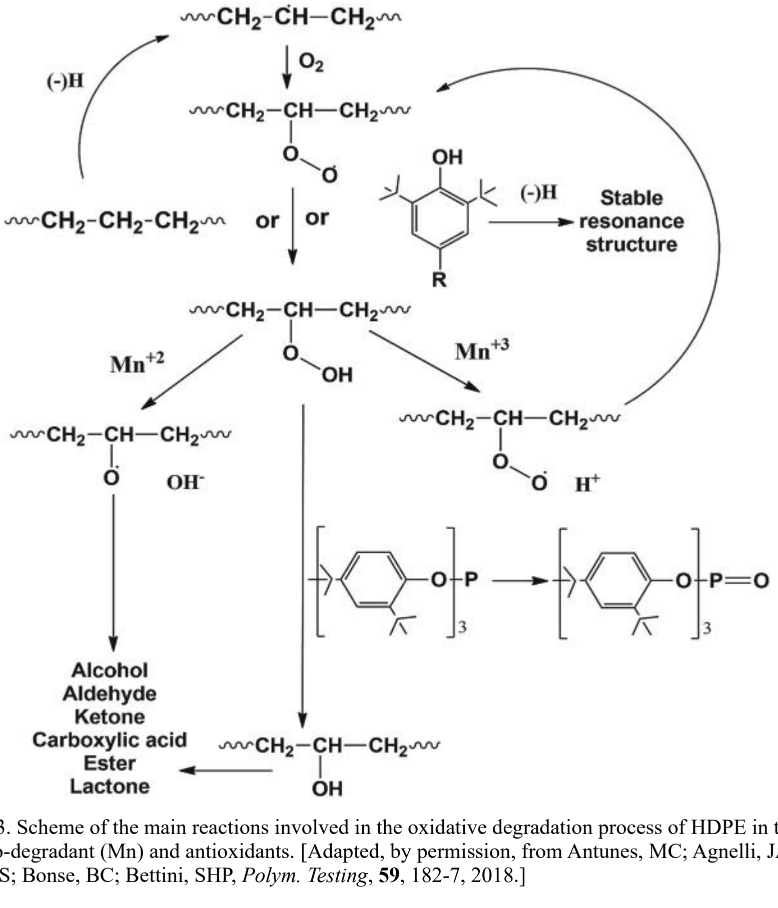


Figure 5.13. Scheme of the main reactions involved in the oxidative degradation process of HDPE in the presence of pro-degradant (Mn) and antioxidants. [Adapted, by permission, from Antunes, MC; Agnelli, JAM; Babetto, AS; Bonse, BC; Bettini, SHP, *Polym. Testing*, **59**, 182-7, 2018.]

Metallophthalocyanines [M: Co (II), Cu (II), Zn (II), Mn (II)] bearing eight peripheral 2,6-di-tert-butyl phenol groups were evaluated for radical scavenging of 1,1-diphenyl-2-picrylhydrazyl.[2] The highest DPPH activity was obtained from phthalocyanine copper (II).[2] The phthalocyanine complexes effectively inhibited the oxidation degradation of polypropylene and high-density polyethylene.[2]

Three reactive (graftable) antioxidants with hindered phenol and hindered amine antioxidant functions were examined for their grafting efficiency and their retention and stabilizing performance in peroxide-crosslinked high-density polyethylene pipe.[3] The addition of the graftable antioxidants did not affect the level of crosslinking of PEX pipes.[3] The antioxidant was uniformly distributed.[3] Retention of the graftable antioxidant, and its long-term stabilizing performance was significantly better than that of the conventional antioxidant.[3]

The impact of α and β radiation on antioxidant depletion in high-density polyethylene geomembranes of different thickness has been studied.[4] No change in oxidative induction time occurred in the 2-mm-thick HDPE geomembrane after exposure for 50h, but in membrane having a thickness of 0.04 mm significant antioxidant depletion occurred, most likely due to the penetration of α and β particles.[4] The α particles from a sealed source of ^{241}Am carrying 4.7 MeV penetrate approximately 28 μm into a 2-mm-thick HDPE, and β particles from ^{99}Tc source carrying 294 keV penetrate approximately 0.48 mm.[4] The shallow penetration was consistent with the antioxidant depletion thickness measured in geomembrane.[4]

Lignin, which is one of the components of plant fibers, contains phenols, having antioxidant properties.[5] Flax fibers commonly used to reinforce mechanical properties of high-density polyethylene composites can also enhance antioxidative properties because of the presence of lignins in their composition.[5] The oxidation induction time of the polyethylene matrix increased from 0 to 25 min when the flax fiber content was raised from 0 to 54%.[5] The presence of fibers also caused a slight increase in the degradation temperature of the polyethylene matrix, but the temperature degradation shift was not proportional to the number of fibers.[5] Aging at 80°C for up to 99 days of unstabilized and unreinforced polyethylene showed carbonyl formation and a drop in weight average molecular mass, which is characteristic of oxidation of this polymer.[5] Under the same conditions of aging, the material containing 38 wt% of flax fibers has not been oxidized, and the amount of antioxidants present in the lignin was slightly decreased.[5]

Sterilization of implants and other clinical accessories is an integral part of any medical application.[6] The role of multiwalled carbon nanotubes as an effective antioxidant and radical scavenger in resisting the deteriorating effects of sterilization of irradiated high-density polyethylene has been studied.[6] The addition of 1 wt% MWCNTs into virgin HDPE decreased the oxidation index of the composite at 100 kGy by 56.2%.[6] The addition of MWCNTs into polyethylene limited the loss of mechanical properties and improved its post-irradiation oxidative stability (Figure 5.14).[6]

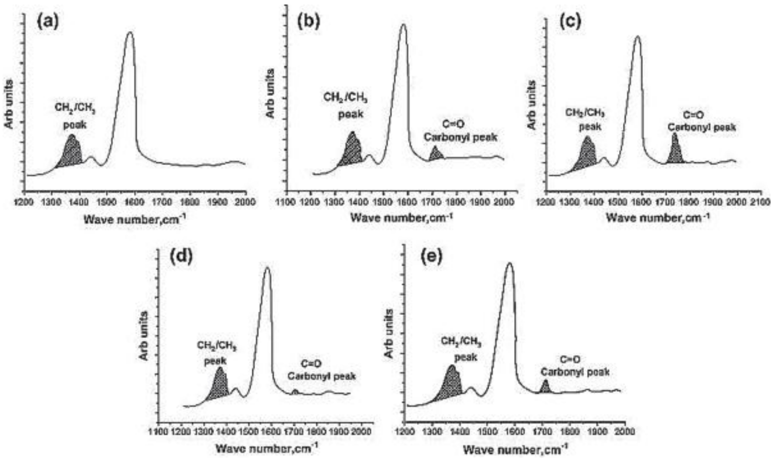


Figure 5.14. FTIR spectrum of (a) unirradiated virgin HDPE (b) virgin HDPE at 50 kGy (c) virgin HDPE at 100 kGy dose (d) 1 wt% MWCNTs composite at 50 kGy dose (e) 1 wt% MWCNTs composite at 100 kGy dose. [Adapted, by permission, from Sreekanth, PSR; Kumar, NN; Kanagaraj, S, *Compos. Sci. Technol.*, **72**, 3, 390-6, 2012.]

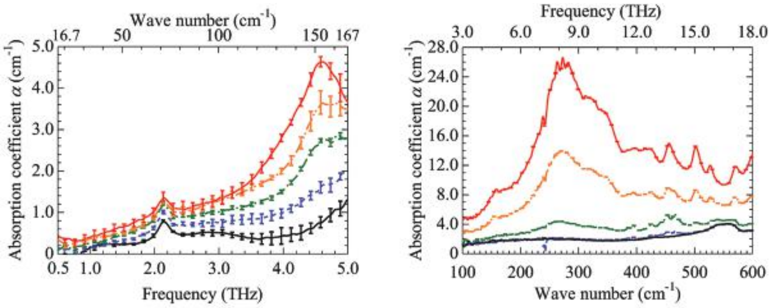
The stabilization of polyethylene is usually done by addition of primary antioxidants such as hindered phenolics (Irganox 1076 and Irganox 1010), and secondary antioxidants are also used, such as phosphate esters (e.g., Irgafos 168).[7] Antioxidant of the invention improves stabilizing performance, reduces cost, and improves rheological properties of polyolefin melt.[7] The antioxidants of the invention are 3,4-diethyl-3,4-diphenyl hexane and similar.[7]

References

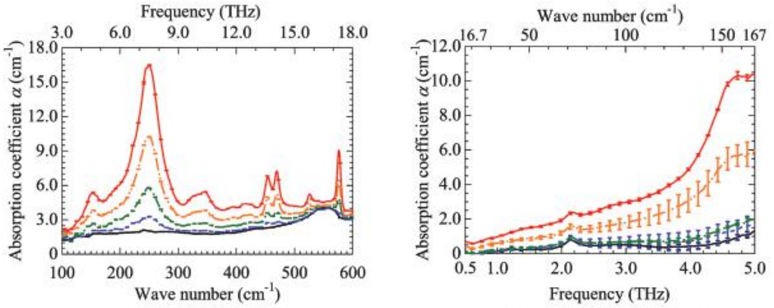
1 Antunes, MC; Agnelli, JAM; Babetto, AS; Bonse, BC; Bettini, SHP, *Polym. Testing*, **59**, 182-7, 2018.
2 Salehi, MH; Karimi, AR, *Polym. Deg. Stab.*, **151**, 105-13, 2018.
3 Al-Malaika, S; Riasat, S; Lewucha, C, *Polym. Deg. Stab.*, **145**, 11-24, 2017.
4 Tian, K; Benson, CH; Yang, Y; Tinjum, JM, *Geotextiles Geomembranes*, **46**, 4, 426-35, 2018.
5 Van Schoors, L; Minerbe, MG; Moscardelli, S; Rabii, H; Davies, P, *Ind. Crops Prod.*, **126**, 333-9, 2018.
6 Sreekanth, PSR; Kumar, NN; Kanagaraj, S, *Compos. Sci. Technol.*, **72**, 3, 390-6, 2012.
7 Demirors, M; Karjala, TP, **WO2012096962A1**, *Dow Global Technologies Llc*, Jan. 10, 2012.

5.23 LDPE (LOW-DENSITY POLYETHYLENE)

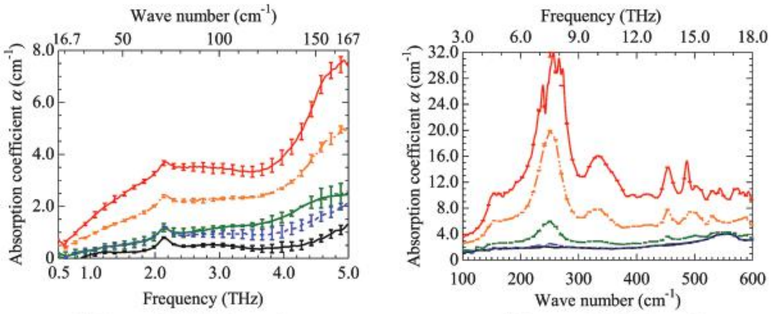
Three phenol-type antioxidants, BHT, Irganox 1010, and Irganox 1330, were added to sheets of low-density polyethylene, and their absorption spectra were recorded at terahertz and far-infrared frequencies.[1] Absorption with various peaks characteristic to each antioxidant increased monotonically with an increase in the content of antioxidant, which permits identification and quantification of each antioxidant added in LDPE (Figure 5.15).[1]



(a) BHT (THz range) (d) Irganox 1010 (FIR range)



(b) BHT (FIR range) (e) Irganox 1330 (THz range)



(c) Irganox 1010 (THz range) (f) Irganox 1330 (FIR range)

Figure 5.15. Spectra of absorption coefficients (α) at frequencies from 0.5 to 5.0 THz (a, c, e) or wave numbers from 100 to 600 cm^{-1} (b, d, f), measured for the samples containing four different contents of phenol-type antioxidants. (a, b) BHT, (c, d) Irganox 1010, (e, f) Irganox 1330; 0, 0.1, 1.0, 5.0, 10 wt%. Each curve and bar shows the average and standard deviation of three measurements. [Adapted, by permission, from Ogishima, T; Kuroda, O; Hirai, H; Ohki, Y, *Polym. Testing*, **76**, 10-8, 2019.]

Nanosilica-immobilized antioxidant was prepared on fumed nanosilica, which was first modified with aminosilane coupling agent and then reacted with 3,5-di-tert-butyl-4-hydroxybenzoic acyl chloride (Figure 5.16).[2] The nanosilica-immobilized antioxidant significantly improved the thermal oxidative stability of LDPE nanocomposite.[2]

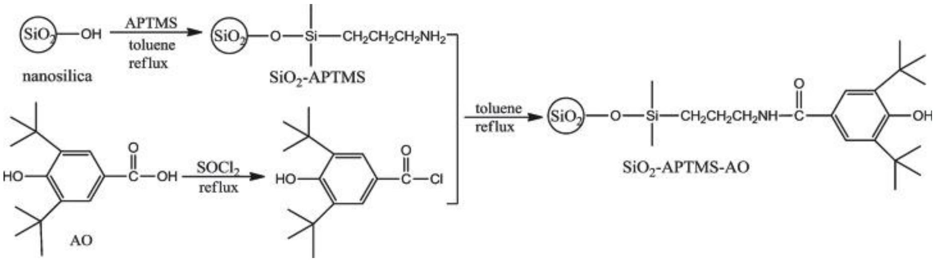


Figure 5.16. Synthesis of functionalized nanosilica. [Adapted, by permission, from Liu, P; Tang, H; Lu, M; Gao, C; Yang, M, *Polym. Deg. Stab.*, **135**, 1-7, 2017.]

Active biocomposite films of low-density polyethylene containing 5 wt% of curcumin were produced by melt extrusion and hot pressing.[3] The curcumin molecules, homogeneously dispersed in the whole volume of the LDPE matrix, caused a notable increase in the thermal stability of the LDPE polymer, without altering its thermal processability.[3] Effective antioxidant scavenging activity was observed against the 2,2-diphenyl-1-picrylhydrazyl free radicals (DPPH•).[3]

Low-density polyethylene film containing α-tocopherol adsorbed on MCM-41 mesoporous the molecular sieve was prepared by extrusion for food packaging.[4] The releasing time of α-tocopherol in LDPE absorbed on molecular sieve was prolonged by about 36%, and the diffusivity of the antioxidant decreased by 53%.[4] DPPH radical scavenging assay proved the effectiveness of the antioxidant.[4]

Molecular structure changes for low-density polyethylene, irradiated under three different atmospheres (nitrogen/oxygen to give oxygen concentrations of 0, 21 and 100 vol%) with doses between 33 and 222 kGy were analyzed, with emphasis on the changes of longer polymethylene crystallizable lengths.[5] The presence of oxygen in the irradiation atmosphere gives higher reaction rates.[5] Thick samples irradiated in oxygen show a lower carbonyl index than thin samples.[5]

A maximum in the torque vs. time curve can be seen for low-density polyethylene containing an antioxidant.[6] Material without antioxidant does not have any maximum in the torque vs. time curve and, after a certain time, directly undergoes chain scission.[6] The presence of the antioxidant in a low-density polyethylene seems to change the kinetics of two competing reactions: long-chain branching formation/crosslinking and chain scission.[6] The antioxidant stops peroxide formation, which slows the molecular weight decrease but does not influence long chain branching formation or crosslinking.[6]

The antioxidant-functionalized graphene oxide was used to enhance the thermal oxidative stability and retain the excellent electrical insulating properties of low-density polyethylene.[7] Figure 5.17 illustrates the method of production of functionalized graphene.[7] The oxidative induction time of LDPE composite containing 2.0 wt% antioxidant-functionalized reduced graphene increased to 19 min from 0.5 min for pure LDPE. The excellent electrical insulating properties of LDPE were retained.[7]

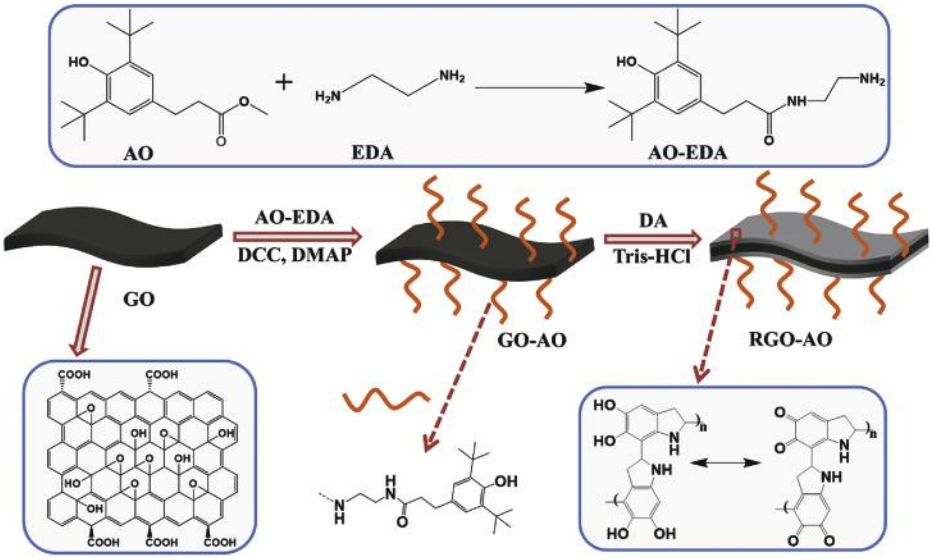


Figure 5.17. Illustration of the preparation of antioxidant functionalized graphene. AO (methyl 3-(3, 5-di-tert-butyl-4-hydroxyphenyl) propionate) – antioxidant, EDA – ethylenediamine, GO – graphene oxide, RDO – reduced graphene oxide, DA – dopamine. [Adapted, by permission, from Bu, J; Huang, X; Li, S; Jiang, P, *Carbon*, **106**, 218-27, 2016.]

With the aim to develop new materials for active food packaging, composites of low-density polyethylene with chitosan or chitosan sodium montmorillonite clay nanocomposites, with or without Irganox 1076 or vitamin E were prepared by melt processing.[8] Chitosan provided LDPE films with antimicrobial properties whereas vitamin E increased the oxidation induction period, especially in materials containing chitosan nanocomposites.[8]

Natural (outdoor) weathering test was performed to investigate the UV stability of thin films (0.06 mm) of linear low-density polyethylene and low-density polyethylene.[9] Some films contained a single high molecular mass HALS, along with a primary antioxidant (i.e., Irganox 1010) and a secondary antioxidant (i.e., Irgafos 168 or Alkanox TNPP), while other films contained HALS and UVA (i.e., Chimassorb 81 or Tinuvin P or Tinuvin 326) and the above antioxidants.[9] Films containing a single HALS had improved UV stability by two to 12 fold over control films without stabilizers.[9] Films that contained a combination of HALS and UVA had further improved UV stability over the films containing a single HALS (both with antioxidants).[9]

Tree-resistant, crosslinkable polyethylene compositions for wire and cable contained thiobis-phenolic antioxidant, which was incorporated by mixing with polyalkylene glycol prior to compounding with a polymer.[10] The incorporation of thiobis-phenolic antioxidant in polyalkylene glycol blend into polyethylene provided the low-density polyethylene with high oxidative induction time.[10]

The material consisted of a system promoting migration of an active component to the packaged product during its storage or marketing.[11] It replaced the direct addition of antioxidants to the packaged products and lengthened their shelf life.[11] The material was formed from 89 wt% of the base polymer, 3.5 to 10 wt% tocopherol antioxidant, and 0.1 to 1.0 wt% of any surface modifier having a hydrophobic portion and a hydrophilic portion in its molecule, whose use as an additive in contact with foods was approved by FDA.[11]

References

1 Ogishima, T; Kuroda, O; Hirai, H; Ohki, Y, *Polym. Testing*, **76**, 10-8, 2019.
2 Liu, P; Tang, H; Lu, M; Gao, C; Yang, M, *Polym. Deg. Stab.*, **135**, 1-7, 2017.
3 Zia, J; Paul, UC; Heredia-Guerrero, JA; Athanassiou, A; Fragouli, D, *Polymer*, **175**, 137-45, 2019.
4 Sun, L-n; Lu, L-x; Qiu, X-l; Tang, Y-l, *Food Control*, **71**, 193-9, 2017.
5 Pérez, CJ; Failla, MD; Carella, JM, *Thermochim Acta*, **538**, 67-74, 2012.
6 Mariani, P; Carianni, G; La Mantia, FP, *Polym. Deg. Stab.*, **85**, 3, 1003-7, 2004.
7 Bu, J; Huang, X; Li, S; Jiang, P, *Carbon*, **106**, 218-27, 2016.
8 Vasile, C; Darie, RN; Cheaburu-Yilmaz, CN; Pricope, G-M; Duraccio, D, *Composites Part B: Eng.*, **55**, 314-23, 2013.
9 Basfar, AA; Idriss Ali, KM, *Polym. Deg. Stab.*, **91**, 3, 437-43, 2006.
10 Adamczyk, A; Emley, D; Dunchus, NW; Cogen, JM; Song, S, **WO2012162019A1**, *Union Carbide Chemicals & Plastics Technology Llc, Dow Global Technologies Llc*, May 15, 2012.
11 Soto-Valdez, H; Graciano-Verdugo, AZ; Peralta, E; Yuridia, C, **US20120276357A1**, *Centro de Investigacion en Alimentacion y Desarrollo AC (CIAD),* Nov. 1, 2012.

5.24 LLDPE (LINEAR LOW-DENSITY POLYETHYLENE)

The ability of piperidine-based compounds to confer oxidative stability to polyolefin thermosets without compromising the yields of peroxide-initiated crosslinking and monomer grafting has been demonstrated.[1] Unlike phenolic, nitroxyl and phosphite antioxidants that lower the concentration of macroradical intermediates which support polyolefin modifications, the additives based on 2,2,6,6-tetramethylpiperidine had little to no effect on the extent of LLDPE crosslinking or the conversion of vinyltriethoxysilane to grafted hydrocarbon adducts.[1] This class of hindered light stabilizer limits the extent of radical oxidation of linear low-density polyethylene in an accelerated aging test.[1] The latent antioxidant concept is extended to an alternate approach, wherein 4-acryloyloxy-2,2,6,6-tetramethylpiperidine-N-oxyl has been used as an alkyl radical scavenger bearing an oligomerizable functional group.[1] When added at a fraction of the peroxide loading used to produce an LLDPE thermoset, 4-acryloyloxy-2,2,6,6-tetramethylpiperidine-N-oxyl provided a predictable induction delay without impacting ultimate crosslink density and produced polymer-bound alkoxyamine functionality that stabilized the product against oxidation.[1]

The thermal exposure leads to a progressive increase, until 6000 h, in tensile strength, a slight increase in hardness, and a proportional decrease in elongation at break.[2] These results can be explained by the increase of crystallinity, followed by the increase of crosslinking density and the decrease in chain mobility due to thermal oxidation as the exposure time increases.[2] The additional aging of the antioxidant-depleted LLDPE pipe led to a decrease in mechanical properties.[2] The oxidation induction time results suggested that after 6000 h of the thermal aging, the depletion of antioxidant originally added in the LLDPE pipe occurred.[2]

Linear low-density polyethylene films were impregnated with eugenol using supercritical CO_2 impregnation, to obtain material for active food packaging.[3] Eugenol, the main component of clove oil, is a natural antioxidant and antimicrobial agent.[3] A decrease in the crystallinity degree in the impregnated samples and in films subjected to pressurization with CO_2 but not loaded with eugenol was observed.[3] An 80% DPPH inhibition was observed, regardless of the eugenol loading.[3]

Effects of γ-irradiation on residual and migration levels of antioxidants, tris-(2,4-di-tert-butyl phenyl) phosphite (Irgafos 168) and octadecyl-3-(3,5-di-tert-butyl-4-hydroxyphenyl) propionate (Irganox 1076), and their radiolysis products were investigated in the linear low-density polyethylene packaging samples treated with doses of 0 to 200 kGy.[4] 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.[4]

Green tea and thermoplastic starch were extruded with linear low-density polyethylene.[5] Active functions of modified films depended on hydrophobicity and release of green tea extract.[5]

Active linear low-density polyethylene composites were manufactured by immobilization of resveratrol in the polymeric matrix and by pre-incorporation of the resveratrol in montmorillonite clay prior to melt mixing with the polymer.[6] The composites showed strong antioxidant activity and antimicrobial activity.[6] This technology could potentially extend the shelf-life of red meat by a few days due to free radicals trapping and the subsequent arrest in food oxidation processes.[6]

Blends of linear low-density polyethylene and nanorod-polyaniline, formed by a falling pH synthesis, were prepared by dispersing PANI in the melt of LLDPE at 150°C.[7] The blends had 5, 10, 15 and 20 wt% loading of PANI.[7] The blends did not show any chemical interaction between the components.[7] With an increased loading of PANI in the blends, the amount of PANI present on the surface of the samples increased, and the crystallinity of LLDPE decreased.[7] The blends had very good free radical scavenging activity, dependent upon the amount of PANI included in the blends.[7]

The composition comprised: (a) a linear low-density polyethylene (b) from 20 to 500 part by weight of a primary antioxidant comprising 3,4-dihydro-2,5,7,8-tetramethyl-2-(4,8,12-trimethyltridecyl)-2H-1-benzopyran-6-ol per one million parts of LLDPE; (c) optionally from 2 to 200 parts by weight of an optical brightening agent; and (d) optionally from 20 to 1000 parts by weight of a secondary antioxidant (e.g., tris (2,4-di-tert-butyl phenyl)phosphite) per one million parts of LLDPE.[8]

References

1 Twigg, C; Ford, K; Parent, JS, *Polymer*, **176**, 293-9, 2019.
2 Weon, J-i, *Polym. Deg. Stab.*, **95**, 1, 14-20, 2010.
3 Goñi, ML; Gañán, NA; Strumia, MC; Martini, RE, *J. Supercritical Fluids*, **111**, 28-35, 2016.
4 Jeon, DH; Park, GY; Kwak, IS; Lee, KH; Park, HJ, *LWT - Food Sci. Technol.*, **40**, 1, 151-6, 2007.
5 Panrong, T; Karbowiak, T; Harnkarnsujarit, N, *Food Packaging Shelf Life*, **21**, 100331, 2019.
6 Sun, L-n; Lu, L-x; Qiu, X-l; Tang, Y-l, *Food Control*, **71**, 193-9, 2017.
7 Nand, AV; Ray, S; Travas-Sejdic, J; Kilmartin, PA, *Mater. Chem. Phys.*, **135**, 2-3, 903-11, 2012.
8 Vanspeybroeck, RSL, **WO2014190298A1**, *Dow Global Technologies Llc*, May 23, 2014.

5.25 NBR (ACRYLONITRILE-BUTADIENE ELASTOMER)

N,N-substituted p-phenylene diamines (N-isopropyl-N′-phenyl-p-phenylenediamine, phenyl β-naphthylamine, and N-(1,3-dimethylbutyl)-N-phenyl-p-phenylene diamine) were used as antioxidants to improve the resistance of acrylonitrile-butadiene rubber seals against γ-irradiation up to 5 MGy to which they were exposed in nuclear facilities.[1] The best physical and mechanical performance resulted from the addition of N-(1,3-dimethylbutyl)-N-phenyl-p-phenylenediamine.[1]

Aging-resistance is an important property of rubber products for their long-term applications, but blooming of antioxidants results in loss of aging protection and induces toxicity and pollution.[2] Phenolic antioxidant, such as 3,9-bis-{1,1-dimethyl-2[β-(3-tert-butyl-4-hydroxy-5-methylphenyl-)propionyloxy]ethyl}-2,4,8,10-tetraoxaspiro[5,5]-undecane was chemically grafted on carbon nanotubes, producing antioxidants with loading efficiency from 3.7 to 10.3 wt%.[2] When 20 phr of grafted antioxidant (3.7 wt%) were added to NBR, it withstood 1 year of natural aging and a 60-days thermal-oxidative test at 90°C without antioxidant blooming.[2] Figure 5.18 illustrates grafting procedure.[2]

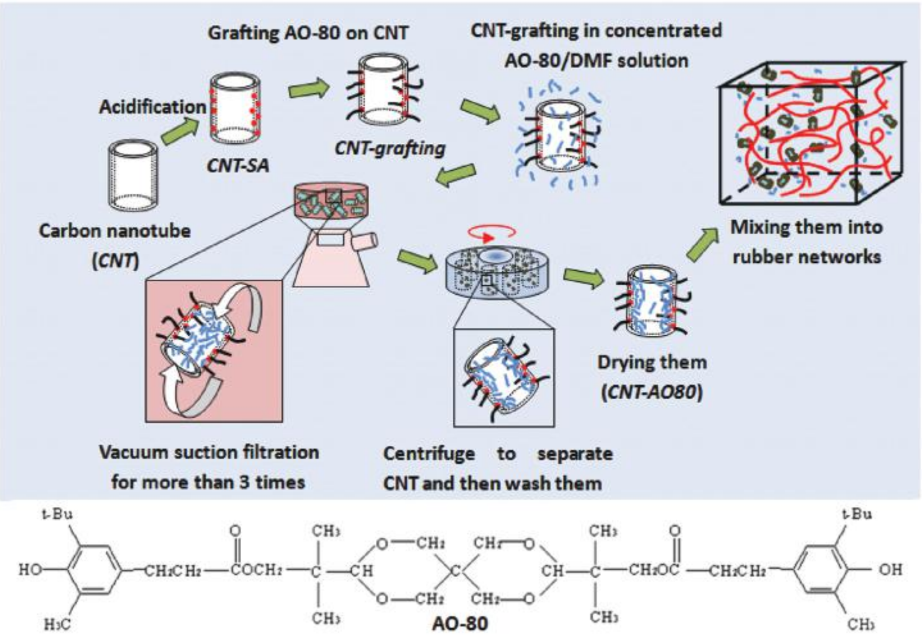


Figure 5.18. Preparation processes of antioxidant-loaded carbon nanotubes. [Adapted, by permission, from Zhang, J; Zhang, H; Wang, S; Liu, M, *Polym. Deg. Stab.*, **144**, 93-9, 2017.]

Rubber composition contained nitrile rubber, sulfur, vulcanization accelerators, anti-scorching agent, and antistatic agent.[3] Antioxidant (2,2,4-trimethyl-1,2-dihydroquinoline polymer, 4,4'-bis (alpha, alpha-dimethylbenzyl) diphenylamine) was used in a concentration of at least 0.5 wt%.[3]

Polyesteramidesulfone was acting as an antioxidant and reinforcement nanofiller in reclaimed natural rubber/acrylonitrile-butadiene rubber blend.[4] The functional groups of polyesteramidesulfone interacted with acrylonitrile-butadiene rubber.[4]

References

1 Ahmed, FS; Shafy, M; Abd El-Megeed, AA; Hegazi, EM, *Mater. Design*, **36**, 823-8, 2012.
2 Zhang, J; Zhang, H; Wang, S; Liu, M, *Polym. Deg. Stab*., **144**, 93-9, 2017.
3 **WO2015080114A1**, Nov. 26, 2014.
4 Morsi, SMM; Mohamed, HA; El-Sabbagh, SH, *Mater. Chem. Phys*., **224**, 206-16, 2019.

5.26 PA (POLYAMIDE)

Subjecting polymers to elevated temperatures and extended exposure times can significantly increase the melt viscosity and prevent impregnation progress of carbon fiber reinforced thermoplastics, which was studied for polyamide 6 and copolyamide by subjecting them to repeated heating cycles, such as used in production processes.[1] Both polymers have a strong tendency to thermooxidative degradation.[1] The addition of antioxidant reduced the extent of thermooxidative degradation but revealed decreased efficiency with increasing dwell times.[1] The phosphorous-based hydroxide decomposer (Hostanox P-EPQ) proved to be the most effective.[1]

Hindered phenol antioxidant was grafted onto graphene oxide surface, and polyamide 6 nanocomposite was manufactured *via* melt processing.[2] Efficient grafting of PA6 molecules onto graphene oxide was possible because of hydrogen bonding.[2] The oxidation induction time, thermal degradation temperature, and activation energy were significantly increased on the addition of grafted graphene oxide.[2] Figure 5.19 illustrates the chemistry of the process.[2]

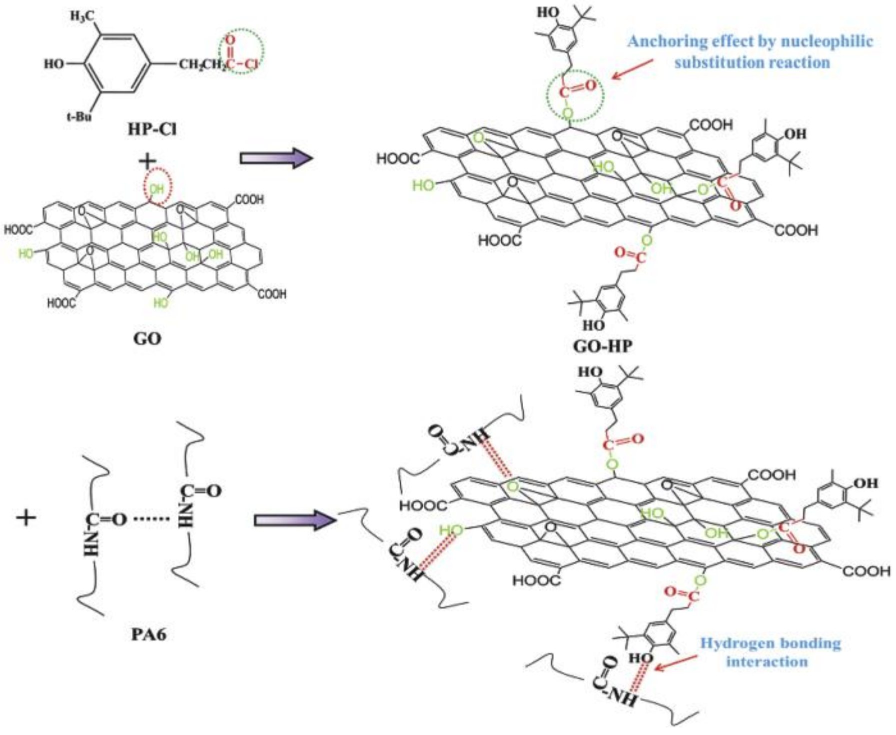


Figure 5.19. Anchoring effect of hindered phenol antioxidant and PA6 molecules onto graphene oxide surface. [Adapted, by permission, from Li, R; Shi, L; Ye, L; Li, G, *Composites Part B: Eng.*, **162**, 11-20, 2019.]

Polyamide film was immersed for 48 h in green tea extract and used for fresh minced meat active packaging applications.[3] Film protected meat for 23 days.[3]

Chemiluminescence accompanying oxidation of lactam-based polyamides stabilized with phenols, secondary aromatic amines, and hindered nitroxyl radicals was measured.[4] Because antioxidants react with peroxy radicals in several consecutive inhibition reactions having different yields of chemiluminescence, the intensity of chemiluminescence depended on the rate of initiation of the oxidation.[4] The intensity of chemiluminescence and the rate of oxygen consumption during oxidation of stabilized polyamides differed for various polyamides depending on their end-group content, the concentration of antioxidant, and the conditions of oxidation, especially on the rate of initiation determining the rate of antioxidant consumption.[4]

Biobased aliphatic polyamide 11 has acquired significant interest as an environmentally friendly thermoplastic polymer.[5] The photooxidative degradation processes in PA11 composites were controlled by thymol and halloysite nanotubes.[5] Halloysite nanotubes playing the role of reinforcing filler were also used as green nano-container of natural antioxidant molecules.[5] The composite containing thymol/halloysite hybrid had superior durability performance.[5]

The cosmeto-textiles with an active substance incorporated into their structure are increasingly used in the cosmetics and pharmaceutical industries.[6] An *in vitro* percutaneous absorption demonstrated the delivery of resveratrol from the textile to the different skin layers (stratum corneum, epidermis, and dermis).[6] Cosmeto-textiles containing resveratrol were applied onto the forearms of volunteers to evaluate the textiles' efficacy in skin penetration.[6] Resveratrol was detected in the dermis, epidermis, and stratum corneum.[6] The antioxidant's antiradical capacity was evaluated using the DPPH method.[6] The cosmeto-textiles acted as a reservoir system capable of progressively deliver the active substance to the skin layers.[6]

Melt processing of polycondensate polymers must be carried out after drying to avoid hydrolytic chain scission caused by water.[7] The effect of two antioxidants (tetrakis-(2,4-di-tert-butyphenyl)-4, 4′-biphenylylene-diphosphonite and tris-(2,4-di-tert-butylphenyl)-phosphite) on the processing and flow properties of a polyamide 6 processed without drying has been studied.[7] One of these stabilizers seems to protect the wet polymer from hydrolytic chain scission.[7] Diphenylene stabilizer protected the wet polymer from hydrolytic chain scission.[7]

Diffusion coefficients and solubilities of a phenolic antioxidant (Irganox® 1098) in polyamide 6 were determined in the temperature range of 139-180°C.[8] Diffusion coefficient, and solubility indicated Arrhenius and van't Hoff dependences on temperature, with discontinuities at the melting temperature of the antioxidant.[8] The activation energies for diffusion and enthalpies of solution were lower above than below the melting temperature. Blooming of Irganox® 1098 as a function of temperature and time can be calculated based on diffusion coefficient and solubility.[8]

Antioxidant for polyamides containing a sterically hindered phenol (Ralox LC) shows a significantly improved antioxidant effect compared to conventional antioxidants.[9]

Water-treatment separation membrane includes porous support and polyamide layer formed on the porous support, and the polyamide layer contains antioxidant.[10] The preferred antioxidant was bis(dialkylphenyl) pentaerythritol diphosphite ester.[10]

Polyamide composition for an LED reflection plate comprises a polyamide, titanium oxide, magnesium oxide, a phenolic antioxidant (3,9-bis [1,1-dimethyl -2- [β- (3-t- butyl-4-hydroxy-5-methylphenyl) propionyloxy] ethyl] -2,4,8,10-spiro [5.5] undecane), and a phosphorus-based antioxidant (tris (2,4-di -t- butyl-phenyl) phosphite).[11]

References

1 Radlmaier, V; Heckel, C; Winnacker, M; Erber, A; Koerber, H, *Thermochim. Acta*, **648**, 44-51, 2017.
2 Li, R; Shi, L; Ye, L; Li, G, *Composites Part B: Eng.*, **162**, 11-20, 2019.
3 Borzi, F; Torrieri, E; Wrona, M; Nerín, C, *Food Chem.*, **300**, 125242, 2019.
4 Lánská, B; Matisová-Rychlá, L; Rychlý, J, *Polym. Deg. Stab.*, **72**, 2, 249-58, 2001.
5 Gorrasi, G; Bugatti, V; Ussia, M; Mendichi, R; Carroccio, SC, *Polym. Deg. Stab.*, **152**, 53-51, 2018.
6 Alonso, C; Martí, M; Martínez, V; Rubio, L; Coderch, L, *Eur. J. Pharm. Biopharm.*, **84**, 192-9, 2013.
7 La Mantia, FP; Scaffaro, R, *Polym. Deg. Stab.*, **75**, 3, 473-7, 2002.
8 Dong, W; Gijsman, P, *Polym. Deg. Stab.*, **95**, 6, 955-9, 2010.
9 Asbahr, H-O; Bomba, T, **WO2003008492A1**, *Degussa AG*, Jan. 30, 2003.
10 Kim, K-H; Song, K-W; Shin, C-K, **EP2835175A1**, *LG Chem Ltd*, Nov. 4, 2015.
11 **WO2017002824A1**, Jan. 5, 2017.

5.27 PANI (POLYANILINE)

The emeraldine base form of polyaniline can be reduced by common antioxidants (such as glutathione and ascorbic acid), which results in changes of the solution color and the UV-vis absorption spectra.[1]

Polyaniline nanofiber/carbon dot nanohybrid acts as a good antioxidant.[2] It can scavenge up to 86% of 2,2-diphenyl picryl hydrazyl radicals within 30 min.[2]

Starch/polyaniline composites have been synthesized using oxidative polymerization of polyaniline in an aqueous dispersion of starch. Composite possessed antioxidant nature which increased with the concentration of polyaniline.[3]

Polyaniline nanofibers were synthesized by photo-assisted chemical oxidative polymerization of aniline in the presence of different dopant acids.[4] The radical scavenging ability of the produced PANI nanofibers was determined by the DPPH assay.[4] The antioxidant activity of PANI nanofibers was higher than that of the conventional PANI and increased with decreasing the average diameter of the nanofibers.[4]

The thermal stability of chemically synthesized polyaniline was examined.[5] The free radical scavenging capacity of the samples was evaluated using the 1,1-diphenyl-2-picrylhydrazyl assay.[5] The rapid decline in free radical scavenging capacity occurred on exposure to temperatures above 200°C.[5]

Aqueous dispersions of colloidal polyaniline were prepared by different methods using a water-soluble polymer polyvinylpyrrolidone acting as a steric stabilizer.[6] The aggregation between PANI particulates was significantly reduced by using polyvinylpyrrolidone as the dispersing medium.[6] The oxidation state of PANI in these dispersions and the hydrodynamic diameter of the colloidal particles were the critical factors of the free radical scavenging capacity and antibacterial activity.[6]

Electrostatic dissipative rubber product was made poly(butadiene-co-acrylonitrile) containing an electrically conductive filler derived from sulfonic acid doped polyaniline.[7] Antioxidant has been added to increase the durability of the rubber compound.[7]

References

1 Li, Y; Li, W; Zhou, H; Wang, F; Yu, C, *Sensors Actuators B: Chem.*, **208**, 30-5, 2015.
2 Saikia, A; Karak, N, *Mater. Today Commun.*, **14**, 82-9, 2018.
3 Saikia, JP; Banerjee, S; Kumar BK; Kumar, A, *Colloids Surf. B: Biointerfaces*, **81**, 1, 158-64, 2010.
4 Wang, J; Zhu, LH; Li, J; Tang, HQ, *Chinese Chem. Lett.*, **18**, 8, 1005-8, 2007.
5 Nand, AV; Ray, S; Gizdavic-Nikolaidis, S; Travas-Sejdic, J; Kilmartin, PA, *Polym. Deg. Stab.*, **96**, 12, 2159-66, 2011.
6 Wu, JC-C; Ray, S; Gizdavic-Nikolaidis, M; Jin, J; Cooney, RP, *Synthetic Metals*, **217**, 202-9, 2016.
7 Yong, KC, **WO2014123405A1**, *Lembaga Getah Malaysia*, Jan. 2, 2014.

5.28 PB (POLYBUTYLENE)

The degradation of the PB pipe was promoted by chlorine derivatives.[1] It was accelerated due to the decreasing amount of antioxidant (Irganox 1010 or 1076) even underwater pressure.[1] Figure 5.29 shows the distribution of antioxidant on exposure to different concentrations of chlorine.[1]

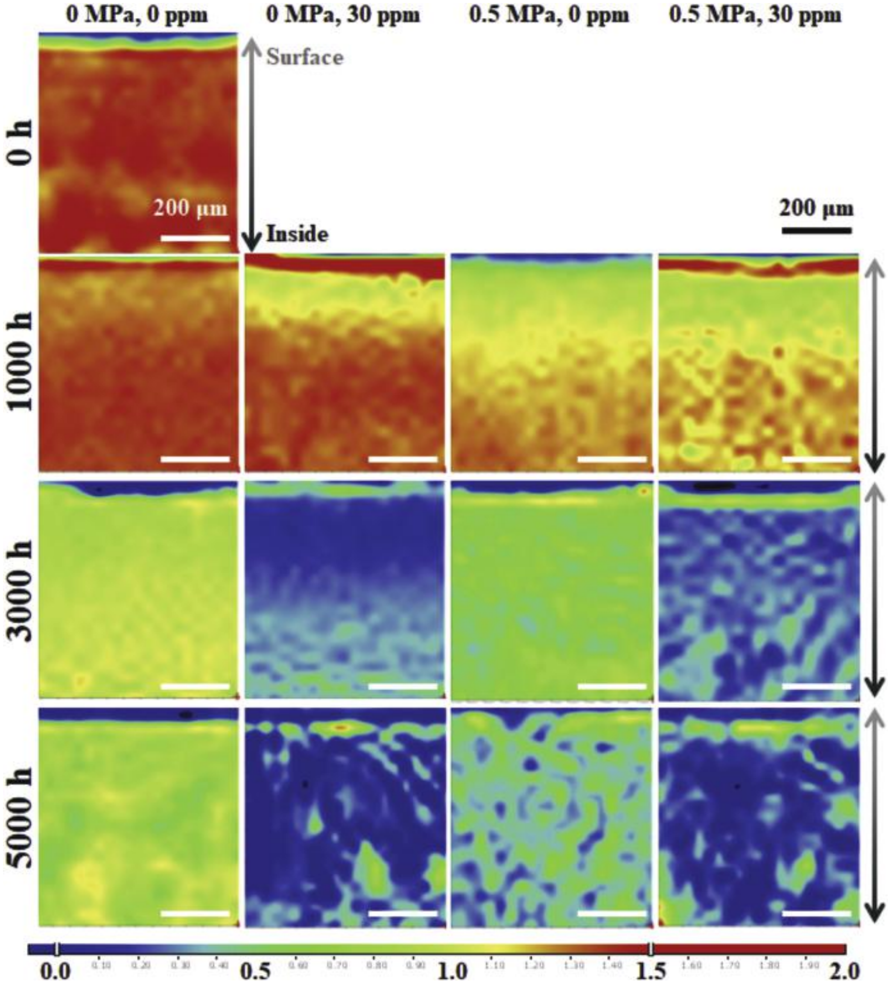


Figure 5.20. Micro-FT-IR images of antioxidants from the surface to the inside for each condition (concentration of chlorine, water pressure, and time of exposure). [Adapted, by permission, from Fujii, T; Matsui, Y; Hirabayashi, H; Igawa, K; Yamada, K, *Polym. Deg. Stab*., **167**, 1-9, 2019.]

The image shifts from red to blue as the degradation progresses under all conditions because the amount of antioxidant in the PB pipe decreases with time. Increased water pressure resulted in an increased loss.[1] Also, the loss of antioxidant was accelerated by the presence of chlorine.[1] Antioxidants are generally reduced by physical migration and leaching into the contact environment, which is evident from depth profiles.[1]

The lifetime of polymer tubes was estimated as the time at which the amount of antioxidant in the material was reduced to 10% of the initial value.[2] Lifetimes predicted for a range of thin-walled (1-3 mm) tubes were of the order of 1 year of continuous operation.[2] Once the rate of antioxidant depletion was predicted, failure occurred through an attack of the base polymer material by hot chlorinated water.[2]

References

1 Fujii, T; Matsui, Y; Hirabayashi, H; Igawa, K; Yamada, K, *Polym. Deg. Stab*., **167**, 1-9, 2019.
2 Mittelman, G; Davidson, JH; Mantell, SC; Su, Y, *Solar Energy*, **82**, 5, 452-61, 2008.

5.29 PBD (POLYBUTADIENE)

The thermal oxidation of hydroxy telechelic polybutadiene stabilized with 2,2′-methylene-bis(4-methyl-6-tert-butylphenol) was studied at 100°C by weight change and liquid chromatography.[1] The initial rate of stabilizer depletion was proportional to the initial stabilizer concentration.[1] An experiment conducted under nitrogen showed that physical stabilizer loss was negligible.[1] The major part of the initial stabilizer was lost by a competing non-stabilizing process *via* reaction with oxygen, essentially resulting in oxidation of the antioxidant itself.[1]

Polyurethane was synthesized by a reaction of OH-telechelic, 1,2-rich, low-molecular-weight polybutadiene with toluene 2,4-diisocyanate.[2] To the pendent vinyls of the polybutadiene blocks of the polyurethane, a sterically hindered phenolic antioxidant bearing a sulfanyl group (i.e., 6-sulfanylhexyl 3-(3,5-di-tert-butyl-4-hydroxyphenyl)propanoate) was added by a free-radical mechanism, forming antioxidant structures as side chains.[2] This stabilized polyurethane was added to unstabilized polyurethane.[2] The antioxidant effect of the polymeric stabilizer was approximately the same as that of a low-molecular-weight analogue.[2]

Thermal degradation studies of a stabilized hydroxy-terminated polybutadiene-based elastomer were conducted at temperatures from 50 to 110°C. The depletion rate of antioxidant was temperature-dependent.[3] Only fractions of the total antioxidant available were involved in the inhibition process.[3] At aging temperatures below 65°C, antioxidant levels remained higher and changed more slowly, but degradation of the polymer nevertheless occurred and resulted in mechanical failure.[3] Furthermore, because antioxidant levels appeared to remain relatively constant during the later stages of the degradation process, measurements of antioxidant levels had limited value for lower aging temperatures.[3]

Two antioxidants were used in stabilization of polybutadiene: AO1 − stearyl-β-(3,5-di-tert-butyl-4-hydroxy-phenyl)-propionate (fully sterically hindered) and AO2 − triethyleneglycol-bis-3(3-tert-butyl-4-hydroxy-5-methylphenyl)-propionate (partially hindered bis-phenol).[4] One-side shielding (AO2) increased the mobility of the hydrogen atom, compared to the fully hindered phenol, which had both beneficial and disadvantageous consequences: the high temperature stabilizing efficiency increased at low concentrations, but the additive became prone to self-association.[4] This latter effect was reflected in low solubility, limited efficiency at high temperatures, and reduced stabilizing effectiveness under oven aging conditions.[4]

References

1 Coquillat, M; Verdu, J; Colin, X; Audouin, L; Celina, M, *Polym. Deg. Stab.*, **91**, 9, 1689-94, 2008.
2 Podešva, J; Kovářová, J; Hrdličková, M; Netopilík, M, *Polym. Deg. Stab.*, **94**, 4, 647-50, 2009,
3 Celina, M; Skutnik Elliott, JM; Winters, ST; Assink, RA; Minier, LM, *Polym. Deg. Stab.*, **91**, 8, 1870-9, 2006.
4 Földes, E; Lohmeijer, L, *Polym. Deg. Stab.*, **66**, 1, 11-9, 1999.

5.30 PC (POLYCARBONATE)

The reaction of the antioxidant (2,2'-methylene-bis(4-methyl-6-tertbutyl- phenol)), dissolved in polycarbonate, with oxygen has been studied at 200°C, and oxygen pressure 300 mm Hg.[1] The reaction followed first-order kinetics related to the antioxidant concentration; its rate was directly proportional to the oxygen pressure.[1] Peroxides were found among volatile oxidation products.[1]

The mobility of small molecules in glassy polymers is determined by the amount of free volume.[2] The free volume can be altered by change in the physical state of a polymer.[2] Physical aging reduces free volume, whereas the thermal rejuvenation increases it.[2] A clear correlation existed between the physical aging and oxygen permeability.[2] Mobility of antioxidants and oxygen were important parameters for the stabilization of polymers against oxidation.[2] Therefore, the physical state of the polymer can have a significant influence on the service life of the product.[2] Physical aging at room temperature and annealing at temperatures just below T_g are different processes.[2] The oxygen permeability in polycarbonate decreased significantly upon aging, but only slightly when annealed at 110°C.[2] The stress-strain behavior of aged samples deviated from annealed samples indicating a different polymer morphology.[2] The effect of physical aging on permeability can be described using an exponential decay function of the free volume with only one relaxation time.[2] The loss of free volume with aging is comparable for the glassy polymers studied, namely polycarbonate, polystyrene, polymethylmethacrylate, and polysulfone.[2]

Polycarbonate composition contained an aromatic dihydroxy compound/carbonic diester transesterification polycarbonate having terminal hydroxyl groups and a phenolic antioxidant.[3] The polycarbonate composition was insusceptible to discoloration during production (molding) and when a molded article produced from the composition experienced high-temperature atmosphere.[3]

Polycarbonate resin composition had improved thermal stability and apparent physical properties, such as yellowness index and transparency (haze) during high-temperature processing due to the incorporation of a hindered phenol-based compound (Irganox 101) and a phosphite-based compound (DovorPhos S-9228), which acted as antioxidants.[4]

References

1 Tyuleneva, NK; Shlyapnikov, YA, *Polym. Deg. Stab.*, **47**, 2, 257-60, 1995.
2 Boersma, A; Cangialosi, D; Picken, SJ, *Polym. Deg. Stab.*, **79**, 3, 427-38, 2003.
3 Hachiya, H; Komiya, K, **US5719254A**, *Asahi Kasei Corp*, Feb. 17, 1998.
4 **WO2015002428A1**, Jan. 8, 2015.

5.31 PCL (POLY(ε -CAPROLACTONE))

The polyphenolic compounds extracted from fruits and leaves of sweet cherry were introduced into poly(ε-caprolactone)-based films modified with bioactive glass particles.[1] The composite had excellent *in vitro* bioactivity, improved hydrophilicity, and high antioxidant potential.[1]

An antioxidant is critical for the successful nerve tissue regeneration, and biomaterials with antioxidant activity might be favorable for peripheral nerve repair.[2] Lignin-polycaprolactone copolymers were synthesized *via* solvent-free ring-opening polymerization, incorporated to PLC, and engineered into nanofibrous scaffolds for supporting the growth of neuron and Schwann cell.[2] The addition of lignin-PCL enhanced the mechanical properties of PCL nanofibers and endowed them with good antioxidant properties (up to 98.3% free radical inhibition within 4 h).[2]

Biomaterials with intrinsic antioxidant properties represent a valuable strategy for preventing peri-implant disease onset.[3] Quercetin, a naturally occurring flavonoid, has been entrapped in a silica/poly(ε-caprolactone)-based hybrid material by a sol-gel route.[3] The hydrogen-bonded interactions between quercetin and silica and polymer matrices were strongly affected by the amount of polymer.[3] Poly(ε-caprolactone) did not interact with quercetin when it was loaded at high doses (50 wt%).[3] Materials containing 6 wt% of PCL and 15 wt% of quercetin produced the strongest antiradical efficacy.[3]

An open wound is highly susceptible to microbial infection leading to an elevated level of inflammatory response.[4] For prompt healing, a wound requires a biomimetic dressing material with ideal hydrophilicity and tensile strength, possessing antimicrobial and antioxidant property.[4] PCL-gelatin-based electrospun nanofibers, enriched with quercetin and ciprofloxacin hydrochloride were evaluated by film-diffusion against *Staphylococcus aureus*. The material was suitable for accelerated wound healing.[4] Figure 5.21 illustrates method of production and results of characterization and application.[4]

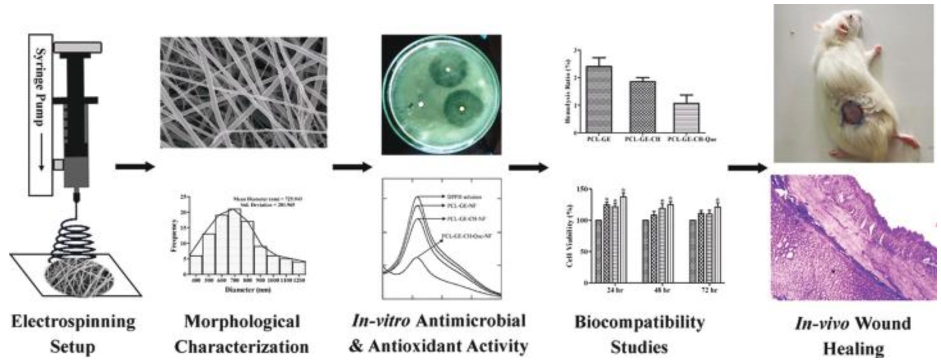


Figure 5.21. Evaluation of PCL-gelatin-based electrospun nanofibers enriched with quercetin and ciprofloxacin hydrochloride. [Adapted, by permission, from Ajmal, G; Bonde, GV; Mittal, P; Khan, G; Mishra, B, *Int. J. Pharm.,* **567**, 118480, 2019.]

Epoxidized natural rubber/polycaprolactone contained flavonoids to improve their anti-aging characteristics.[5] Flavonoids and amino acids considerably improved the resistance of ENR/PCL composites to aging under climatic conditions with variable air humidity and solar radiation.[5]

Polycaprolactone nanofibers encapsulating α-tocopherol/β-cyclodextrin inclusion complex which had high antioxidant activity and photostability was produced *via* electrospinning.[6] The nanofibers provided oxidative stability and strong photostability.[6]

Chitosan/ferulic acid-coated poly(ε-caprolactone) electrospun materials had antioxidant, antibacterial, and antitumor properties.[7] The hybrid fibrous mats had higher killing rates against pathogenic bacteria *S. aureus* than that of ferulic acid-containing mats or chitosan-coated mats alone.[7] Ferulic acid preserved its antioxidant activity when incorporated in the fibers.[7]

References

1 Dziadek, M; Dziadek, K; Kopec, A; Zagrajczuk, B; Cholewa-Kowalska, K, *Mater. Lett.,* **203**, 28-31, 2017.
2 Wang, J; Tian, L; Luo, B; Ramakrishna, S; Mo, X, *Colloids Surfaces B: Biointerfaces*, **169**, 356-65, 2018.
3 Catauro, M; Bollino, F; Papale, F; Piccolella, S; Pacifico, S, *Mater. Sci. Eng. C*, **58**, 945-52, 2016.
4 Ajmal, G; Bonde, GV; Mittal, P; Khan, G; Mishra, B, *Int. J. Pharm.,* **567**, 118480, 2019.
5 Masek, A; Zaborski, M; Piotrowska, M, *Compt. Rend. Chim*., **17**, 11, 1128-35, 2014.
6 Aytac, Z; Uyar, T, *Eur. Polym. J*., **79**, 140-98, 2016.
7 Yakub, G; Ignatova, M; Manolova, N; Rashkov, I; Markova, N, *Int. J. Biol. Macromol*., **A107**, 689-702, 2018.

5.32 PDL (POLYLYSINE)

Curcumin was conjugated to ε-polylysine using copper-catalyzed “click chemistry”.[1] Polylysine and curcumin were converted to ε-polylysine azide and monoalkyne curcumin.[1] Then, the Huisgen cycloaddition (“click chemistry”) between the azide group and monoalkyne group led to the formation of a triazole linkage between ε-polylysine and curcumin (Figure 5.22).[1] The antioxidant activity of ε-polylysine-curcumin conjugate was 3.6 times higher than the ε-polylysine alone, indicating that conjugated curcumin retained its functional properties.[1]

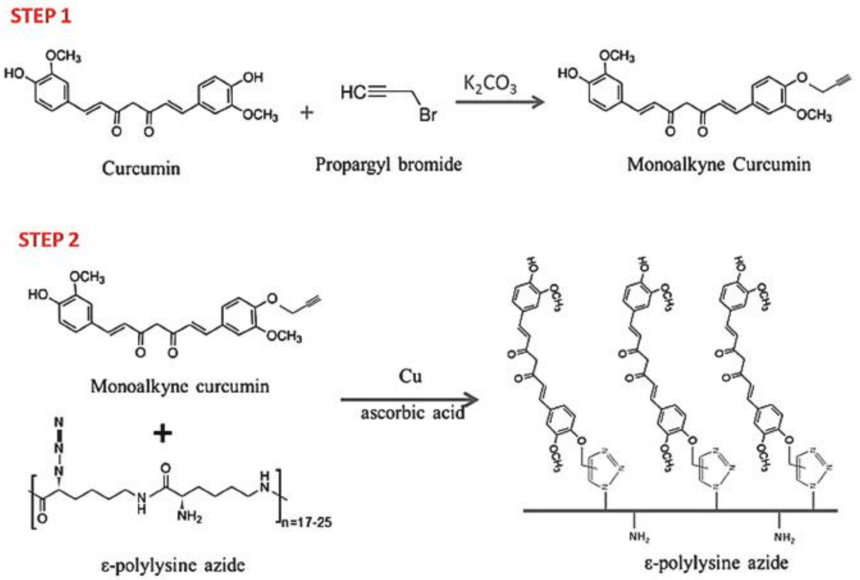


Figure 5.22. Schematic representation of the synthesis protocol. [Adapted, by permission, from Tikekar, RV; Hernandez, M; Land, DP; Nitin, N, *Food Res. Int.*, **54**, 1, 44-7, 2013.]

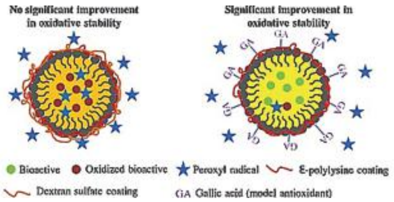


Figure 5.23. Effect of coating and antioxidant presence on protection against oxidation. [Adapted, by permission, from Pan, Y; Nitin, N, *Colloids Surfaces B: Biointerfaces*, **135**, 472-80, 2015.]

Oxidation of encapsulated bioactive in emulsion limits the shelf-life of many emulsion containing products.[2] The role of layer-by-layer coatings and localization of antioxidant molecules at the emulsion interface to protect the encapsulated bioactives has been studied. The emulsion was coated at the interfacer by one or two layers of ϵ-polylysine and dextran sulfate.[2] The antioxidant molecules (gallic acid) was chemically conjugated with ϵ-polylysine and subsequently deposited on emulsion using electrostatic interactions.[2] The structure and results are given in Figure 5.23.[2]

A composition of L-ascorbic acid derivative is described, comprising L-ascorbic acid and lysine or lysine moieties. L-ascorbic acid was covalently bound to the lysine or lysine moieties.[3] The antioxidant composition was used to prevent the degradation of the extracellular matrix, stabilize connective tissue, and treat damage to the skin.[3]

References

1 Tikekar, RV; Hernandez, M; Land, DP; Nitin, N, *Food Res. Int.*, **54**, 1, 44-7, 2013.
2 Pan, Y; Nitin, N, *Colloids Surfaces B: Biointerfaces*, **135**, 472-80, 2015.
3 Roomi, WM; Netke, S; Ivanov, V; Niedzwiecki, A; Rath, M, **US7230124B2**, Jun. 12, 2007.

5.33 PDMS (POLYDIMETHYLSILOXANE)

Crosslinked polydimethylsiloxanes with three different chain-breaking antioxidants (Irganox 1076, Irganox 565, and Tinuvin 770) were exposed to air plasma.[1] Samples containing antioxidants were more resistant to oxidation than the reference sample with no antioxidant.[1] Higher doses of air plasma were required to form a brittle silica-like layer on the samples with antioxidant than on the reference sample with no antioxidant.[1] Tinuvin 770 was the best antioxidant, whereas Irganox 1076 and Irganox 565 were similar in their efficiencies.[1]

Polydimethylsiloxane oil was selected as an inert solvent to compare the reaction of five hindered phenolic antioxidants with molecular oxygen.[2] The solubility coefficient of oxygen in silicone oil at 90°C was 4.92×10^{-8} mol l^{-1} Pa^{-1}.[2] All stabilizers were destroyed by reaction with oxygen in a pseudo first-order process.[2] The observed differences in reactivity were relatively small.[2]

The addition of liquid polydimethylsiloxane to isotactic polypropylene retarded its non-inhibited and inhibited oxidation by molecular oxygen due to migration of mobile free radicals and the reversible transition of antioxidant into inclusions of liquid siloxane in the polymer matrix.[3]

References

1 Fateh-Alavi, K; Gällstedt, M; Gedde, UW, *Polym. Deg. Stab.*, **74**, 1, 49-57, 2001.
2 Navarro, R; Audouin, L; Verdu, J, *Polym. Deg. Stab.*, **96**, 7, 1389-96, 2011.
3 Monakhova, TV; Bogaevskaya, TA; Shlyapnikov, YA, *Polym. Deg. Stab.*, **66**, 1, 149-51, 1999.

5.34 PEEK (POLYETHERETHERKETONE)

The addition of carbon nanotubes to polyetheretherketone improved the mechanical properties and its thermal resistivity because carbon nanotubes functioned as an antioxidant.[1] The PEEK–CNT composite did not show a large weight loss at 450°C.[1] 1,4-Diphenoxybenzene radical (a decomposition product of PEEK) was trapped at a high-temperature environment of 450°C by carbon nanotubes.[1] Figure 5.24 illustrates the role of carbon nanotubes in quenching auto-oxidation reactions.[1]

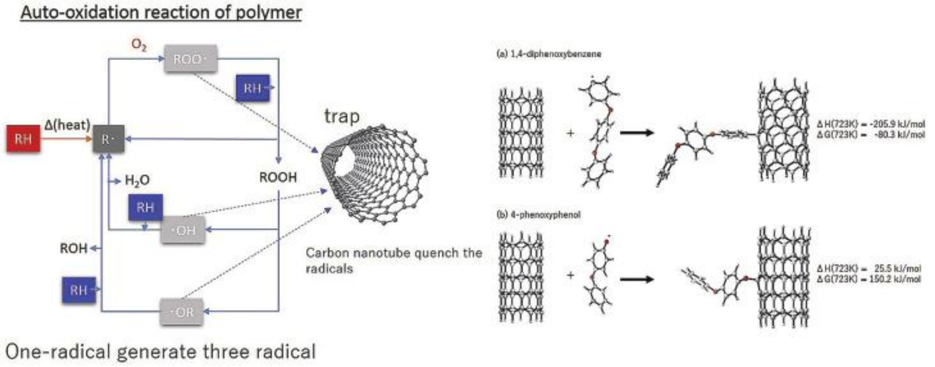


Figure 5.24. Carbon nanotubes quench radicals. Diagram of stabilization energy calculation of (a) 1,4-diphenoxybenzene and (b) 4-phenoxyphenol. [Adapted, by permission, from Ata, S; Hayashi, Y; Thi, TBN; Tomonoh, S; Hata, K, *Polymer*, **176**, 60-5, 2019.]

The influence of an organophosphonite antioxidant, Irgafos P-EPQ, on the thermal behavior of optimized polyetheretherketone/poly(ether imide) (50/50) blend has been reported.[2] The antioxidant addition limited the rate of thermooxidation of the blend as revealed from TGA measurements and limiting oxygen index values.[2] The optimum improvement in the thermooxidation was achieved when P-EPQ content was 1 wt%.[2]

References

1 Ata, S; Hayashi, Y; Thi, TBN; Tomonoh, S; Hata, K, *Polymer*, **176**, 60-5, 2019.
2 Ramani, R; Alam, S, *Thermochim. Acta*, **550**, 33-41, 2012.

5.35 PET (POLY(ETHYLENE TEREPHTHALATE))

Phosphite antioxidants are extensively used in the polyester industry due to extraordinary antioxidative and chromaticity protection capabilities.[1] Unfortunately, they are highly susceptible to hydrolysis leading to reduced antioxidative activity.[1] High performance optical poly(ethylene terephthalate) materials were synthesized by *in situ* adding hydrolysis resistant hybridized phosphite in the polycondensation process.[1] Only adding 0.05 wt% of the hydrolysis resistant hybridized phosphite containing 10 wt% of layered double hydroxides can remarkably improve the anti-oxidative and chromaticity performances of the resultant PET.[1] Figure 5.25 illustrates the synthesis of hybridized phosphites.[1]

Figure 5.25. Schematic representation of fabrication of the hybridized antioxidant and its *in situ* addition into PET. [Adapted, by permission, from Sun, S; Wang, L; Song, P; Ding, L; Bai, Y, *Chem. Eng. J.*, **328**, 406-16, 2017.]

Supercritical carbon dioxide impregnation technique was used to adsorb α-tocopherol, a natural antioxidant, on monolayer and multilayer poly(ethylene terephthalate)/polypropylene films to obtain active packaging.[2] Supercritical impregnation experiments were performed at 17 MPa and 40°C.[2] The antioxidant activity tests confirmed that the impregnation process did not damage the α-tocopherol structure, which effectively protected food from oxidation.[2] High loading values, up to 3.20 and 2.66 mg α-tocopherol/cm^2film, for monolayer and multilayer films, respectively, were obtained.[2]

A natural citrus extract having antioxidant activity was evaluated as an ingredient for the production of active food packaging.[3] The methanol solution of extract was sprayed onto the surface of poly(ethylene terephthalate) trays.[3] For comparison, the second set of trays were prepared using α-tocopherol as a coating.[3] PET trays coated with citrus extract had a significant antioxidant effect on cooked meat in refrigerated storage.[3] Compared to citrus extract, α-tocopherol on PET was ineffective in inhibiting lipid oxidation.[3]

Compounds found in plastic packaging were analyzed in PET-bottled water stored at different temperatures: 40, 50, and 60°C.[4] 2,4-Di-tert-butylphenol, a degradation compound of phenolic antioxidants, was detected.[4]

The reduction of friction effect between poly(ethylene terephthalate) preforms and bottles was achieved by using formulation including (i) a fatty acid amide selected from the group consisting of oleyl palmitamide, ethylene bis stearamide, ethylene bis oleomide, and stearyl erucamide; (ii) a partially or fully calcined porous polymethylsilsequioxane; and (iii) a stabilizer comprising a primary and a secondary antioxidant.[5] The primary antioxidant was tetrakis[methylene(3,5-ditert.butyl-4-hydroxy-hydrocinnamate)] methane, and the secondary antioxidant was (2,4-di-tert.butylphenyl)phosphite.[5] The primary and secondary antioxidants were present at a ratio of 1:4.[5] The primary antioxidant was present in the molded article at a concentration of 0.28 wt%, and the secondary antioxidant was present in the molded article at a concentration of 0.08 w%.[5]

References

1 Sun, S; Wang, L; Song, P; Ding, L; Bai, Y, *Chem. Eng. J.*, **328**, 406-16, 2017.
2 Franco, P; Incarnato, L; De Marco, I, *J.* CO_2 *Utilization*, **34**, 266-73, 2019.
3 Contini, C; Katsikogianni, MG; O'Neill, FT; O'Sullivan, M; Monahan, FJ, *LWT*, **47**, 2, 471-7, 2012.
4 Bach, C; Dauchy, X; Severin, I; Munoz, J-F; Chagnon, M-C, *Food Chem.*, **139**, 1-4, 2013.
5 Hall, GH; Jenkins, SD; Neal, MA; Siddiqui, JA, **CA2400163A1**, *Invista Technologies Sarl*, Oct. 4, 2001.

5.36 PEX (SILANE-CROSSLINKABLE POLYETHYLENE)

Three synthesized reactive (graftable) antioxidants with hindered phenol and hindered amine antioxidant functions were examined for their grafting efficiency in polyethylene and their retention and stabilizing performance in peroxide-crosslinked polyethylene pipe material.[1] Figure 5.26 shows the method of preparation of reactive antioxidant.[1]

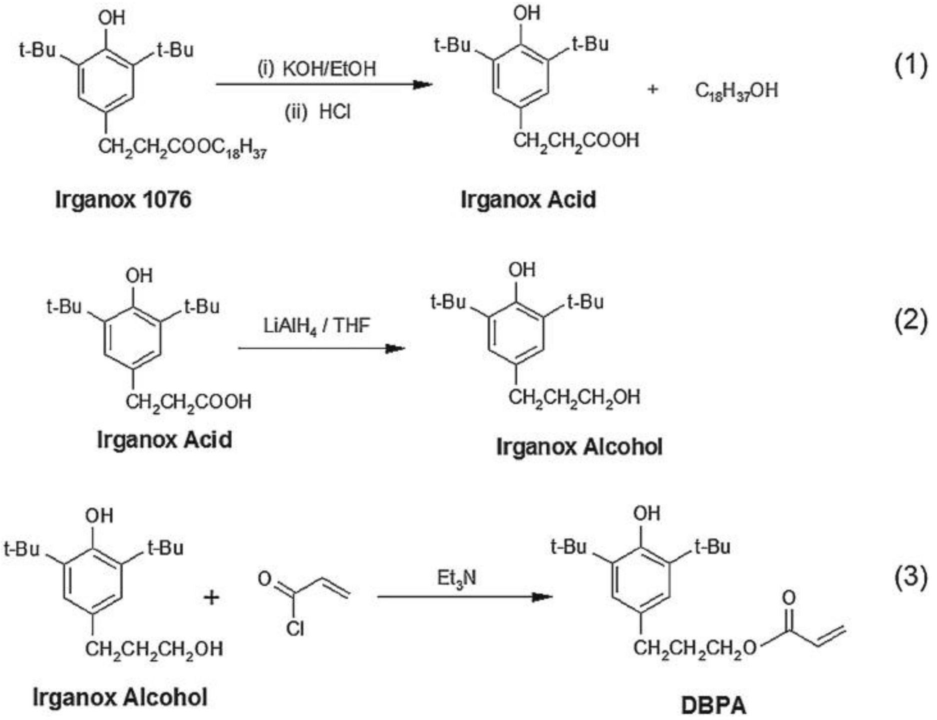


Figure 5.26. Synthetic reactions for the preparation of the reactive hindered phenol 3-(3′,5′-di-tert.-butyl-4′-hydroxy phenyl) propyl-1-acrylate, DBPA. [Adapted, by permission, from Al-Malaika, S; Riasat, S; Lewucha, C, *Polym. Deg. Stab.*, **145**, 11-24, 2017.]

The presence of the graftable antioxidants did not affect the level of crosslinking of the PEX pipes, which remained high (>85%).[1] The antioxidants were retained to a very great extent in the PEX material after solvent extraction and were uniformly distributed across the length and thickness of PEX pipes.[1] The stabilizing efficacy of the reactive antioxidants was compared with that of conventionally stabilized PEX material containing analogous antioxidants.[1] The level of retention (in the pipes) of the graftable antioxidants and their long-term stabilizing performance was shown to be significantly higher than that of the conventional antioxidants.[1] The graftable antioxidants discussed above have been patented.[2]

A crosslinked polyethylene potable water pipe is extensively used.[3] The tap water quality was investigated at a six-month-old plumbing system, and chemical and odor quality impacts of six PEX pipe brands were examined.[3] Eleven PEX related contaminants were found in the plumbing system; one regulated (toluene) and several unregulated, such as antioxidants and their degradation products, resin solvents, initiator degradation products, or manufacturing aides.[3] 2,4-Di-tert-butylphenol, an antioxidant used in polymer synthesis, was detected.[3] 7,9-Di-tert-butyl-1-oxaspiro(4,5)deca-6,9-diene-2,8-dione which is an antioxidant degradation product was also detected.[3]

A concentration profile of two antioxidants and degradation products of antioxidants in the crosslinked polyethylene materials were determined.[4] Irganox® 1076, and two degradation products in a PEX pipe were detected after extraction in chloroform.[4] The composition of Irganox® 1076 was homogeneous in the radial direction and heterogeneous in the longitudinal direction.[4] 2,6-Di-tert-butyl-p-benzoquinone, and 2,4-di-tert-butyl phenol (degradation products) were detected.[4] The composition of 2,6-di-tert-butyl-p-benzoquinone was found to be homogeneous in the radial, and longitudinal direction.[4] 2,4-Di-tert-butyl phenol was homogeneous in the radial direction but heterogeneous in the longitudinal direction.[4]

Pipe or tubing of crosslinked polyethylene containing less than 2 wt% carbon black provides improved resistance to oxidizing agents such as chlorine and hypochlorous acid in water.[5] The pipe may be further protected with a thin tubular core (inner layer) of high-density polyethylene or chlorinated polyethylene.[5]

The composition of pipe material comprises a polyethylene pipe resin, a primary antioxidant, and an acid.[6] The composition has an increased oxidative induction time and environmental stress cracking resistance.[6] Pentaerythrityl tetrakis(3-(3,5-di-tert-butyl-4-hydroxyphenol)propionate) (Irganox®1010) is suitable as the primary antioxidant.[6]

References

1 Al-Malaika, S; Riasat, S; Lewucha, C, *Polym. Deg. Stab*., **145**, 11-24, 2017.
2 Al-Malaika, S; Lewucha, C, **US8889239B2**, *Aston University*, Nov. 18, 2014.
3 Kelley, KM; Stenson, AC; Dey, R; Whelton, AJ, *Water Res*., **67**, 19-32, 2014.
4 Denberg, M; Mosbæk, H; Hassager, O; Arvin, E, *Polym. Testing*, **28**, 4, 378-85, 2009.
5 Mahabir, CM; Backman, AL; Dalal, GT, **US7255134B2**, *Lubrizol Advanced Materials Inc*, Aug. 14, 2008.
6 Sherman, RL; Holland, SJCS; Hundley, MC, **US8114493B2**, *Equistar Chemicals LP,* Feb. 14, 2012.

5.37 PFPE (PERFLUOROPOLYETHER)

Perfluoropolyethers show promising properties for coil coating application, and a suitable layer is obtained by incorporating them in a crosslinked polyurethane network.[1] However, photooxidative stability of urethane linkages is intrinsically low, and an appropriate stabilizer is needed. N-methyl HAS bis(1,2,2,6,6-pentamethyl-4-piperidyl) sebacate (Tinuvin765) has been tested for this application.[1] During curing, N-methyl HAS was partially transformed into –NH derivatives which were still active antioxidants.[1] During photooxidation HAS acted as a radical scavenger but slowly evaporated from the film.[1]

References

1 Luda, MP; Camino, G; Laurenti, E; Novelli, S; Turri, S, *Polym. Deg. Stab.*, **73**, 3, 387-92, 2001.

5.38 PHB (POLY(3-HYDROXYBUTYRATE))

Effect of chitosan and catechin addition (1-5 wt%) on the structural, thermal, mechanical and disintegration properties of plasticized electrospun PLA-PHB (3:1) biocomposites has been studied.[1] Catechin's antioxidant effect improved the thermal stability of biocomposite.[1] Chitosan produced some bead defects in the fibers, which leads to a reduction of the mechanical performance on biocomposites.[1]

Transesterification reaction of PHB was carried out under reflux conditions in the presence of 1,4-butanediol to form telechelic PHB-diol.[2] PHB-diol was further modified by reaction with acryloyl chloride followed by grafting with amino compounds such as 1,4-butanediamine, 1,3-propanediamine, 1,2-ethylenediamine, piperazine, cyclohexylamine, 2,2′-(ethane-1,2-diylbis(oxy)) diethanamine (Jeffamine EDR 148) and morpholine *via* Michael-type addition reaction.[2] The amino-PHB polymers had antibacterial, antioxidant and anticancer properties.[2] All amino-PHB polymers had reasonable antioxidant activity.[2] Figure 5.27 illustrates synthesis and properties.[2]

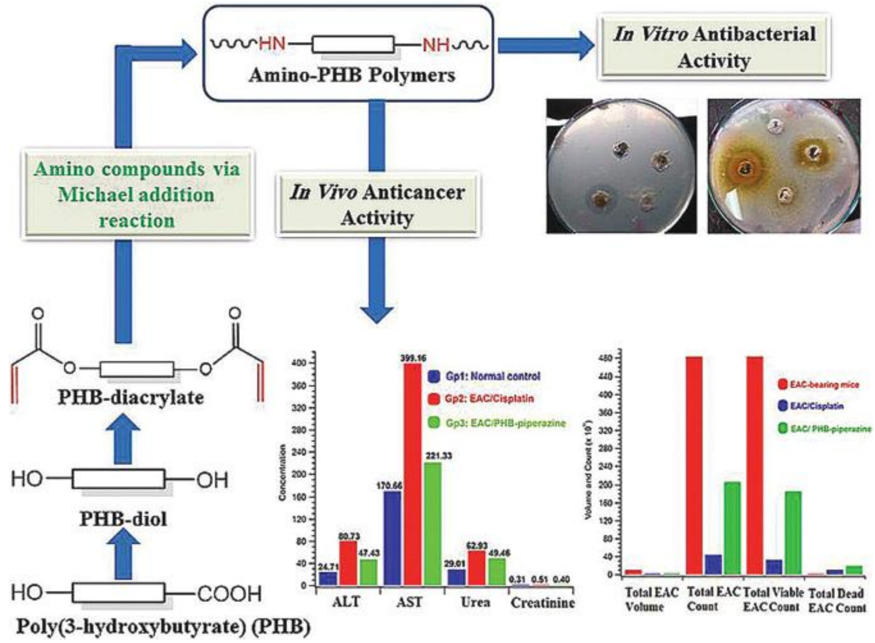


Figure 5.27. Synthesis and properties of amino-PHB. [Adapted, by permission, from Abdelwahab, MA; El-Barbary, AA; El-Said, KS; El Naggar, SA; ElKholy, HM, *Int. J. Biol. Macromol.*, **122**, 793-805, 2019.]

Poly(3-hydroxybutyrate) (PHB)-thermoplastic starch (TPS)/organically modified montmorillonite (OMMT)/eugenol bionanocomposites were prepared by melt blending to be used for active packaging.[3] Bionanocomposites with eugenol exhibited antifungal activity against *Botritys cinerea* and antioxidant activity, as indicated by high percentages of 1,1-diphenyl-2-picrylhydrazyl radical removal.[3]

Quaternized chitosan/κ-carrageenan/caffeic acid-coated poly(3-hydroxybutyrate) fibrous materials showed antibacterial and antioxidant properties.[4] Highest antioxidant activity of these fibrous mats might be attributed to the combination of the antioxidant activity of caffeic acid, chitosan, and κ-carrageenan.[4]

The microalgae *Spirulina* sp. LEB 18 synthesized bioproducts, such as polyhydroxybutyrate (PHB), which were biodegradable and had similar mechanical and thermal properties to polymers of petrochemical origin.[5] Moreover, phenolic compounds of microalgae had antibacterial, antifungal, and antioxidant activities.[5]

Reference

1 Arrieta, MP; López, J; López, D; Kenny, JM; Peponi, L, *Polym. Deg. Stab.*, **132**, 145-56, 2016.
2 Abdelwahab, MA; El-Barbary, AA; El-Said, KS; El Naggar, SA; ElKholy, HM, *Int. J. Biol. Macromol.*, **122**, 793-805, 2019.
3 Garrido-Miranda, KA; Rivas, BL; Pérez -Rivera, MA; Sanfuentes, EA; Peña-Farfal, C, *LWT*, **98**, 260-7, 2018.
4 Ignatova, M; Manolova, N; Rashkov, I; Markova, N, *Int. J. Pharm.*, **513**, 1-2, 528-37, 2016.
5 Kuntzler, SG; Araujo de Almeida, AC; Vieira Costa, JA; de Morais, MG, *Int. J. Biol. Macromol.*, **113**, 1008-14, 2018.

5.39 PHEMA (POLY(2-HYDROXYETHYL METHACRYLATE))

Electrospun poly(2-hydroxyethyl methacrylate) fibers were loaded with synthetic and natural antioxidants, such as vanillic, gallic, syringic acids, catechin, or natural spruce bark extract to investigate their release behavior and antioxidant activity.[1] Fiber diameter was increased with increasing concentration of additives because of hydrogen bonding between active ingredients and polymeric matrix, which caused an increase in shear viscosity, affecting the drawing process during fiber formation.[1] High release rates in the first phase were followed by a smooth release at long term.[1] Polyphenols retained their activity after incorporation into the pHEMA nanofibers.[1]

References

1 Ghitescu, R-E; Popa, A-M;. Popa, VI; Rossi, RM; Fortunato, G, *Int. J. Pharm.*, **494**, 278-87, 2015.

5.40 PI (POLYIMIDE)

Winery effluents are substantial sources for the recovery of antioxidant compounds, namely polyphenols and polysaccharides.[1] Pressure-driven membrane processes were used for recovery of antioxidant compounds from winery effluents.[1] Polyimide hollow fiber membrane with 0.4 μm pore size was used for the purpose.[1]

Duramem™ organic solvent resistant crosslinked polyimide nanofiltration membrane was used for the concentration of antioxidant extracts of rosemary (*Rosmarinus officiallis* L).[2] The experimental data and model predictions demonstrated the efficacy of a semi-batch cross-flow diafiltration process for concentration of fresh rosemary extracts.[2]

Polyimide film reduced oxygen mobility and its effect on thermal oxidative processes.[3]

Polyamide-based water treatment separation membrane had excellent oxidation resistance and chlorine resistance after addition of antioxidant having a solubility parameter value of 9 to 22 $(J/cm^3)^{1/2}$.[4] Suitable antioxidants include pentaerythritol tetrakis(3-(3,5-di-tert-butyl-4-hydroxyphenyl)propionate (Irganox 1010) and N,N'-hexane-1,6-diyl-bis(3-(3,5-di-tert-butyl-4-hydroxyphenylpropionamide).[4]

References

1 Giacobbo, A; Meneguzzi, A; Bernardes, AM; de Pinho, MN, *J. Cleaner Prod.*, **155**, Part 1, 172-8, 2017.
2 Peshev, D; Peeva, LG; Peev, G; Baptista, IIR; Boam, AT, *Chem. Eng. Res. Design*, **89**, 3, 318-27, 2011.
3 Boersma, A; Cangialosi, D; Picken, SJ, *Polym. Deg. Stab.*, **79**, 3, 427-38, 2003.
4 Ko, Y-H; Kim, J-H; Song, K-W; Shin, C-K, **EP2835175A1**, *LG Chem Ltd,* Nov. 4, 2015.

5.41 PIB (POLYISOBUTYLENE)

Paraphenylene diamine was chemically attached to low molecular weight chlorinated polyisobutylene.[1] The rubber vulcanizates showed improved aging and ozone resistance in comparison to vulcanizates containing a conventional antioxidant.[1]

Polyisobutylene-bound para phenylene diamines have been prepared by a condensation reaction.[2] They have been compared with conventional amine type antioxidants in NR, SBR, IIR, and NBR and in elastomer blends like NR/BR and NR/SBR. The oligomer-bound antioxidants improved ozone, flex resistance, and mechanical properties of the vulcanizates with better results than the conventional antioxidants.[2]

References

1 Sulekha, PB; Joseph, R; George, KE, *Polym. Deg. Stab.*, **63**, 2, 225-30, 1999.
2 Sulekha, PB; Joseph, R; Madhusoodanan, KN; Thomas, KT, *Polym. Deg. Stab.*, **77**, 3, 403-16, 2002.

5.42 PIP (POLYISOPRENE)

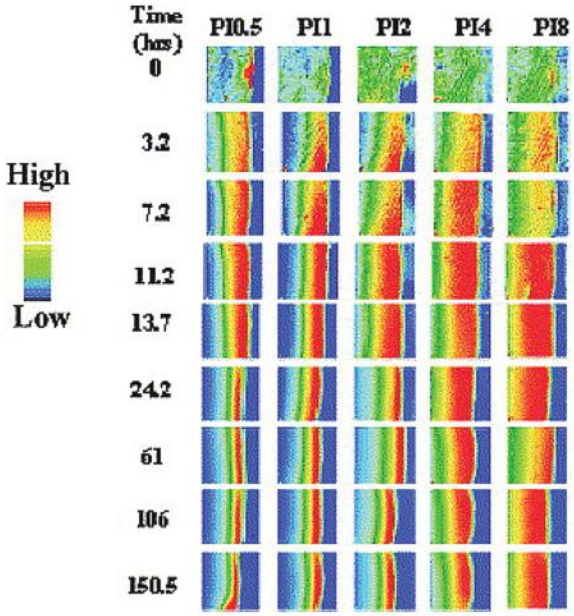


Figure 5.28. FTIR images of the PIP rubber with different concentrations of antioxidant (0.5 to 8%) by 1715 cm^{-1} at 140 °C taken at different thermal aging times at the measurement times as indicated in the left column. Each image has a dimension of 400×400 μm corresponding to 64×64 pixels. All the images are auto-scaled. [Adapted, by permission, from Li, G-Y; Koenig, JL, *Polym. Deg. Stab*., **81**, 3, 377-85, 2003.]

The stabilization of polyisoprene rubber by a number of triazinone derivatives against thermal oxidation has been studied.[1] The antioxidant effect has been estimated by the induction periods of the carbonyl and hydroxyl group accumulation, and the oxygen sorption at 353 and 363 K.[1] The triazinone-phenol mixtures had a large synergistic effect.[1] Synergistic mixtures of phenol antioxidants with some mercapto-derivatives of triazinones can be used as efficient additives for stabilization, especially useful since they do not change the color of the protected composition.[1]

FTIR imaging was used to monitor the oxidation of polyisoprene in the presence of N-phenyl-N′-dimethyl-butyl-p-phenylenediamine antioxidant.[2] Antioxidant concentrations of 0.5 wt% or larger protected the PIP rubber surface at a temperature of 140°C for up to 10 h (the oxidation inhibiting effect).[2] At the same time, the self-protective crosslinked oxidation layer was also retarded by the antioxidant, causing larger amounts of oxygen to diffuse into the rubber, increasing total oxidation (the oxygen permeation effect).[2] Using the spatial sensitivity of FTIR imaging, it was possible to observe the chemical results of these two competing effects at different distances from the rubber surface.[2] Figure 5.28 illustrates results.[2] The pseudo color images are a reflection of the integrated intensity of the carbonyl bond from the band at 1715 cm^{-1}, where red denotes the highest absorbance (upper limit) and blue denotes the lowest absorbance (lower limit) with the order of red>orange>yellow>green>blue.[2]

The antioxidant activity of six N,N′-substituted p-phenylenediamines in polyisoprene rubber matrix has been studied by differential scanning calorimetry.[3] Protection decreased with increasing temperature and decreasing concentration of the antioxidant.[3] The effectiveness of the antioxidants was inversely proportional to the dissociation energy of the C–H bond at the carbon atom in the neighborhood of the nitrogen atom.[3] The substitution of all hydrogen atoms at that carbon atom led to a loss of antioxidant properties.[3]

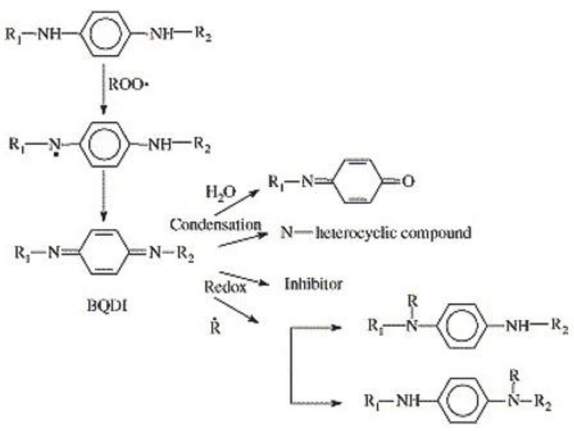


Figure 5.29. The mechanism of inhibition effect of phenylene diamines. [Adapted, by permission, from Cibulková, Z; Šimon, P; Lehocký, P; Balko, J, *Polym. Deg. Stab*., **87**, 3, 479-86, 2005.]

The mechanism of inhibition effects of phenylenediamines is given in Figure 5.29.[3] Compounds with benzoquinone monoimine structures, and N-heterocyclic compounds are formed, and the structure of substituted phenylenediamines is regenerated.[3] Benzoquinone diimines trap $R^{\cdot}$ radicals.[3] This contributes to the antioxidant efficiency of the originally added phenylenediamine derivative due to the regeneration of the $RO^{\cdot}_2$ trapping species.[3]

The coating of the invention is formed from synthetic polyisoprene rubber that may or may not contain minor amounts of other components.[4] The coating is preferably directly bonded to the underlying elastomeric article.[4] Wingstay L and Vulcanox BKF are suitable antioxidants.[4]

Material for manufacturing a special safety tire rubber for wheeled combat vehicles and aircraft in the army was fabricated from the following components in parts by weight: 28-40 parts of polyisoprene, 19-30 parts of silicone rubber, 15-25 parts of thermoplastic elastomer, 10-18 parts of magnetic powder, 10-15 parts of paraffin oil, 0.8-2 parts of flexibilizer, 5-10 parts of silicone oil, and 0.5-2 parts of antioxidant.[5] The antioxidant was selected from compounds, such as diphenylamine, p-diphenylamine, and dihydroquinoline.[5]

References

1 Pustoshnaya, LS; Pustoshnyi, VP; Mazitova, AK; Khamaev, VP; Minsker, KS, *Polym. Deg. Stab*., **70**, 1, 39-41, 2000.
2 Li, G-Y; Koenig, JL, *Polym. Deg. Stab*., **81**, 3, 377-85, 2003.
3 Cibulková, Z; Šimon, P; Lehocký, P; Balko, J, *Polym. Deg. Stab*., **87**, 3, 479-86, 2005.
4 Chen< SF; Wang, S; Wong, WC; Chong, CS, **US9080025B2**, *Allegiance Corp*, Jul. 14, 2015.
5 Xia, H; Xia, K, **US20150291781A1**, Jun. 14, 2016.

5.43 PK (POLYKETONE)

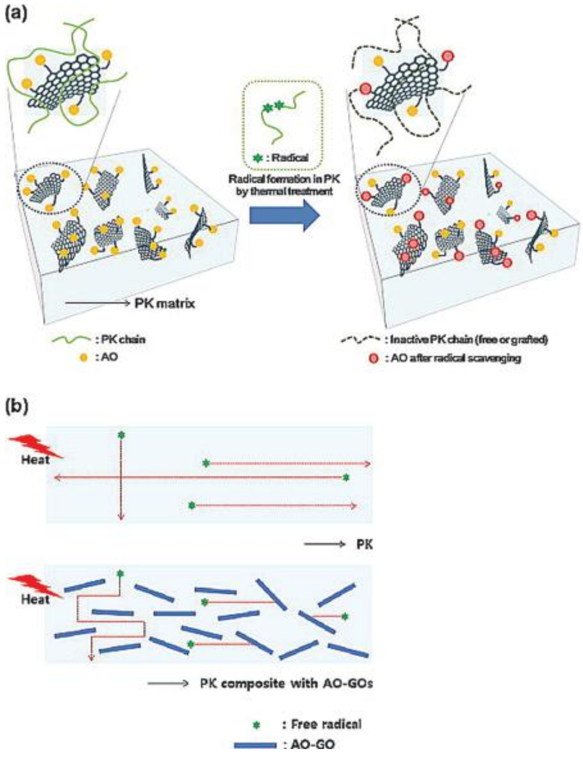


Figure 5.30. Schematic illustration of the antioxidant mechanism of antioxidant-graphene oxide: (a) formation of inactive polymer chains by radical scavenging of graphene oxide and the antioxidant and (b) barrier effect of antioxidant-graphene oxide in polyketone matrix. [Adapted, by permission, from Lim, M-Y; Oh, J; Kim, HJ; Kim, KY; Lee, J-C; *Eur. Polym. J.*, **69**, 156-67, 2015.]

Polyketone composites were prepared by a polymer powder coating using carbon nanomaterials, such as carbon nanotube, graphene oxide, and antioxidant grafted graphene oxide as fillers.[1] The antioxidant grafted graphene oxide was obtained using hindered amine and hindered phenol, respectively.[1] The polyketone composites containing the carbon nanomaterials showed much improved thermal stabilities and mechanical properties compared to polyketone.[1] The antioxidant grafted graphene oxide was more effective in increasing the thermal properties of polyketone than carbon nanotube and graphene oxide without any antioxidant moieties.[1] The enhanced thermal stability and mechanical property by the antioxidant grafted graphene oxide can be explained by the combined antioxidant effect of the antioxidant functional groups and the rigid conjugated carbon units in the graphene oxide having the ultrathin sheets.[1] Figure 5.30 illustrates the mechanism.[1]

The thermal oxidative stability of polyketone polymers is improved by combining a major amount of linear alternating polyketone polymer and a minor amount of a primary antioxidant, a secondary antioxidant, and a scavenger.[2] The primary antioxidant was N,N'-1,6-hexanediyl bis[3,5-bis(1,1-dimethylethyl)-4-hydroxy-benzenepropanamide].[2] The secondary antioxidant was tris(2,4-di-tert-butylphenyl)phosphite.[2] The scavenger was $Mg(OH)_2$ and/or an organic carbodiimide.[2]

References

1 Lim, M-Y; Oh, J; Kim, HJ; Kim, KY; Lee, J-C; *Eur. Polym. J.*, **69**, 156-67, 2015.
2 Ash, CE, **EP0714938A2**, *Shell Internationale Research Maatschappij BV*, Feb. 4, 1998.

5.44 PLA (POLY(LACTIC ACID))

Durvillaea antarctica antioxidant algae extract was obtained by an aqueous extraction process and encapsulated into electrospun PVA fibers.[1] The fibers improved the thermal stability, the mechanical, and the barrier performance of plasticized-PLA and showed antioxidant activity in fatty food simulant.[1]

The plant isolated antioxidant quercitrin has been encapsulated in poly-d,l-lactide nanoparticles.[2] The encapsulation efficiency was 40%.[2] The *in vitro* release kinetics of quercitrin under physiological condition revealed initial burst release followed by sustained release.[2] The method of encapsulation of quercitrin aims at applications for intestinal anti-inflammatory effect and nutraceutical compounds.[2]

Antioxidant-active packaging is a promising technology for food protection. Release of synthetic phenolic antioxidants from the extruded poly(lactic acid) film has been studied.[3] The synthetic phenolic antioxidants included butylated hydroxyanisole, butylated hydroxytoluene, propyl gallate, and tert-butylhydroquinone.[3] Diffusion of antioxidants showed a Fick's behavior with diffusion coefficient between 10^{-8} and 10^{-11} cm^2 s^{-1} with 0-100% of release.[3] Propyl gallate and butylated hydroxytoluene had, respectively, the highest and lowest release rate of all simulants due to their different molecular properties such as polarity, log P, and molecular volume.[3]

β-Carotene, α-tocopherol, and rosmarinic acid were encapsulated in PLA/PLGA microcarriers by supercritical emulsion extraction to study encapsulation efficiency, drug's shelf-life, and antioxidant activity.[4] Encapsulation efficiencies were in the range of 50-80%.[4] The co-encapsulation of α-tocopherol with β-carotene gained prolonged shelf life.[4] Better performance in terms of shelf-life was observed for PLGA capsules loaded with β-carotene/α-tocopherol; whereas, PLA formulation with β-carotene/α-tocopherol showed a superior antioxidant activity.[4] Figure 5.31 illustrates encapsulation and some results.[4]

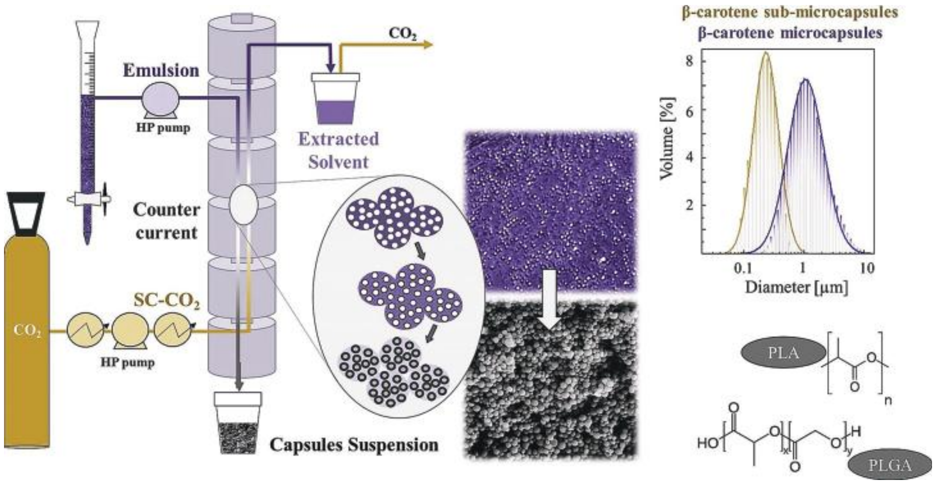


Figure 5.31. Microencapsulation. [Adapted, by permission, from Gimenez-Rota, C; Palazzo, I; Scognamiglio, MR; Mainar, A; Della Porta, G, *J. Supercritical Fluids*, **146**, 199-207, 2019.]

Facile melt processing technique was used for the preparation of super ductile PLA–PEG multiblock copolymers with the help of catalyst and antioxidant.[5] Loading of Ti-based catalyst improved mechanical properties of the final multiblock copolymer products.[5] When an appropriate amount of catalyst (0.75 phr) was used in combination with antioxidant (Irganox 1010), the long-chain copolymers exhibited extraordinarily high ductility with strain-to-break values exceeding 500%.[5]

Direct formation of bilayer films was achieved without surface modification of PLA films.[6] The release profiles of thymol from bilayer films were well fitted with Fick's second law.[6] PLA layer limited thymol release, and bilayer films possessed directional releasing properties.[6]

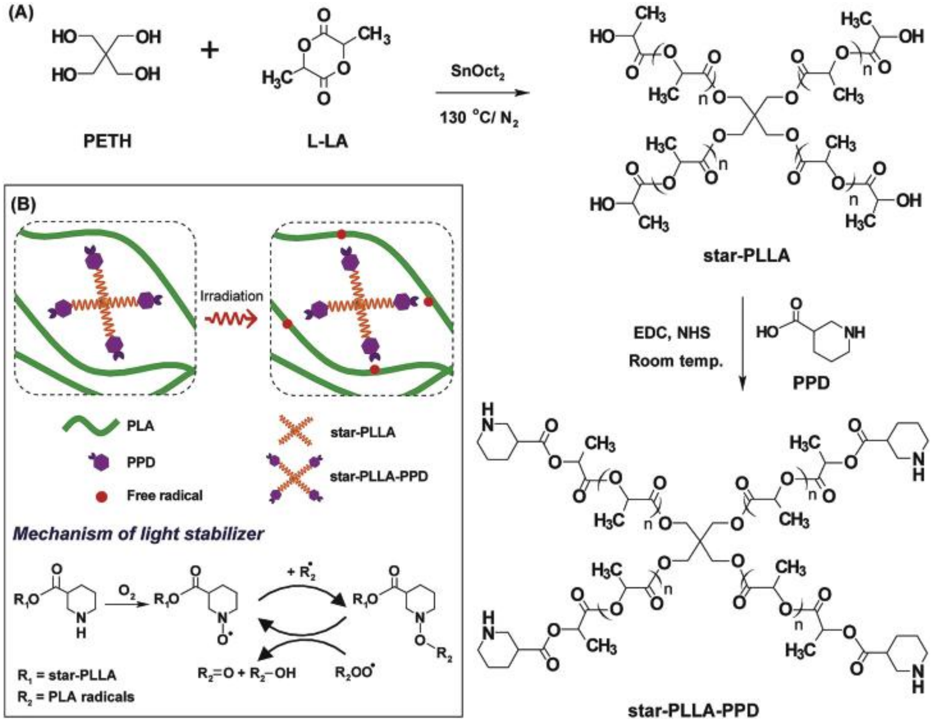


Figure 5.32. (A) Synthesis route and molecular structure of star-PLLA and star-PLLA-piperidine, PPD. (B) Free radical scavenging mechanism of the star-PLLA-PPD in PLA under irradiation. [Adapted, by permission, from Haema, K; Piroonpan, T; Taechutrakul, S; Kempanichkul, A; Pasanphan, W, *Polym. Deg. Stab.*, **143**, 145-54, 2017.]

Antioxidant-conjugated star-shaped PLLA was originally proposed as a novel polyfunctional-free radical stabilizing additive for bioplastics.[7] By a simple ring-opening polymerization of l-lactide on a polyfunctional core molecule (i.e., pentaerythritol) using tin(II)-2-ethylhexanoate as a catalyst, the 4-arms star-shaped PLLA was prepared.[7] Conversion to 4-arms star-PLLA was 78.50%.[7] Free radical scavenging ability was demonstrated using EPR spectroscopy.[7] The star-PLLA-piperidine efficiently scavenged free radicals in PLA matrix upon irradiation.[7] The star-PLLA-piperidine additive retarded the degradation of PLA under irradiation as observed by protecting molecular weight reduction.[7] The star-PLLA-piperidine additive was suitable as a polyfunctional bio-based antioxidant additive for bioplastics, especially for food packaging and biomedical materials.[7] Figure 5.32 illustrates the method of production and mechanism of protection.[7]

Due to the negative impacts of non-biodegradable plastic films on the environment, the biodegradable packaging materials have become a research hotspot.[8] Novel biodegradable active films based on polylactic acid blended with poly(butylene succinate adipate), carvacrol, and thymol were developed as a biodegradable active film for application to salmon slices.[8] The films with either carvacrol or thymol have a high release rate and antioxidant efficiency.[8] They extended the preservation of salmon slices by 3-4 days during cold storage.[8]

References

1 Arrieta, MP; de Dicastillo, CL; Garrido, L; Roa, K; Galotto, MJ, *Eur. Polym. J.*, **103**, 145-57, 2018.
2 Kumari, A; Yadav, Sk; Pakade, YB; Kumar, V; Yadav, SC, *Colloids Surfaces B: Biointerfaces*, **82**, 1, 224-32, 2011.
3 Jamshidian, M; Tehrany, EA; Desobry, S, *Food Control*, **28**, 2, 445-55, 2012.
4 Gimenez-Rota, C; Palazzo, I; Scognamiglio, MR; Mainar, A; Della Porta, G, *J. Supercritical Fluids*, **146**, 199-207, 2019.
5 Koosomsuan, W; Phinyocheep, P; Sirisinha, K, *Polym. Deg. Stab.*, **157**, 160-74, 2018.
6 Zhu, J-Y; Tang, C-H; Yin, S-W; Yang, X-Q, *Carbohydrate Polym.*, **181**, 727-35, 2018.
7 Haema, K; Piroonpan, T; Taechutrakul, S; Kempanichkul, A; Pasanphan, W, *Polym. Deg. Stab.*, **143**, 145-54, 2017.
8 Yang, C; Tang, H; Wang, Y; Liu, Y; Li, L, *Food Packaging Shelf Life*, **22**, 100393, 2019.

5.45 PMMA (POLYMETHYLMETHACRYLATE)

High molar mass phenolic phosphite antioxidant, tetrakis-(2,5-di-tert-butyl-4-hydroxyphenyl)-2,5-di-tert-butyl-hydroquinonediyl diphosphite, was prepared and used in PMMA protection.[1] 0.5 wt.% of phenolic phosphite antioxidant retarded the 10% weight loss temperature and reduced the maximum rate of weight loss.[1] The stabilized-PMMA showed a clear oxidative induction time onset that increased with increasing antioxidant content.[1]

Polymethylmethacrylate films were reinforced with coconut shell lignin fractions to enhance their UV-blocking, antioxidant, and thermo-mechanical properties.[2] TGA and DSC showed improved thermal and thermooxidative stabilities.[2] DMA analyses of the films indicated that lignin-soluble fractions had a plasticizing effect, while non-fractionated lignin increased PMMA films glass transition temperature.[2] The antioxidant capacity of the films was also enhanced with the addition of lignins.[2]

Antioxidant has the advantages of both the hindered phenols and the phosphite antioxidant.[3] It was prepared from phosphorus trichloride and 2,5-di-tert-butylhydroquinone, such as tetrakis-(2,5-di-tert-butyl-4-hydroxyphenyl)-2,5-di-tert-butyl-hydroquinonediyl diphosphite.[3] The combination of radical scavenger (hindered phenol) with hydroperoxide decomposer (organophosphite) provided a powerful synergism for the protection of polymers.[3] The antioxidant had a performance superior to the commercially available antioxidants.[3]

References

1 Chang, TC; Yu, PY; Hong, YS; Wu, TR; Chiu, YS, Polym. Deg. Stab., 77, 1, 29-34, 2002.

2 Avelino, F; de Oliveira, DR; Mazzetto, SE; Lomonaco, D, *Int. J. Biol. Macromol.*, **125**, 171-80, 2019.

3 Wu, T-R; Yu, P-Y; Lin, Y-C; Chang, T-C, **US6759461B2**, *National Chung Shan Institute of Science and Technology*, Apr. 17, 2015.

5.46 PP (POLYPROPYLENE)

Long-chain amine containing molecules were covalently attached to the polypropylene surface.[1] The polymeric antioxidant was prepared by amide bond formation between phenolic stabilizer containing carboxylic acid moiety and amine functionalized polypropylene.[1] The resultant product exhibited reduced crystallinity.[1] Its crystallization temperature shifted toward higher values, suggesting simultaneous effects of steric hindrance and nucleation of long-chain structures.[1] Immobilization of phenolic stabilizer resulted in improving thermooxidative stability of polypropylene.[1] Figure 5.33 characterizes the chemistry of the process.[1]

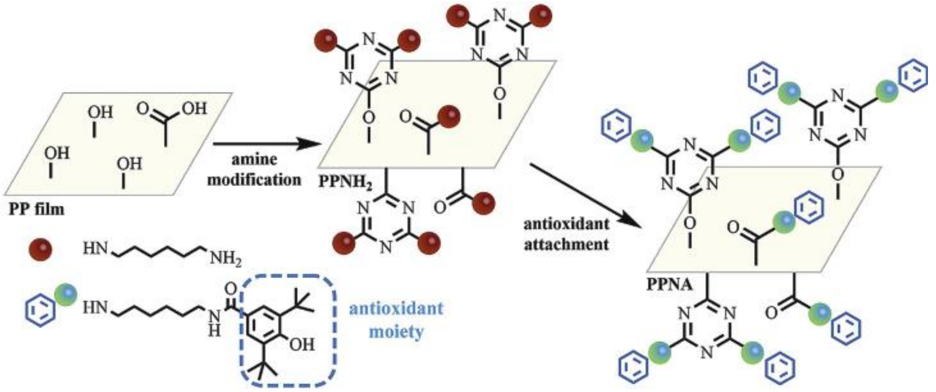


Figure 5.33. Attachment of antioxidant to polypropylene chain. [Adapted, by permission, from Manteghi, A; Ahmadi, S; Arabi, H, *Polymer*, **138**, 41-8, 2018.]

The structural effect of natural antioxidant from technical Kraft lignin on the oxidation induction time of polypropylene was quantitatively investigated using the correlation analysis model.[2] The non-condensed phenolic –OH had a dominating role in improving thermal oxidation stability, followed by molecular weight, and polydispersity.[2]

A nanosilica-immobilized antioxidant (3,5-di-tert-butyl-4-hydroxycinnamic acid was immobilized using aminosilane coupling agent N-(2-aminoethyl)-3-aminopropyltrimethoxysilane) was prepared and incorporated into polypropylene by melt compounding.[3] The antioxidant efficiency of the nanosilica-immobilized antioxidant was superior to the corresponding low molecular counterpart.[3]

Serious safety issues have been raised about toxic chemicals such as butylated hydroxytoluene and pentaerythritol tetrakismethylene-(3,5-di-tert-butyl-4-hydroxyhydrocinnamate) (Irganox 1010), which may migrate from polypropylene packaging into foods.[4] The effects of severe processing conditions, such as autoclave heating (121°C), microwave radiation (700 W), and freezer storage (-30°C) on migration behavior were confirmed.[4]

A green tea extract, a natural antioxidant, was immobilized on polypropylene through the incorporation of anhydride maleic grafted polypropylene.[5] The incorporation of green tea extract improved polymer stability, and the presence of grafted polymer did not affect polymer morphology.[5] Green tea components release profiles depended on the type of food and polymer formulation.[5]

The functions of rutile TiO_2 nanoparticles and antioxidants were integrated by preparing multifunctional TiO_2 nanoparticles with the capacity of both UV absorption and antioxidation.[6] Rutile TiO_2 nanorods were prepared and encapsulated by SiO_2 to decrease its photocatalytic activity.[6] Then, functionalized antioxidant was deposited on silica-coated TiO_2 nanorods.[6] The hybrid improved both photo and thermal stabilities of polypropylene. Figure 5.34 illustrates the chemistry and results.[6]

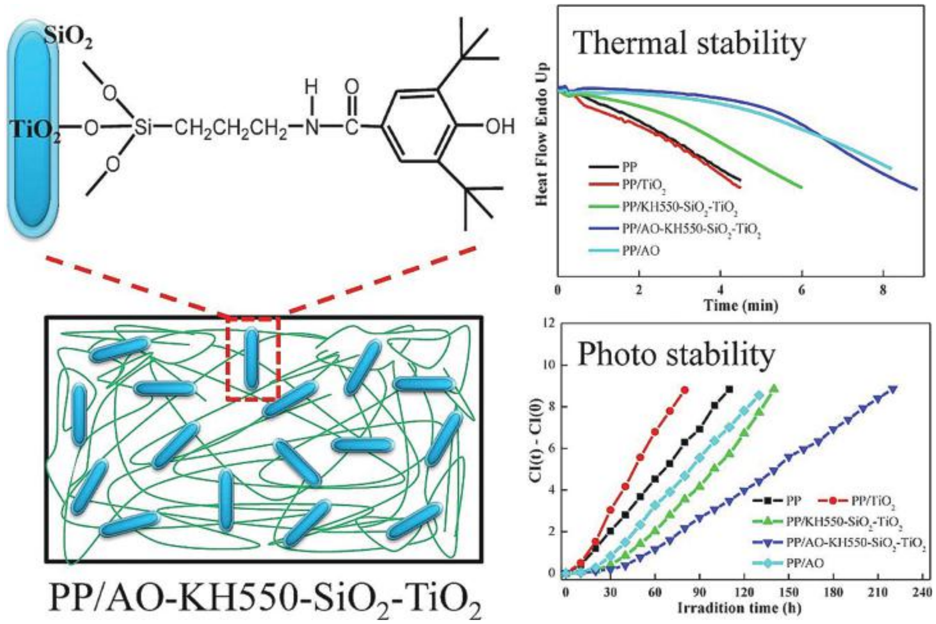


Figure 5.34. Structure of UV stabilizer/antioxidant and its effects on polypropylene stability. [Adapted, by permission, from Li, G; Wang, F; Liu, P; Gao, C; Yang, M, *Appl. Surf. Sci*., **475**, 682-90, 2019.]

A commercial tannin wine seed extract powder, a seed polyphenol extract, and virgin wine seeds wastes have been mixed with polypropylene and tested as long-term stabilizers.[7] Their stabilizing activity has been compared with that of a synthetic antioxidant commonly used within PP (Irganox 1010).[7] The PP-based film photooxidation has been followed by the C=O formation after aging.[7] All wine derived additives withstood both thermal and UV long-term degradation.[7] The wine seeds extracts exhibited the best results in terms of stabilization (even better than Irganox 1010) without compromising the PP mechanical, thermal, morphological, and rheological properties.[7]

Polypropylene-talc composite with reduced malodor contains an organic antioxidant and a triazine derivative.[8] The most preferred phenolic antioxidant is pentaerythrityl-tetrakis (3-(3,5-di-tert-butyl-4- hydroxyphenyl) propionate.[8]

The production of a stabilized polyolefin comprising an olefin homo- or copolymer and an antioxidant has been developed.[9] The antioxidant was fed during the process prior to and/or during a post-production step selected from depressurization, degassing, and catalyst deactivation steps.[9] The antioxidant was of vitamin E type.[9]

References

1 Manteghi, A; Ahmadi, S; Arabi, H, *Polymer*, **138**, 41-8, 2018.
2 Chen, K; Ye, D; Gu, S; Zhou, Z, *Int. J. Biol. Macromol.*, **A107**, 478-85, 2018.
3 Gao, X; Meng, X; Wang, H; Wen, B; Yang, M, *Polym. Deg. Stab*., **93**, 8, 1467-71, 2008.
4 Chang, Y; Kang, K; Park, S-j; Choi, JC; Han, J, *J. Food Eng.*, **244**, 142-9, 2019.
5 López de Dicastillo, C; del Mar Castro-López, M; López-Vilariño, JM; González-Rodríguez, MV, *Food Res. Int*., **53**, 1, 522-8, 2013.
6 Li, G; Wang, F; Liu, P; Gao, C; Yang, M, *Appl. Surf. Sci*., **475**, 682-90, 2019.
7 Nanni, A; Battegazzore, D; Frache, A; Messori, M, *Polym. Deg. Stab.*, **165**, 49-59, 2019.
8 Kastner, E; Lederer, K; Otte, M; Siebert, H; Dicke, R, **WO2011023594A1**, *Borealis Ag*, Aug. 17, 2010.
9 Bergstra, M; Eriksson, E; Hagstrand, P-O; Anke, M; Vahteri, M; Fosse, K, **WO2013050087A1**, *Borealis Ag*, Jun. 06, 2012.

5.47 PPG (POLY(PROPYLENE GLYCOL))

Elaborate antioxidant pathways have evolved to minimize the threat of excessive reactive oxygen species and to regulate them as signaling entities.[1] The reactive oxygen species are chemically and functionally similar to reactive sulfur species and both reactive oxygen species, and reactive sulfur species have been shown to be metabolized by the antioxidant enzymes, superoxide dismutase and catalase.[1] Antioxidant inhibitors, generally known for their ability to increase cellular reactive oxygen species, have various effects on cellular reactive sulfur species, which illustrates the importance of careful evaluation of reactive sulfur species metabolism when biologically or pharmacologically attempting to manipulate reactive oxygen species.[1]

PEG-modified liposomes can be used for the delivery of naturally occurring resveratrol.[2] The incorporation of resveratrol in PEG-modified liposomes did not affect its intrinsic antioxidant activity, as DPPH radical was almost completely inhibited, and the vesicles were also able to ensure optimal protection against oxidative stress in an *ex vivo* human erythrocytes-based model.[2] The antioxidant efficacy of the polyphenol can be exploited against oxidative stress associated with cancer.[2]

References

1 Olson, KR; Gao, Y, *Free Radical Biol. Med.*, **115**, 1-14, 2019.
2 Caddeo, C; Pucci, L; Gabriele, M; Carbone, C; Manconi, M, *Int. J. Pharm.*, **538**, 1-2, 40-7, 2018.

5.48 PPS (POLY(P-PHENYLENE SULFIDE))

Tetrakis [methylene (3,5,-di-t-butyl-4-hydroxyhydrocinnamate)] methane antioxidant was used to retard the rate of hydrothermal oxidation of PPS used in anti-corrosion and anti-fouling coatings of carbon steel substrates in geothermal environments at temperatures up to 200°C.[1] A phenolic hydrogen donor within an antioxidant acted to trap the free sulfur and aryl radicals generated by hydrothermal degradation of PPS during a period of the oxidative induction, thereby terminating the propagation of oxidation in the PPS.[1]

Crosslinked polymer containing poly(phenylene sulfide) and an impact modifier and optionally antioxidant has been used as cable coverings, such as a jacket or insulation.[2] The preferred antioxidant was thiodiethylene bis[3-[3,5-di-tert-butyl-4-hydroxyphenyl]propionate commercially known as Irganox® 1035.[2]

Reference

1 Sugama, T, *Mater. Lett.*, **43**, 4, 185-91, 2000.
2 Mhetar, V, **US20120037397A1**, *General Cable Technologies Corp*, Feb. 16, 2012.

5.49 PPY (POLYPYRROLE)

When food cannot be consumed immediately after production, food packaging must create a protective atmosphere around the food product.[1] This work emphasizes the antioxidant activity and high barrier properties against the diffusion of oxygen, carbon dioxide, and water vapor from a nanocomposite-based on polypyrrole and TEMPO-oxidize nanofibrillated cellulose, as well as its biodegradability for food packaging applications.[1] Antioxidant activity depends on the capability of the PPy to donate active hydrogen atoms or transfer electrons to reduce the DPPH.[1] Polypyrrole-based composites have a strong antioxidant property, conferred by chains of PPy owing to their redox active nature that reduces radicals.[1] The improvement in the barrier properties and antioxidant activity can be attributed to the polypyrrole particles which coat the dense network formed by nanofibrils.[1]

Polypyrrole nanotube antioxidant activity increased with a decrease in nanotubes diameter, which can be attributed to the increased surface area per unit volume of the nanotubes.[2] Time-dependent antioxidant activity revealed the existence of both faster and slower processes in the scavenging mechanism.[2]

Biodegradable conductive nanocomposites based on polypyrrole/dextrin have been synthesized by *in situ* polymerization of pyrrole in the presence of dextrin.[3] Antioxidant activity of nanocomposites was increased by increasing the amount of polypyrrole in the nanocomposite matrix.[3]

The conducting polymers such as polypyrrole are difficult to suspense in solution after chemical or electrochemical polymerization.[4] Suspensible chitosan-polypyrrole composites with antioxidant properties have been produced.[4] The chitosan-polypyrrole composites were formed as membranes (coatings). Impedance measurements indicated their conductivity was in the range of 10^{-3} to 10^{-7} S cm^{-1}.[4] The radical scavenger activity of the composites was renewable by means of electrochemical cycling.[4]

References

1 Bideau, B; Bras, J; Adoui, N; Loranger, E; Daneault, C, *Food Packaging Shelf Life*, **12**, 1-8, 2017.
2 Upadhyay, J; Kumar, A; Gogoi, B; Buragohain, AK, *Synth. Metals*, **189**, 119-25, 2014.
3 Zare, EN; Lakouraj, MM; Mohseni, M, *Synth. Metals*, **187**, 9-16, 2014.
4 Lee, R-J; Temmer, R; Tamm, T; Aabloo, A; Kiefer, R, *Reactive Functional Polym*., **73**, 8, 1072-7, 2013.

5.50 PR (PROTEINS)

Proteins have covalent and non-covalent interactions with polyphenols (Figure 5.35).[1]

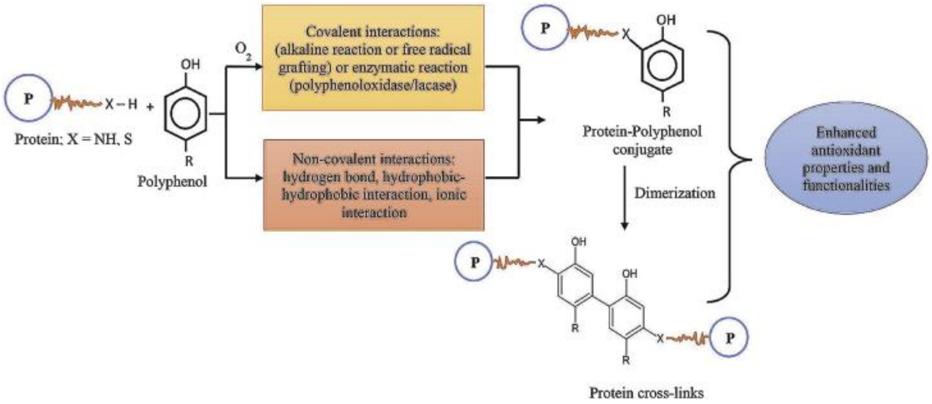


Figure 5.35. Protein interactions with polyphenols. [Adapted, by permission, from Quan, TH; Benjakul, S; Sae-leaw, T; Balange, AK; Maqsood, S, *Trends Food Sci. Technol.*, **91**, 507-17, 2019.]

The interaction of proteins and polyphenols mainly results from non-covalent (H-bonding, electrostatic interactions) or covalent bonds taking place mostly based on the oxidation of proteins or polyphenol by enzymatic or non-enzymatic pathways.[1] Protein-polyphenol interaction greatly depends on environmental conditions such as temperature and pH as well as on the conformation or type of proteins and polyphenols.[1] The protein-polyphenol conjugates with higher thermal stability, antioxidant activities, better emulsifying properties, and enhanced gelling property can be used as food additives for improvement of functionalities and quality of food products.[1]

The effect of enzymolysis-assisted electron beam irradiation on the structural characteristics and antioxidant activity of rice protein has been studied.[2] The amino acid content of rice protein was increased by enzymatic hydrolysis and gradually decreased with the irradiation dose increased.[2] The antioxidant activity of the rice protein hydrolysates was improved by electron beam irradiation, reaching the highest point of radical scavenging at 50 kGy.[2]

Different conditions of extrusion variables (temperature and moisture content) were applied to shrimp shell wastes, and their effects on the physicochemical, functional properties and antioxidant activities of shrimp shell wastes protein were investigated.[3] Extrusion caused marked improvements in the protein content.[3] It also changed amino acid composition, functional, thermal, and morphological properties.[3] Extrusion improved antioxidant properties which were maximized when extrusion occurred at 25% moisture content and 150°C.[3]

The structure of watermelon seed protein was altered by divergent sonication. Slit divergent ultrasound improved the antioxidant activity of hydrolysates.[4] Watermelon protein hydrolysates with molecular weight <1 kDa showed the highest antioxidant activity.[4]

Grape seed procyanidins and soy protein isolate had a hydrogen bond-dominated interaction.[5] Formation of complexes improved antioxidant properties, thermal, light, and pH stability.[5]

Soy sauce has a unique flavor but also antimicrobial and antioxidant properties.[6] Variation in chemical composition is mainly due to differences in the fermentation process and the addition of supplementary ingredients like flavor enhancers, among others.[6] Addition of soy sauces to whey protein-based edible films improved film organoleptic properties but also conferred antioxidant activity and antimicrobial activity on the film surface.[6]

The above examples are only a small sample of a large body of scientific publications on the use of antioxidant in protein formulations.

References

1 Quan, TH; Benjakul, S; Sae-leaw, T; Balange, AK; Maqsood, S, *Trends Food Sci. Technol.*, **91**, 507-17, 2019.
2 Li, T; Wang, L; Sun, D; Li, Y; Chen, Z., *J. Cereal Sci.*, **89**, 102789, 2019.
3 Yuan, G; Pan, Y; Li, W; Wang, C; Chen, H, *Int. J. Biol. Macromol.*, **136**, 1096-105, 2019.
4 Wen, C; Zhang, J; Zhang, H; Duan, Y; Ma, H, *Food Chem.*, **299**, 125165, 2019.
5 Zou, Y-C; Wu, C-L; Ma, C-F; He, S; Yuan, Y, *LWT*, **115**, 108465, 2019.
6 García, A; Pérez, LM; Piccirilli, GN; Verdini, RA, *LWT*, **117**, 108587, 2019.

5.51 PS (POLYSTYRENE)

A method of improving the color of a high impact polystyrene includes the preparation of reaction mixture of styrene, elastomer, and at least one antioxidant. The color improving additive has been added prior to the addition of any oxidizing agents to the reaction mixture.[1] The yellowness index of this high impact polystyrene was reduced by 50-200%.[1]

References

1 Sosa, JM; Ellis, B; Gray, SD, **US20080021157A1**, *Fina Technology Inc,* Jan. 24, 2008.

5.52 PSR (POLYSULFIDE)

The antioxidant activity of sulfides increases with the number of sulfur atoms.[1] Sulfides with long chains have good antioxidant activity, whereas the antioxidant activity of cyclic sulfides is poor.[1]

Polysulfides act as anti-wear agents, extreme pressure agents, and antioxidants in lubricants, such as gear oils and metalworking fluids.[2] The invention related to a composition containing polysulfides and inhibitors that had a reduced odor level, and a method for reducing the odor level of polysulfides.[2] These polysulfide compositions were useful in many industrial applications such as metalworking fluids.[2] The polysulfides of this invention are the reaction products of an olefin selected from the group consisting of isobutylene and diisobutylene with sulfur and H_2S in the presence of a catalyst.[2]

References

1 Qiu, C; Han, S; Cheng, X; Ren, T, *Thermochim. Acta*, **447**, 1, 36-40, 2006.
2 Forester, RD; Gober, AV; Malik, BB; Sowerby, LR, **DE60107945T2**, *Lubrizol Corp*, Dec. 15, 2005.

5.53 PSU (POLYSULFONE)

Silibinin is a plant extract with antioxidant, anti-inflammatory, and cytoprotective effects.[1] Silibinin-modified polysulfone hemodialysis membranes have been fabricated using an immersion phase transformation method.[1] The antioxidant properties of the membranes were evaluated in terms of their 2,2-diphenyl-1-picrylhydrazyl and 2,2′-azinobis-(3-ethyl-benzothiazoline-6-sulfonate) free radical scavenging activities and lipid peroxidation inhibition.[1] With increasing silibinin content, the antioxidant properties, and the stability of the free radical scavenging rate of the blend membranes were improved. Red blood cells and platelet adhesion, and superoxide dismutase levels, were decreased using these membranes.[1] Figure 5.36 illustrates methods of membrane production and antioxidant activity of silibinin.[1]

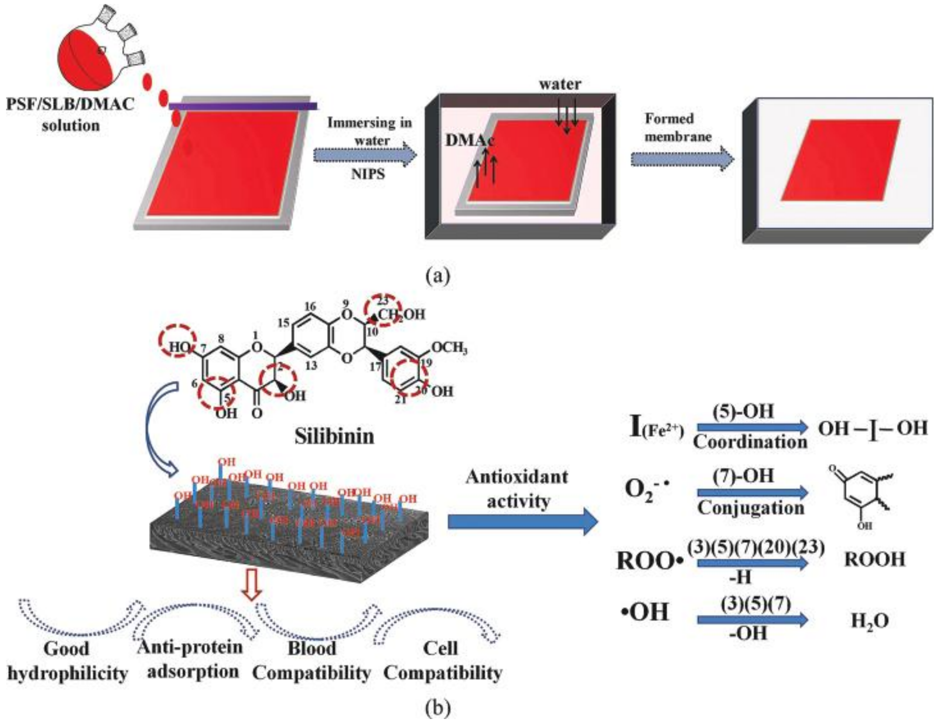


Figure 5.36. Schematic illustration of (a) the process of preparing PSU/silibinin, SLB, membranes and (b) the properties of PSU/SLB membranes where the numbers represent the position of the hydroxyl group in the SLB molecular chain. [Adapted, by permission, from Yang, N; Jia, Y; Wang, D; Wei, C; Zhao, Y, *J. Membrane Sci*., **574**, 86-99, 2019.]

A series of polysulfones of new structural types on the basis of azanorbornenes, 2,2-diallyl-1,1,3,3-tetraethylguanidiniumchloride and tris(diethylamino)diallylaminophosphonium salts were obtained by the free radical polymerization reaction.[2] Their antioxidant properties in lipid peroxidation induced by iron/ascorbate and in erythrocyte hemolysis by

H_2O_2 were evaluated.[2] The polysulfone of 2,2-diallyl-1,1,3,3-tetraethylguanidinium chloride showed protection of erythrocytes against hydrogen peroxide and thermal shock, protected epithelial cells against UV irradiation.[2]

The lipophilic antioxidant (vitamin E) was used as a surface modifier (or coating agent) of hollow-fiber hemodialyzer membranes with the aim of increasing their biocompatibility and preventing oxidative stress, which are the main clinical drawbacks in hemodialysis therapy.[3] The antioxidant capacity of miniaturized polysulfone-vitamin E samples assessed in this study was 14.5 μM Fe^{2+}, which corresponded to the transformation of nearly one-third of the vitamin E bound to the hollow-fiber membrane to its oxidation end product α-tocopherol quinone.[3]

In water production plants using membrane processes, contact with chemicals such as chlorine plays an important role in membrane aging.[4] An oxidation mechanism involved the catalytic effect of dissolved metal ions and the inhibitor effect of an antioxidant.[4] The degradation mechanism involved radical oxidation by hydroxyl radicals catalyzed by the presence of some metal ions, such as Fe^{3+} and Cu^{2+}, suggesting a Fenton-like reaction.[4] The consumption of hydroxyl radicals by an antiradical, tertiobutanol, added to chlorine solution inhibited oxidation of the polysulfone chains in membrane material.[4] This allowed an increase in membrane lifetime.[4]

References

1 Yang, N; Jia, Y; Wang, D; Wei, C; Zhao, Y, *J. Membrane Sci*., **574**, 86-99, 2019.
2 Gorbunova, M; Anikina, L, *Eur. J. Med. Chem*., **63**, 655-61, 2013.
3 Floridi, A; Piroddi, M; Pilolli, F; Matsumoto, Y; Galli, F, *Acta Biomaterialia*, **5**, 8, 2974-82, 2009.
4 Causserand, C; Rouaix, S; Lafaille, J-P; Aimar, P, *Chem. Eng. Processing: Process Intensification*, **47**, 1, 48-56, 2008.

5.54 PU (POLYURETHANE)

Phenolic acid grafted oligochitosan (PA-g-OCS and GA-g-OCS) have been synthesized through the reaction of protocatechuic acid, and gallic acid with oligochitosan, which was catalyzed by laccase.[1] Waterborne polyurethane incorporated with phenolic groups were prepared as coatings.[1] The chain extension step was done by using different phenolic acids grafted oligochitosan.[1] The antioxidant activity and mechanical property of the material were significantly enhanced.[1] Figure 5.37 shows the methods of synthesis.[1]

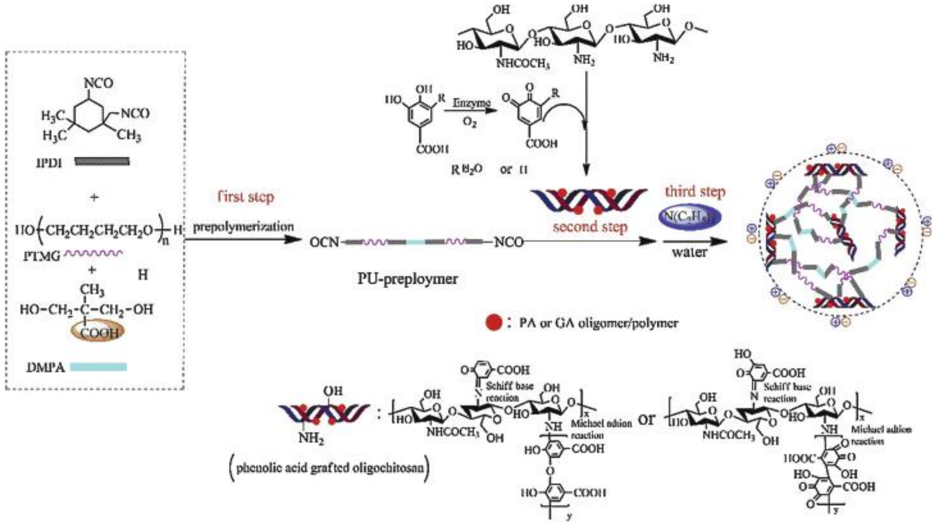


Figure 5.37. The synthetic route of modified waterborne polyurethanes. [Adapted, by permission, from Ren, L; Guo, X; Zhao, Y; Qiang, T, *Prog. Org. Coat.*, **135**, 410-6, 2019.]

Medical device-related infections are a major problem in the hospital.[2] The risk of developing an infection is linked to the bacterial adhesion ability of pathogen strains on the device and their ability to form a biofilm.[2] Antioxidant blooming onto the polyurethane surface made the surface stiffer and more hydrophobic.[2] Also, the surface topography was dramatically changed increasing the surface roughness.[2] Bacterial adhesion was promoted by antioxidant blooming and its crystallization created anchoring sites for bacteria.[2] Needles formed by antioxidant were preferential anchoring sites. Bacteria were localized on the needles, and they were very difficult to remove.[2]

Conducting polymers are used for electrically excitable cells to increase electrical signal propagation within the cell-loaded substrates.[3] Biodegradable electroactive polyurethane containing aniline pentamer was used in this application.[3] Its antioxidant activity was confirmed using 1,1-diphenyl-2-picrylhydrazyl scavenging assay.[3] Natural and synthetic antioxidants were used to prevent the uncontrolled oxidation of lipids, proteins, and DNA caused by the development of various diseases like cardiac and cerebral ischemia, infection, and cardiovascular diseases.[3]

Catechin was added to a polyurethane based on poly(l-lactic acid), and poly(ε-caprolactone).[4] Catechin in the polyurethane matrix improved its thermal stability due to antioxidant effect, shifting the PU onset degradation temperature to substantial higher values, (25-55°C).[4]

High energy ionizing radiation and oxidizing treatment have a very different impact on the surface of polyurethane films that are covered with bloomed additives.[5] In the case of ionizing treatment, the PU surface is not efficiently protected by the antioxidant to effectively scavenge free radicals created during chain scission.[5] Bloomed additives do not seem to be damaged by the irradiation, but the film surface becomes rougher.[5] In the case of the oxidation treatment, no significant increase in roughness was observed, but the bloomed additive suffered from degradation.[5]

Songwon International has developed a new antioxidant to strengthen and enhance the value of its range of stabilizers for polyols and polyurethanes.[6] Songnox® 5057 is a liquid, butylated, octylated aminic antioxidant suitable for application in various substrates, including polyols.[6] It protects polyols against degradation during storage and transportation.[6]

Castor oil, naturally polyol, is inexpensive, environmentally friendly and a very valuable renewable resource.[7] Metals are believed to influence the antioxidant property of ligands.[7] Metals, such as copper, zinc, cobalt, and barium were incorporated with castor oil and studied for antioxidant activities.[7] Figure 5.38 shows some results.[7]

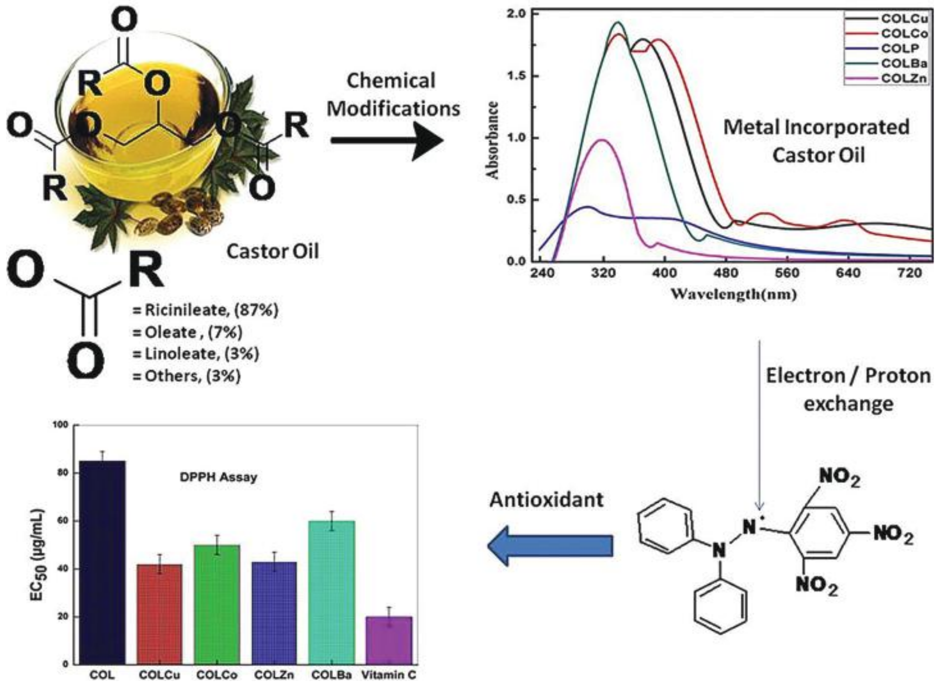


Figure 5.38. Antioxidant activity of some metal ligands of castor oil. [Adapted, by permission, from Talukdar, IA; Akram, K; Singh, T; Malik, MA; Hashmi, AA, *Food Chem*., **284**, 213-8, 2019.]

Organosolv wheat straw lignin was reacted with 4,4′-methylene diphenylene diisocyanate.[8] The content of lignin in PU compositions was varied in a range of 5-40%.[8] Activity of lignin fractions as antioxidants of PU compositions was studied.[8] The antioxidative activity was apparent with only a small addition of lignin (5%), which caused enhancement of thermooxidative stability of synthesized resin.[8]

Three low-molecular-weight stabilizers, bearing in their molecules a tri(dimethylsiloxane) chain, end-capped with primary OH groups, have been synthesized and characterized.[9] One is based on a sterically hindered phenolic antioxidant, the others on sterically hindered piperidines.[9] When added to the reaction mixture of soluble elastomeric polyurethanes (containing a polybutadiene α,ω-diol, a diisocyanate, and a catalyst), each of these stabilizers, due to the presence of the OH group, was joined by a covalent bond at one or both chain ends of the polyurethane formed, and acted as a molecular-weight regulator.[9] The advantage of these chemically fixed stabilizers was that they remained in the matrix and could not be evaporated or washed out.[9]

Exposure to UV triggers the chain scission reactions which change the intrinsic properties of heat-treated wood and discoloration of the wood surface.[10] Water based acrylic polyurethane coatings are highly efficient, non-toxic and durable coatings with upgraded film properties.[10] Their properties were still improved by incorporating natural antioxidant (bark extract) and inorganic UV absorbers (nano and micro titania and nano zinc oxide).[10] The coating thickness decreased with increasing weathering time, and a tissue deformation beneath the coating surface took place during weathering.[10] Inclusion of natural antioxidant together with inorganic UV absorbers improved retention of the acrylic polyurethane coatings.[10] The coating containing titania nano particles was less effective than the other two coatings for protecting the heat-treated jack pine surface.[10]

A composite antioxidant for spandex or thermoplastic polyurethane, based on pentaerythritol tetrakis(4-(3,5-di-tert-butyl-4-hydroxyphenyl)-propionate was mixed with 1,1,3-tris(2-methyl-4-hydroxy-5-tert-butylphenyl)butane, and the mixture was added into the spandex or thermoplastic polyurethane.[11] The composite antioxidant can greatly improve the indoor yellowing resistance, NO_x resistance, and the thermal stability of the spandex.[11]

Thermoplastic polyurethane having a light stabilization useful for ophthalmic applications comprised precursors of polyurethane and antioxidant.[12] The antioxidant was benzenepropanoic acid, 3(1,1-dimethylethyl)-4-hydroxy-5-methyl-1,1′-[1,2-ethanediylbis (oxy-2,1-ethanediyl)]ester and the light stabilizer was bis(1,2,2,6,6-pentamethyl-4-piperidinyl)-[[3,5-bis(1,1-dimethylethyl)-4-hydroxyphenyl]methyl]butylmalonate together with phenol, 2-(5-chloro-2H-benzotriazole-2-yl)-6-(1,1-dimethylethyl)-4-methyl or 2,2′-methylenebis(6-(2H-benzotriazol-2-yl)-4-1,1,3,3-tetramethylbutyl)phenol).[12]

Impact strength of synthetic resin lens with the transparency of a synthetic resin lens material of polyurethane and releasability was improved by antioxidant belonging to phenol or phosphorus family.[13]

Polyether carbonate polyols were used for the production of polyurethane foams with stable color. Tocopherol and its mixtures were suitable antioxidants in this application as were some phenolic antioxidants.[14]

References

1 Ren, L; Guo, X; Zhao, Y; Qiang, T, *Prog. Org. Coat*., **135**, 410-6, 2019.
2 Saunier, J; Herry, J-M; Marlière, C; Renault, M; Yagoubi, N, *Mater. Sci. Eng. C*, **56**, 522-31, 2015.
3 Baheiraei, N; Yeganeh, H; Ai, J; Gharibi, R Faghihi, F, *Mater. Sci. Eng. C*, **44**, 24-37, 2014.
4 Arrieta, MP; Peponi, L, *Eur. Polym. J*., **89**, 174-84, 2017.
5 Nouman, M; Saunier, J; Jubeli, E; Marlière, C; Yagoubi, N, *Eur. Polym. J*., **90**, 37-53, 2017.
6 *Additives Polym*., **2019**, 1-2, 2, 2019.
7 Talukdar, IA; Akram, K; Singh, T; Malik, MA; Hashmi, AA, *Food Chem*., **284**, 213-8, 2019.
8 Arshanitsa, A; Krumina, L; Telysheva, G; Dizhbite, T, *Ind. Crops Prod*., **92**, 1-12, 2016.
9 Hetflejš, J; Šabata, S; Podešva, J; Kovářová, J; Sýkora, J, *Polym. Deg. Stab*., **95**, 4, 579-86, 2010.
10 Saha, S; Kocaefe, D; Krause, C; Larouche, T, *Prog. Org. Coat*., **70**, 4, 170-7, 2011.
11 **CN102030979A**, Aug. 27, 2011.
12 Chiu, H-W; Neuzil, R; Herod, TE, **US9163133B2**, *Essilor International (Cie Generale d Optique) SA*, Oct. 20, 2015.
13 Tamura, K; Mitsuuchi, S; Chang, C-T, **US7216976B2**, *Talex Optical Co Ltd*, May 15, 2007.
14 Brassat, L; Pohlig, R; Pirkl, H-G, **WO2016135259A1**, *Covestro Deutschland A*g, Feb. 25, 2016.

5.55 PVAL (POLY(VINYL ALCOHOL))

Natural antioxidants are being incorporated into polymers to produce active packaging, preventing the formation of off-flavors and undesirable textures in foods, and increasing the food shelf-life.[1] Poly(vinyl alcohol) contained solid lipid nanoparticles with entrapped α-tocopherol (Figure 5.39).[1] PVAl films were more hydrophilic compared to the control film.[1] The nanoparticles incorporation changed the structure of the film, decreasing the crystallinity, and increased antioxidant capacity.[1] The α-tocopherol controlled release gave the possibility of its use as active food packaging.[1]

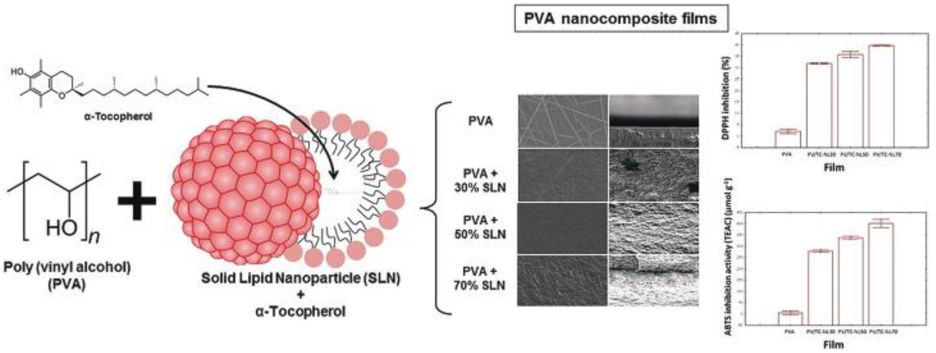


Figure 5.39. Structure and effects of lipid nanoparticles containing α-tocopherol on the structure and properties of PVAl films. [Adapted, by permission, from Matos de Carvalho, S; Montanheiro Noronha, C; Gonçalves da Rosa, C; Sganzerla, WG; Manique Barreto, PL, *Colloids Surf. A: Physicochem. Eng. Aspects*, **581**, 123793, 2019.]

Nanocelluloses with and without residual lignin were isolated from wheat straw.[2] Their effect as reinforcing agent of poly(vinyl alcohol) films has been studied.[2] The ability to block UV-light increased from 10% for PVAl to >50% for lignin-containing nanocellulose, and 30% for lignin-free samples.[2] The antioxidant capacity of films was increased by 10% using lignin-containing nanocellulose as compared to 4.7% for PVAl.[2]

Durvillaea antarctica antioxidant algae extract obtained by an aqueous extraction process was encapsulated into electrospun PVAl fibers, which were used as a reinforcement phase and active agent in plasticized poly(lactic acid) films.[3] The addition of PVAl fibers improved thermal stability and mechanical and barrier performance of plasticized poly(lactic acid).[3] The antioxidant activity was also improved.[3]

Storage ability of Thompson seedless grapes stored at 4°C for 70 days was studied using coating treatment with chitosan/PVAl/salicylic acid.[4] The presence of salicylic acid increased antioxidant activities of enzymes, such as ascorbate peroxidase, catalase, superoxide dismutase, and peroxidase.[4] It also protected phenolic substances such as total phenols and flavonoids due to the action of polyphenol oxidase, resulting in less browning symptoms during cold storage.[4]

Release kinetics of rosemary (*Rosmarinus officinalis*) polyphenols from poly(vinyl alcohol) electrospun nanofibers into several food simulants has been studied.[5] Higher amount of polyphenols was burst released in hydrophobic simulant.[5] Polymer chain relaxation was the main release mechanism in hydrophilic simulant, while an anomalous release occurred in acid medium.[5] Figure 5.40 illustrates the release behavior in different simulants.[5]

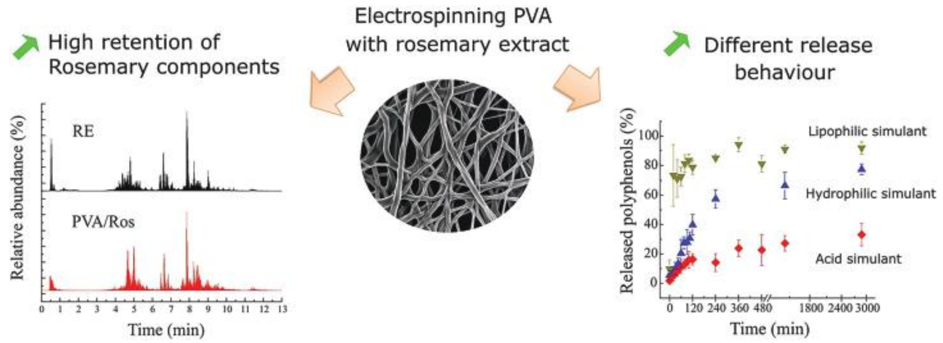


Figure 5.40. Left – HPLC chromatograms of rosemary extract (RE) and after release of polyphenols from PVA/Ros mats. Center – PVC with extract. Right – release behavior in different simulants. [Adapted, by permission, from Estevez-Areco, S; Guz, L; Candal, R; Goyanes, S, *Food Packaging Shelf Life*, **18**, 42-50, 2018.]

Lignin nanoparticles have been esterified and etherified with citric acid and then blended with poly(vinyl alcohol) at various loading levels (up to 10 wt%).[6] Modified lignin nanoparticles of nanocomposite films outperformed the films containing (unmodified) lignin nanoparticles in antioxidant activity.[6] The esterification and etherification of lignin by citric acid induced the formation of intermolecular hydrogen bonds between nanofillers and PVAl matrix.[6]

Postharvest chilling injury of Baladi mandarin has been related to the activity of antioxidant enzyme activities during cold storage.[7] The performance of pectin/polyvinylalcohol blended with ascorbic acid to increase storability tolerance of mandarin fruit under cold storage on were assessed.[7] The coating treatment minimized lipid peroxidation and ion leakage.[7] The coating treatment presented less chilling injury symptoms and improved fruit color.[7]

Honey is an ancient natural wound-healing agent.[8] Honey was incorporated into an alginate/PVA-based electrospun nanofibrous membrane to develop an efficient wound dressing material.[8] The nanofibrous membranes with increasing honey content showed enhanced antioxidant activity, suggesting the ability to control the overproduction of reactive oxygen species.[8] Honey also increased the antibacterial activity towards Gram-positive bacterium (*Staphylococcus aureus*) and Gram-negative bacterium (*Escherichia coli*).[8]

The active poly(vinyl alcohol) films incorporated with clove oil were prepared.[9] The antimicrobial and antioxidant activities in the vapor phase of the films were evaluated by microbiological analyses and lipid oxidation of the packed *trichiurus haumela* without contacting the PVAl films.[9] The oil droplets were observed on the surface and cross-section of the films as clove oil increased from 3% to 9% *via* scanning electron microscope.[9] They resulted from the heterogeneous film structure featuring discontinuities.[9] The PVAl film containing 9% clove oil showed the best protective effectiveness.[9]

A method of preparing an antioxidant polymer includes forming a polymer having reactive pendant groups.[10] The antioxidant was attached to the polymer by an acetal, amide, amine, carbamate, carbonate, ester, ether or thioether linkage or by a carbon-carbon bond.[10] The antioxidant polymers can be used to coat a metal as a rust and corrosion inhibitor.[10] They can protect pharmaceutical products from degradation.[10] The antioxidant polymers can prevent rancidity in food products.[10] In plastics, the antioxidant polymers can prevent the plastic from becoming brittle and cracking.[10] Polyvinylalcohol has been used as a primary example of polymer suitable for the formation of an antioxidant polymer.[10]

Polyvinyl alcohol fibers contained 0.05 wt% of an antioxidant composed of an inorganic or organic water soluble salt of at least one metal selected from the group consisting of manganese, copper, iron, nickel, cobalt, and zinc and a boron compound that acted as a chelating agent for the antioxidant.[11] The boron compound was contained in the fiber with a proportion of 0.5 wt% or more relative to the antioxidant.[11]

References

1 Matos de Carvalho, S; Montanheiro Noronha, C; Gonçalves da Rosa, C; Sganzerla, WG; Manique Barreto, PL, *Colloids Surf. A: Physicochem. Eng. Aspects*, **581**, 123793, 2019.
2 Espinosa, E; Bascón-Villegas, I; Rosal, A; Pérez-Rodríguez, F; Rodríguez, A, *Int. J. Biol. Macromol.*, **141**, 197-206, 2019.
3 Arrieta, MP; López de Dicastillo, C; Garrido, L; Roa, R; Galotto, MF, *Eur. Polym. J.*, **103**, 145-57, 2018.
4 Lo'ay, AA; Taha, NA; El-Khateeb, YA, *Scientia Horticulturae*, **249**, 314-21, 2019.
5 Estevez-Areco, S; Guz, L; Candal, R; Goyanes, S, *Food Packaging Shelf Life*, **18**, 42-50, 2018.
6 He, X; Luzi, F; Hao, X; Yang, W; Puglia, D, *Int. J. Biol. Macromol.*, **127**, 665-78, 2019.
7 Lo'ay, AA; Dawood, HD, *Scientia Horticulturae*, **256**, 108637, 2019.
8 Tang, Y; Lan, X; Liang, C; Zhong, Z; Wang, W, *Carbohydrate Polym.*, **219**, 113-20, 2019.
9 Chen, C; Xu, Z; Ma, Y; Liu, J; Xie, J, *Food Control*, **88**, 105-12, 2018.
10 Cholli, Al; Dhawan, A; Kumar, V, **US7323511B2**, *UMass Lowell*, Jan. 29, 2008.
11 Yamamoto, R; Kobayashi, T; Hayashi, H, **US20160009895A1**, *Kuraray Co Ltd,* Jan. 14, 2016.

5.56 PVB (POLY(VINYL BUTYRATE))

Plasticized poly(vinyl butyral) is used as an adhesive layer of safety glasses.[1] This PVB film must be colorless and possess high transparency.[1] Optical properties deteriorate by oxidation which occurs during processing and use of the polymer.[1] The solubility of phenolic and phosphorus antioxidants in plasticized poly(vinyl butyral) and in pure plasticizers at 20-60°C has been studied.[1] The solubility of antioxidants in PVB is a non-linear function of the plasticizer concentration in the polymer.[1] Antioxidants at concentrations above their solubility limit form a separate phase in polymer compositions, causing turbidity.[1]

Songnox 4425 is a cresol-based antioxidant, which is highly effective in polyamides, polyesters, PVB safety glass laminate, high-impact polystyrene, ABS, and a large range of spin-finish compositions, according to Songwon.[2] A powder-form, primary antioxidant combines very low discoloration, low volatility, and high solubility.[2]

References

1 Mańn, AP; Tatarenko, LA; Shlyapnikov, YA, *Polym. Deg. Stab*., **62**, 3, 507-11, 1998.
2 *Additives Polym*., **2008**, 1, 2-3, 2008.

5.57 PVC (POLY(VINYL CHLORIDE))

Hyperbranched polyglycerol nanoparticles based multifunctional, nonmigrating hindered phenolic macromolecular antioxidants were used to stabilize poly(vinyl chloride).[1] The macromolecular antioxidants showed similar stabilizing efficiency as the tetrafunctional industrial Irganox1010 (Figure 5.41).[1] The antioxidant has an advantage over Irganox 1010 because it was low leaching in both water and hexane.[1]

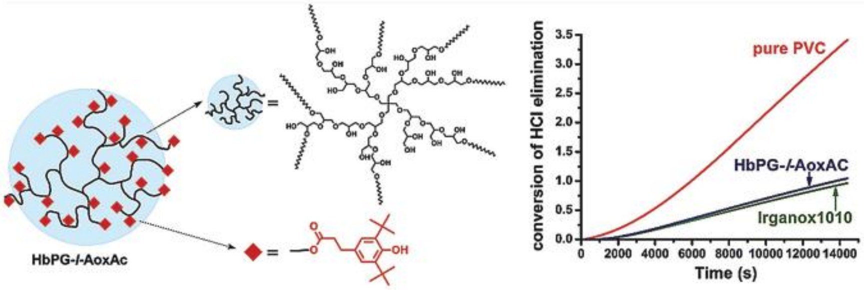


Figure 5.41. Formation and performance of hyperbranched polyglycerol nanoparticles based multifunctional, nonmigrating hindered phenolic macromolecular antioxidants in PVC. [Adapted, by permission, from Kasza, G; Stumphauser, T; Nádor, A; Osváth, Z; Iván, B, *Polymer*, **124**, 210-8, 2017.]

The extent of HCl elimination from PVC (degradation rate) decreased dramatically in the presence of all the investigated antioxidants.[1] The degradative chain scission of PVC during its thermooxidative treatment was also significantly suppressed by the macromolecular antioxidants similar to Irganox1010.[1]

Antimicrobial and antioxidant properties of poly(vinyl chloride)-based films containing 0.4% quercetin and silver nanoparticles at various concentrations levels were considerably affected, as were thermal, mechanical and optical properties of the films.[2] Films incorporated with quercetin and silver nanoparticles had increased antioxidant capacity when evaluated *via* the DPPH method.[2]

The effects of 3 different types of antioxidants; a hindered phenol, a phosphite, and a hindered amine light stabilizer on the radiation-induced crosslinking and oxidative degradation of polyvinyl chloride/epoxidized natural rubber blend with a crosslinking agent were studied.[3] The hindered phenol is an effective antioxidant for the investigated PVC/ENR blend system.[3] The Fourier transform infrared spectroscopy analysis indicated that the radiolysis products of hindered phenol at 60 kGy induced post irradiation reaction in PVC/ENR blends.[3] However, studies did not reveal the exact nature of the radiolysis product responsible.[3]

The effectiveness of phenols in the prevention of PVC degradation during thermal processing was practically independent of the chemical structure but determined by their evaporation rates.[4] The best formulations decreased the chloride ion concentration in the working zone air during PVC linoleum production by approximately three times.[4]

References

1 Kasza, G; Stumphauser, T; Nádor, A; Osváth, Z; Iván, B, *Polymer*, **124**, 210-8, 2017.
2 Braga, LR; Pérez, LM; del V. Soazo, M; Machado, F, *LWT*, **101**, 491-8, 2019.
3 Ratnam, CT; Zaman, K, *Polym. Deg. Stab*., **65**, 3, 481-90, 1999.
4 Mukmeneva, N; Gotlib, E; Verizhnikov, M; Nagumanova, G; Chakirov, R, *Polym. Deg. Stab.*, **73**, 3, 383-6, 2001.

5.58 PVP (POLY(N-VINYL PYRROLIDONE))

Nano and submicron particles of antioxidant/PVP were generated by the supercritical anti-solvent extraction process of mango leaves.[1] The encapsulation of natural extract of antioxidant was used to prevent antioxidant against the degradation of phenolic compounds and to achieve its sustained release.[1] Using different conditions of pressure (120-180 bar), temperature (35-65°C) and mass ratio (1/3-1/9), spherical particles were obtained in a submicron range between 0.11-0.59 μm.[1] Antioxidants/PVP ratio was the most significant variable influencing particle size and release rate of the mangiferin, quercetin 3-d-galactoside, and penta-O-galloyl glucose, meaning that the increase in polymer concentration resulted in higher particle size and smaller release rate.[1]

Chitosan/PVP-salicylic acid coating enhanced antioxidant enzyme activities under low storage temperature stress of Banati guava fruit, decreased $O_2^{\cdot -}$ and H_2O_2 generation, and minimized lipid peroxidation and protein oxidation.[2]

Coprecipitation of β-carotene with polyvinylpyrrolidone by supercritical assisted atomization enhanced β-carotene bioavailability and protected it against oxidation.[3] Figure 5.42 illustrates the process and some results.[3]

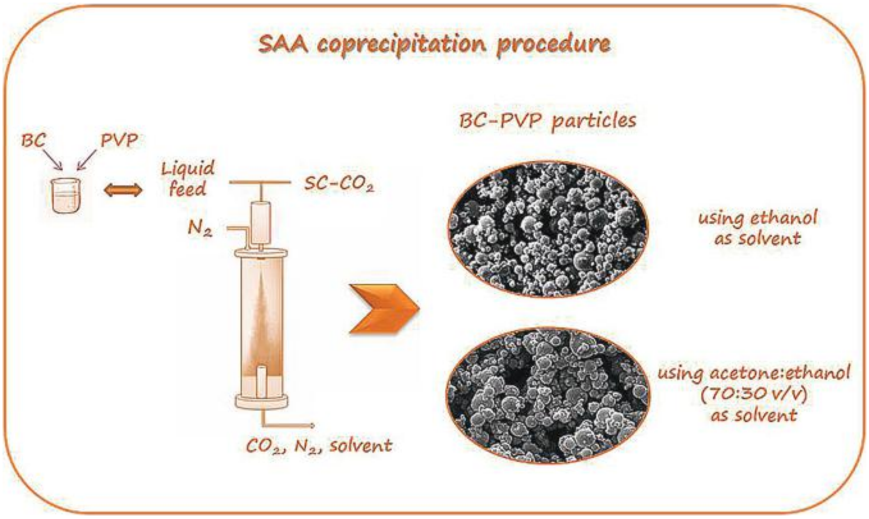


Figure 5.42. Production of β-carotene/PVP microspheres by supercritical assisted atomization. [Adapted, by permission, from Di Capua, A; Adami, R; Cosenza, E; Jalaber, V; Reverchon, E, *Powder Technol.*, **346**, 228-36, 2019.]

β-carotene was encapsulated in polyvinylpyrrolidone using the electrospinning technique to protect β-carotene from degradation and maintain its antioxidant properties.[4] The 10 wt% nanofibers composite of PVP loaded 1 wt% β-carotene gave the best antioxidant performance.[4]

PVP coated naringenin nanoparticles were synthesized and characterized.[5] Naringenin (4,5,7-trihydroxyflavanone), a natural flavonoid aglycone of naringin, is widely distributed in citrus fruits, tomatoes, cherries, grapefruit and cocoa.[5] PVP is a strong hydrophilic polymer that has been applied to improve solubility and bioavailability of poor water-soluble compounds, because it delays the crystallization of compounds by forming molecular adducts.[5] PVP coated naringenin nanoparticles have significant antioxidant and anti-inflammatory potential, without altering any biochemical and hematological parameters.[5]

Oral care composition with cross-linked polymer peroxide contains a crosslinked polyvinyl pyrrolidone-peroxide complex in which the whitening agent comprises hydrogen peroxide.[6]

References

1 Guamán-Balcázar, MC; Montes, A; Pereyra, C; Martínez de la Ossa, E, *J. Supercritical Fluids*, **143**, 294-304, 2019.
2 Lo'ay, AA; Taher, MA, *Scientia Horticulturae*, **238**, 343-9, 2018.
3 Di Capua, A; Adami, R; Cosenza, E; Jalaber, V; Reverchon, E, *Powder Technol.*, **346**, 228-36, 2019.
4 Reksamunandar, RP; Edikresnha, D; Munir, MM; Damayanti, S; Khairurrijal, *Procedia Eng.*, **170**, 19-23, 2017.
5 Kumar, RP; Abraham, A, *Chemico-Biol. Interactions*, **257**, 110-8, 2016.
6 Zaidel, LA; Pan, G;. Chopra, SK; Mandadi, P; Prencipe, M, **US9517194B2**, *Colgate Palmolive Co*, Dec. 13, 2016.

5.59 SBC (STYRENE-BUTADIENE BLOCK COPOLYMER)

The thermal and photooxidative stabilization of styrene-butadiene copolymer) with high styrene content has been studied.[1] Phosphoric acid treatment *via* reflux and zinc dithiocarbamate treatments showed the best performances, the latter was particularly effective at inhibiting the discoloration.[1] The addition of phenolic antioxidants, phosphites/phosphonites, metal deactivator, and HALS was found to stabilize the SBS against thermal and photo-oxidation.[1] In thermal oxidation, the combination of Irganox® 1010/Irgafos® 168 effectively stabilized the polymer.[1] The addition of Tinuvin® 770 to the formulation of Irgafos® 168/Irganox® 1010 had a synergistic effect.[1] The addition of polymeric HALS or Irganox® MD 1024, a metal deactivator, had an antagonistic effect on the stabilization of the polymer.[1]

References

1 Allen, NS; Barcelona, A; Edge, M; Wilkinson, A; Santa Quiteria, VR, *Polym. Deg. Stab*., **91**, 6, 1395-416, 2006.

5.60 SBR (POLY(STYRENE-CO-BUTADIENE))

The aging effects were more pronounced in a natural rubber vulcanizate since the double-bond content was much higher than in an SBR molecular chains.[1]

Mesoporous silica nanoparticles were utilized as the delivery vehicles of antioxidant 2-mercaptobenzimidazole to fabricate aging resistant styrene-butadiene rubber composites.[2] SBR composites with binary protection from mesoporous silica nanoparticles-2-mercaptobenzimidazole and free 2-mercaptobenzimidazole exhibited superior thermo-oxidative stability than the SBR composites with only free 2-mercaptobenzimidazole.[2]

Maleiyl phenylene amide polymers were prepared by the condensation of maleic acid with phenylene diamine (meta and para) in boiling o-xylene.[3] These polymers were evaluated as antioxidants in natural rubber and SBR vulcanizates.[3] The p-maleiyl phenylene amide polymer had better efficiency as an antioxidant than the m-maleiyl polymer adduct.[3] The amide polymers were better antioxidants than the commercial antioxidant phenyl β-naphthylamine.[3]

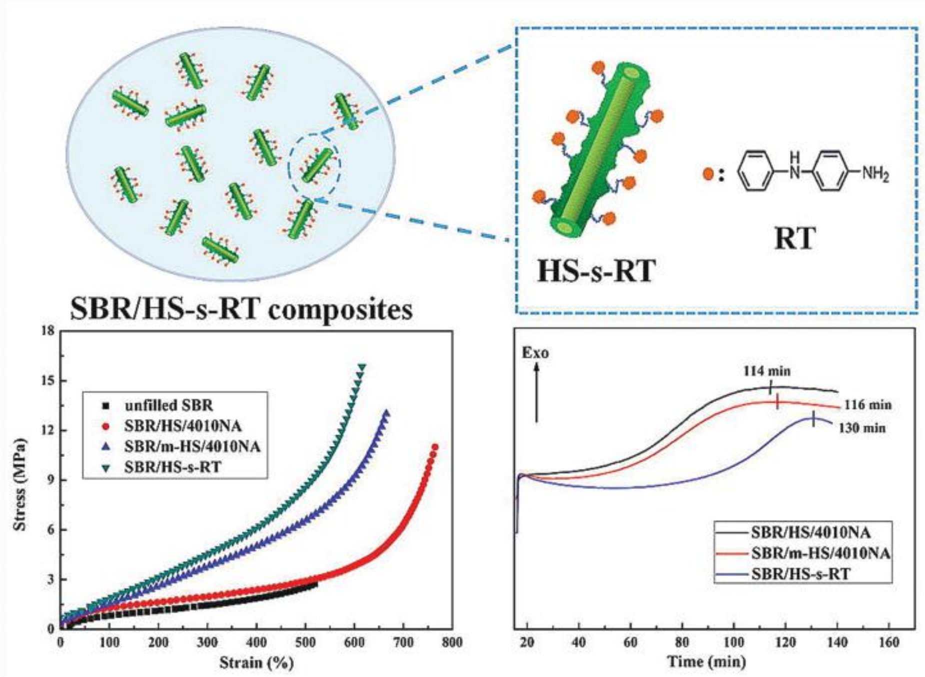


Figure 5.43. SBR composites with improved mechanical properties and antioxidative efficiency. [Adapted, by permission, from Lin, J; Luo, Y; Zhong, B; Hu, D; Jia, D, *Appl. Surf. Sci.*, **441**, 798-806, 2018.]

To improve the reinforcing efficiency of silica nanoparticles and to make the treatment procedure easy to commercialize on industrial level, antioxidant 2, 2′-methylenebis (6-tert-butyl-4-methyl-phenol) and silane were used to modify SiO_2 *via* a non-solvent-assisted process.[4] Antioxidant was chemically grafted onto the surface of SiO_2 with silane coupling agent.[4] The grafted antioxidant performed better than free antioxidant in protecting rubber from thermo-oxidative aging due to the elimination of the so-called "blooming" defects.[4]

Polyaniline was prepared by the chemical oxidation of aniline using potassium persulfate as an initiator.[5] The polymer was evaluated as an antioxidant and antirad in SBR.[5] The rubber vulcanizates were subjected to γ radiation from cobalt 60, and polyaniline showed high performance in protecting SBR vulcanizates against oxidative and radiation deterioration compared with a commercial agent (phenyl-β-naphthyl amine).[5]

Antioxidant intermediate (p-aminodiphenylamine) was grafted onto the surface of halloysite nanotubes/silica hybrid *via* the linkage of silane coupling agent and used for protection of styrene-butadiene composites.[6] The measurement of oxidation induction time showed that hybrid antioxidant effectively improved the aging durability of SBR composites, and it performed much better than corresponding low molecular-weight antioxidant N-isopropyl-N′-phenyl-4-phenylenediamine.[6] The superior antioxidative efficiency was attributed to the uniform dispersion and excellent migration resistance.[6] Figure 5.43 illustrates the structure and effect of hybrid antioxidant.[6]

Preparation of elastomer/graphene composites with high aging resistance and thermal conductivity is of great significance for constructing many advanced materials, such as solar cells and light emitting diodes.[7] An efficient one-step approach was developed to simultaneously reduce and functionalize graphene oxide by N-1,3-dimethylbutyl-N′-phenyl-p-phenylenediamine (antioxidant 4020).[7] The oxygen-containing groups in graphene oxide were effectively removed, and sp^2 carbon network was restored after reduction, and antioxidant molecules (~10 wt%) were chemically immobilized on the surface of reduced graphene oxide (Figure 5.44).[7] Consequently, SBR composites exhibited exceptionally high long-term thermo-oxidative aging resistance.[7]

Figure 5.44. Schematic of reduction and functionalization of graphene oxide by antioxidant. [Adapted, by permission, from Zhong, B; Dong, H; Luo, Y; Zhang, D; Liu, F, *Composites Sci. Technol.*, **151**, 156-63, 2017.]

Blooming of antioxidants was reduced, and aging-resistance of styrene-butadiene rubber was improved by using carbon nanotubes loaded with antioxidant N-(1,3-dimethyl) butyl-N′-phenyl-p-phenylenediamine as filler.[8] The sustained release of antioxidant from carbon nanotubes extended its action time.[8] The concentration of 2 wt% of antioxidant/carbon nanotubes was sufficient to eliminate blooming.[8] A fifteen-day thermal-oxidative aging test at 100°C showed preservation of mechanical properties, and a twenty-four-hour ozone aging test showed no cracks.[8]

The antioxidant effects of iminostilbene, phenothiazine, diphenylamine, three substituted diphenylamines and their mixtures with commercial product N-(1,3-dimethylbutyl)-N′-phenyl-benzene-1,4-diamine in thermal oxidation of styrene–butadiene rubber were examined by non-isothermal DSC measurements.[9] Among the individual compounds, the highest antioxidant performance in the stability of SBR was observed for iminostilbene.[9] In the case of mixtures, the best stabilizing properties were assigned to the mixture of N-(1,3-dimethyl-butyl)-N′-phenyl-benzene-1,4-diamine with 4-phenylamino phenol.[9]

Antidegradant agents have been used to protect rubber mixtures used in tires against aging due to oxidation when they were in contact with air.[10] Para-phenylenediamine was used as an antioxidant and lanthanide acetylacetonate such as a neodymium acetylacetonate as additive, which makes it possible to advantageously reduce the consumption of antioxidant during the thermal oxidizing aging of the composition[10].

References

1 Osswald, K; Reincke, K; Schossig, M; Sökmen, S; Langer, B, *Polym. Testing.*, **79**, 106053, 2019.
2 Hu, D; Luo, Y; Chen, Y; Lin, J; Jia, D, *Polym. Deg. Stab.*, in press, 108987, 2019.
3 El-Ghaffar, MAA; El-Nashar, DE; Youssef, EAM, *Polym. Deg. Stab.*, **82**, 1, 47-57, 2003.
4 Zhong, B; Zeng, Z; Chen, W; Luo, Q; Jia, D, *Polym. Testing*, **78**, 105949, 2019.
5 Ismail, MN; Ibrahim, MS; El-Ghaffar, MAA, *Polym. Deg. Stab.*, **62**, 2, 337-41, 1998.
6 Lin, J; Luo, Y; Zhong, B; Hu, D; Jia, D, *Appl. Surf. Sci.*, **441**, 798-806, 2018.
7 Zhong, B; Dong, H; Luo, Y; Zhang, D; Liu, F, *Composites Sci. Technol.*, **151**, 156-63, 2017.
8 Fu, Y; Yang, C; Lvov, YM; Zhang, L; Wang, W, *Chem. Eng. J.*, **328**, 536-45, 2017.
9 Černá, A; Cibulková, Z; Šimon, P; Uhlár, J; Lehocký, P, *Polym. Deg. Stab.*, **97**, 9, 1724-9, 2012.
10 Salgues, N; Cabioch, J-L; Makiuchi, K, **US20130030097A1**, *Compagnie Generale des Etablissements Michelin SCA*, Jan. 31, 2013.

5.61 SBS (STYRENE-BUTADIENE-STYRENE TRIBLOCK COPOLYMER)

The aging properties of base asphalt and styrene-butadiene-styrene triblock copolymer modified asphalts were evaluated.[1] Zinc dialkyldithiophosphate and zinc dibutyldithiocarbamate as antioxidants can retard the oxidation of the modified asphalts through inhibition of peroxides and radical scavenging.[1]

Oxidation of SBS occurs mainly in butadiene blocks.[2] It is a self-catalyzed reaction containing four steps.[2] The first step is the initiation of a chain by a free radical.[2] The second is the growth and decomposition of the polymer chain.[2] The third is the formation of anhydride from dehydrated carbonyl.[2] The fourth is the annihilation of active centers.[2] Antioxidant, which provides H atom, can easily annihilate active free radicals and protect SBS from thermal oxidation at a lower temperature.[2]

Vitamin E, Irganox 1010, Irgafos P-EPQ, carbon black, hydrated lime, and DLTDP/furfural, were evaluated for their effect on inhibition of hardening of asphalt binders, such as SBS.[3] Binders modified with a combination of furfural and DLTDP were found to posses the lowest aging index.[3] The antioxidant-treated binders exhibited improved performance at both high and low pavement temperatures.[3]

Oil-extended, low styrene content styrene-butadiene-styrene triblock copolymer compositions and articles have been stabilized by use of antioxidants.[4] The most suitable antioxidants include 2,4-bis-(n-octylthio)-6-(4-hydroxy-3,5-di-tertiary-butylanilino)-1,3,5-triazine (IRGANOX™ 565), tetrakis-ethylene-(3,5-di-tertiary-butyl-4-hydroxy-hydrocinnamate)methane (IRGANOX™ 1010), and tris(2,4-di-tert-butylphenyl)phosphite (IRGAPHOS™ 168).[4] Other suitable antioxidants include those developed to minimize butadiene segment degradation, e.g., 2[l-(2-hydroxy-3,5-di-terpentylphenyl) ethyl)] -4,6-di-tert-pentylphenylacrylate (SUMILIZER™ GS) and pentaerythrythyltetrakis(3- dodecylthiopropionate) (SUMILIZER™ T-PD).[4]

Elastic film formulations based on a blend of two styrene block copolymers, namely, styrene-isoprene/butadiene-styrene and styrene-butadiene-styrene.[5] Primary antioxidants scavenge alkoxy radicals and peroxy radicals.[5] Many primary antioxidants that are compatible with styrenic block copolymers may be incorporated into the compositions of the present invention.[5] Primary antioxidants sold under the trade name, Irganox from BASF may be suitable, such as 1010, 1076, and 1330.[5] Secondary antioxidants may also be used along with the primary antioxidants.[5] Secondary antioxidants are typically phosphites and thiosynergists.[5] Secondary antioxidants scavenge hydroperoxides which are generated during the autoxidation cycle of a polymer exposed to heat and oxygen.[5] Various compositions sold under the trade name, Irgafos, may be suitable and are likewise manufactured by BASF.[5] Irgafos 168 and the like may be suitable for the present invention.[5]

References

1 Ouyang, C; Wang, S; Zhang, Y; Zhang, Y, *Polym. Deg. Stab*., **91**, 4, 795-804, 2006.
2 Xu, J; Zhang, A; Zhou, T; Cao, X; Xie, Z, *Polym. Deg. Stab*., **92**, 9, 1682-91, 2007.
3 Apeagyei, AK, *Construction Building Mater*., **25**, 1, 47-53, 2011.
4 Uzee, AJ, **WO2008109245A1**, *Dow Global Technologies Inc*., Feb. 18, 2008.
5 Wright, KJ, Thomas, OP, **US8980994B2**, *Kimberly Clark Worldwide Inc., PolyOne Corp*, Mar. 17, 2015.

5.62 SEBS (STYRENE-ETHYLENE-BUTYLENE-STYRENE TRIBLOCK COPOLYMER)

The photooxidation of hydrogenated poly[styrene-b-butadiene-b-styrene] or poly[styrene-b-(ethylene-co-butylene)-b-styrene] has been studied.[1] Rates of photooxidation measured by carbonyl growth, and discoloration showed that low molecular weight samples were more photostable than those with high molecular weight.[1] Oxidation primarily occurred in the aliphatic part with a predominant absorption associated with terminal carboxylic acid groups at 1712 cm^{-1}.[1] Anhydrides, ketones, aldehydes, esters and α,β-unsaturated carbonyl species were also formed in this matrix.[1] End-group oxidation was a predominant process at the interphase boundary of the soft aliphatic and hard aromatic segments with the immediate autocatalytic formation of high concentrations of primary hydroperoxides during the early stages of oxidation.[1] These species were unstable and were breaking down rapidly, leaving a steady-state concentration of more stable hydroperoxides.[1] Phenolic antioxidants and phosphites exhibited a synergistic effect in inhibiting the discoloration and oxidation processes.[1]

A detailed analysis of the chemiluminescence emission from poly(styrene-b-ethylene-co-butylene-b-styrene) was carried out.[2] A phenol-phosphite stabilization system based on Irgafos 168 and Irganox 1330, was studied.[2] The chemiluminescence emission decay rate correlates well with the amount of the phosphite, Irgafos 168, and confirms the activity of this stabilizer as a radical chain-breaking antioxidant in these copolymers.[2]

References

1 Allen, NS; Luengo, C; Edge, M; Wilkinson, A; Santa Quiteria, VR, *J. Photochem. Photobiol. A: Chem.*, **162**, 1, 41-51, 2004.

2 Peinado, C; Corrales, T; García-Casas, MJ; Catalina, F; Parellada, MD, *Polym. Deg. Stab.*, **91**, 4, 862-74, 2006.

5.63 SIS (STYRENE-ISOPRENE-STYRENE BLOCK COPOLYMER)

A series of epoxidized styrene-isoprene-styrene (SIS) copolymer was obtained with *in situ* epoxidation.[1] Hotmelt pressure-sensitive adhesives were made with the addition of mineral oil and antioxidant (Irganox 101, 1 wt%).[1]

Hydrophile adhesive for medical applications (protective bandages, in particular for treating blisters, skin-deep dermo-epidermic lesions, exudative wounds, and burns) contained poly(styrene/isoprene/styrene), tackifier resin, acrylate polymer with a glass transition temperature less than -20°C, plasticizing oil, hydrocolloid, and antioxidant (combination of phenolic antioxidant (Irganox 1012, 565, or 1076) and zinc dibutyldithiocarbamate).[2]

References

1 Wang, Q; Wang, Y-z; Zhao, Z-f; Fang, B, *Int. J. Adhesion Adhesives*, **34**, 62-7, 2012.
2 Auguste, S; Apert, L, **US6051748A**, *Laboratorires d'Hygiene et de Dietetique Laboratoires Urgo Sas*, Apr. 18, 2000.

5.64 ST (STARCH)

Starch is intrinsically lacking antioxidant and antimicrobial activities.[1] Plant extracts and essential oils are a natural source of antioxidant and antibacterial compounds which can be used to improve the functional properties of starch polymers.[1] Functional and physical properties of corn, oat, and wheat starch emulsions enriched with polysorbate-Zataria essential oil were investigated.[1] Polysorbate-ZEO and starches containing polysorbate-Zataria essential oil exhibited antimicrobial and antioxidant activities.[1]

Carvacrol was encapsulated in nanofibers from soluble potato starch.[2] The carvacrol-loaded nanofibers showed homogeneous morphology, and average diameters ranging from 73 to 95 nm.[2] The carvacrol encapsulated in the nanofibers had greater thermal stability than the free carvacrol.[2] The 40% carvacrol-loaded nanofibers exhibited higher antioxidant activity with 83.1% of inhibition.[2]

Rosemary extract was incorporated into starch-glycerol films in different concentrations (2.5, 5, and 10 wt%).[3] Starch nanocomposites were obtained by the incorporation of rosemary nanoparticles.[3] Rosemary polyphenols incorporated in the films were released to hydrophilic, lipophilic, and acidic simulants in less than 240 min, and similar antioxidant activity was achieved in all the media.[3] The observed fast release of polyphenols was promoted by solubility, swelling, and the absence of interactions between polyphenols and starch.[3]

The physical properties of Job's tears starch films incorporated with clove bud essential oil (0.25-0.75%) and their antioxidant effects on pork belly during storage were investigated.[4] Pork belly packaged with the Job's tears starch film containing 0.5% clove bud essential oil exhibited a lower degree of lipid oxidation determined by peroxide and thiobarbituric acid reactive substances value measurement than non-packaged sample during storage.[4]

Several starch derivatives bearing urea groups based on 6-O-chloroacetylated starch were synthesized.[5] The antioxidant activity of starch derivatives was tested by superoxide-radical scavenging and hydroxyl-radical scavenging assays.[5] The products bearing urea groups showed an excellent antioxidant activity.[5]

The microstructure of cooked gluten-free pasta depends on the ingredients used, and this microstructure affects the starch hydrolysis, the release of phenolic compounds, and their antioxidant capacity.[6] Pasta with the highest content of unripe plantain and chickpea presented the lowest release of phenolic compounds (≈60%).[6] Pasta containing blue maize flour showed a significant increase of phenolic compounds and antioxidant capacity during the digestion phase.[6]

Starch films containing eugenol, which was added to the film-forming dispersion in free form or encapsulated with different wall materials (whey protein or lecithin), were obtained by casting.[7] Encapsulated eugenol modified the film microstructure, yielding less stretchable films with reduced water affinity, transparency, and oxygen permeability as compared to the films formulated with non-encapsulated eugenol.[7] The addition of eugenol microcapsules containing oleic acid promoted the eugenol retention in the starch matrix during film formation.[7] These films exhibited the greatest antioxidant activity.[7] Films developed with encapsulated eugenol powder containing lecithin and oleic acid were highly effective at preventing sunflower oil oxidation even throughout 53 days of storage at 30°C, maintaining low and almost constant values of peroxide index, conjugated dienes and trienes in comparison with the control samples.[7]

Edible films from chitosan containing various amounts of acorn starch and eugenol were developed by casting, and solvent-evaporation method and their physico-chemical, barrier, antimicrobial, antioxidant, and structural properties were also investigated.[8] Figure 5.45 illustrates the composition and properties of edible films.[8]

Figure 5.45. Edible films. [Adapted, by permission, from Zheng, K; Xiao, S; Li, W; Wang, W; Qin, C, *Int. J. Biol. Macromol.*, **135**, 344-52, 2019.]

References

1 Shahrokh, Z; Kavoosi, G; Shakeri, R, *Bioactive Carbohydrates Dietary Fibre*, **19**, 100193, 2019.

2 Martins Fonseca, L; dos Santos Cruxen, CE; Pinheiro Bruni, G; Fiorentini, AM; Guerra Dias, AR, *Int. J. Biol. Macromol.*, **139**, 1182-90, 2019.

3 Estevez-Areco, S; Guz, L; Famá, L; Candal, R; Goyanes, S, *Food Hydrocolloids*, **96**, 518-28, 2019.

4 Kang, J-H; Song, KB, *LWT*, **111**, 711-8, 2019.

5 Zhang, J; Mi, Y; Sun, X; Chen, Y; Guo, Z, *Int. J. Biol. Macromol.*, in press, 2019.

6 Camelo-Méndez, GA; Agama-Acevedo, E; Rosell, CM; de J. Perea-Flores, M; Bello-Pérez, CA, *Food Chem.*, **263**, 201-7, 2018.

7 Talón, E; Vargas, M; Chiralt, A; González-Martínez, C, *LWT*, **113**, 108290, 2019.

8 Zheng, K; Xiao, S; Li, W; Wang, W; Qin, C, *Int. J. Biol. Macromol.*, **135**, 344-52, 2019.

5.65 UHMWPE (ULTRAHIGH MOLECULAR WEIGHT POLYETHYLENE)

Ultrahigh molecular weight polyethylene has been known as the material of choice for bearing components in joint arthroplasty.[1] Oxidation wear of UHMWPE components is considered to be a major drawback limiting the lifespan of implants.[1] Vitamin E was considered as a promising antioxidant to prevent long-term oxidation and reduce the wear degradation of UHMWPE material.[1] Incorporation of 0.5-3 wt% carbon nanoparticles: multiwalled carbon nanotubes, graphene oxide, and nanodiamonds on the mechanical and thermal properties of UHMWPE blended with vitamin E have been evaluated.[1] Addition of multiwalled carbon nanotubes, graphene oxide, and nanodiamonds improved the thermal stability of the nanocomposites compared to neat UHMWPE.[1]

Medical grade UHMWPE was blended with 1.1, 2.3 and 11 mmol/l of vitamin E and consolidated by compression molding, and then electron-beam irradiated at 30, 60 and 90 kGy, both in a vacuum and in air.[2] The reaction between vitamin E and macro-alkyl radicals or with peroxy radicals has been demonstrated and a correlation between the decrease of macroradicals and the stabilization effect of vitamin E has been shown.[2] In the presence of vitamin E, there was a decrease in the crosslinking efficiency, and a preservation of the material from oxidation and chain scission responsible for failures of the prosthetic implants.[2]

Crosslinking reduced UHMWPE wear but combined with post-irradiation melting, it reduced its fatigue strength, therefore limiting its use in high-stress applications.[3] Lipophilic antioxidant (α-tocopherol) can protect UHMWPE against oxidation, eliminating the need for post-irradiation melting of crosslinked UHMWPE, improving its fatigue strength.[3] The increase in oxidative stability of α-tocopherol-doped UHMWPE was attributed to the ability of α-tocopherol to react with peroxy free radicals on lipid chains, preventing oxidation reactions.[3]

The fate of vitamin E and the formation and identification of its transformation products were investigated at different stages of the manufacturing process of commercially produced crosslinked (by γ-irradiation) UHMWPE stabilized with vitamin E (vitamin E infused-post irradiation) used for tibia-components (as articulating surfaces) in total knee arthroplasty (total knee replacement).[4] A number of vitamin E transformation products were formed at different concentrations at two selected stages of the implant manufacturing process that is before and after sterilization by γ-irradiation.[4] Most of the observed products were of dimeric and trimeric nature.[4] Two tocopherol-derived aldehydes (aldehyde 5-formyl-γ-tocopherol and aldehyde 7-formyl-γ-tocopherol) were also formed but at very low concentrations.[4]

Natural polyphenols were effective in protecting highly crosslinked UHMWPE from oxidation.[5] The presence of antioxidants, including natural polyphenols, effectively postponed and reduced oxidation of the squalene-doped irradiated UHMWPE.[5]

The effects of α-tocopherol on residual free radicals in ultra-high molecular weight polyethylene have been investigated.[6] α-Tocopherol was more effective in reducing residual radicals when irradiation was performed in the air as compared to a nitrogen environment.[6] The total amount of residual radicals depended on the average crystallite size.[6] The heat involved during vitamin E diffusion was responsible for the decay of ~98% of the primary trapped radicals.[7]

Radiation crosslinking has been used to decrease wear through decreased plastic deformation; but crosslinking also reduced mechanical properties including fatigue resistance, a major factor limiting the longevity of joint implants.[8] The antioxidant vitamin E reduced crosslinking efficiency in UHMWPE during irradiation with increasing concentration.[8] Spatial control of the crosslink density distribution was achieved by controlling the vitamin E concentration profile.[8] Surface crosslinking UHMWPE prepared using this approach gave high wear resistance and decreased crosslinking in bulk resulting in high fatigue crack propagation resistance.[8]

An antioxidant (tocopherol) was combined with UHMWPE prior to subjecting the UHMWPE to crosslinking irradiation.[9] Antioxidant stabilized crosslinked ultra-high molecular weight polyethylene for medical device applications.[9]

Antioxidant doping of crosslinked polymers was used to form non-eluting bearing components.[10] The process includes the following steps: (a) providing a preform; (b) irradiating the preform with γ-irradiation to crosslink the UHMWPE; (c) doping the crosslinked preform by exposing it to an antioxidant composition at a temperature below the melting point of the UHMWPE; (d) removing the doped material from contact with the antioxidant composition; and then (e) annealing by heating the doped material at a temperature above 30°C and below the melting point of the UHMWPE; followed by (f) making an implant bearing component from the doped material, wherein at least 1 mm but no more than about 15 mm of material are removed to make the component.[10]

Synergistic effects of blending multiple additives in UHMWPE was achieved using phenolic antioxidants and hindered amines, and the second additive is selected from the group consisting of phosphorous additives, polyhydric alcohols, phenolic antioxidants, hindered amines, carotenoids, amino-acid-based additives, thiosynergists, and acid antioxidants.[11] An example includes α-tocopherol and curcumin.[11]

References

1 Melk, L; Emami, N, *Composites Part B: Eng.*, **146**, 20-7, 2018.
2 Costa, L; Carpentieri, I; Bracco, P, *Polym. Deg. Stab.*, **94**, 9, 1542-7, 2009.
3 Oral, E; Wannomae, KK; Hawkins, N; Harris, WH; Muratoglu, OK, *Biomaterials*, **25**, 24, 5515-22, 2004.
4 Doudin, K; Al-Malaika, S, *Polym. Deg. Stab.*, **125**, 59-75, 2016.
5 Shen, J; Liu, X; Fu, J, *Polym. Deg. Stab.*, **110**, 113-20, 2014.
6 Mehmood, MS; Yasin, T; Jahan, MS; Mishra, SR; Ikram, M, *Polym. Deg. Stab.*, **98**, 6, 1256-63, 2013.
7 Mehmood, MS; Walters, BM; Yasin, T; Ahmad, M; Ikram, M, *Eur. Polym. J.*, **53**, 13-21, 2014.
8 Oral, E; Ghali, BW; Rowell, SL; Micheli, BR; Muratoglu, OK, *Biomaterials*, **31**, 27, 7051-60, 2010.
9 Rufner, A; Knight, J; Rowe, T; Pletcher, D; Gsell, R; Brinkerhuff, HE; Schneider, W, **US20080319137A1**, *Zimmer Inc*, Dec. 25, 2008.
10 Schroeder, DW; Freedman, JH, **US8641959B2**, *Biomet Manufacturing LLC*, Feb. 4, 2014.
11 MorrisonML; Pawar, VD; Brunner, L; Jani, SC, **US20140213683A1**, *Smith and Nephew Inc,* Oct. 13, 2015.

5.66 XG (XANTHAN GUM)

Xanthan gum with 1 g L^{-1} furfural showed the best hydroxyl scavenging effects.[1] Xanthan possesses a protective effect against hydroxyl radicals, which is the most harmful reactive oxygen species to biological tissues.[1] The addition of furfural reduced acetyl contents, but increased pyruvate and glucuronic acid contents increased first and then decreased with increasing furfural concentration.[1]

Xanthan gum-shellac nanoparticles were fabricated using antisolvent method.[2] Xanthan gum increased stability of shellac nanoparticles at gastric pH.[2] Cinnamon bark extract containing polyphenols was encapsulated.[2] The bioparticles fortified with cinnamon extract exhibited antioxidant activity and ferric-reducing antioxidant power at the level of 185 mg tannic acid equivalent and of 127 mM ascorbic acid equivalent per gram dry weight of nanoparticles, respectively.[2] From the release study, it was shown that more than 90% of cinnamon polyphenol was released at the intestinal pH.[2]

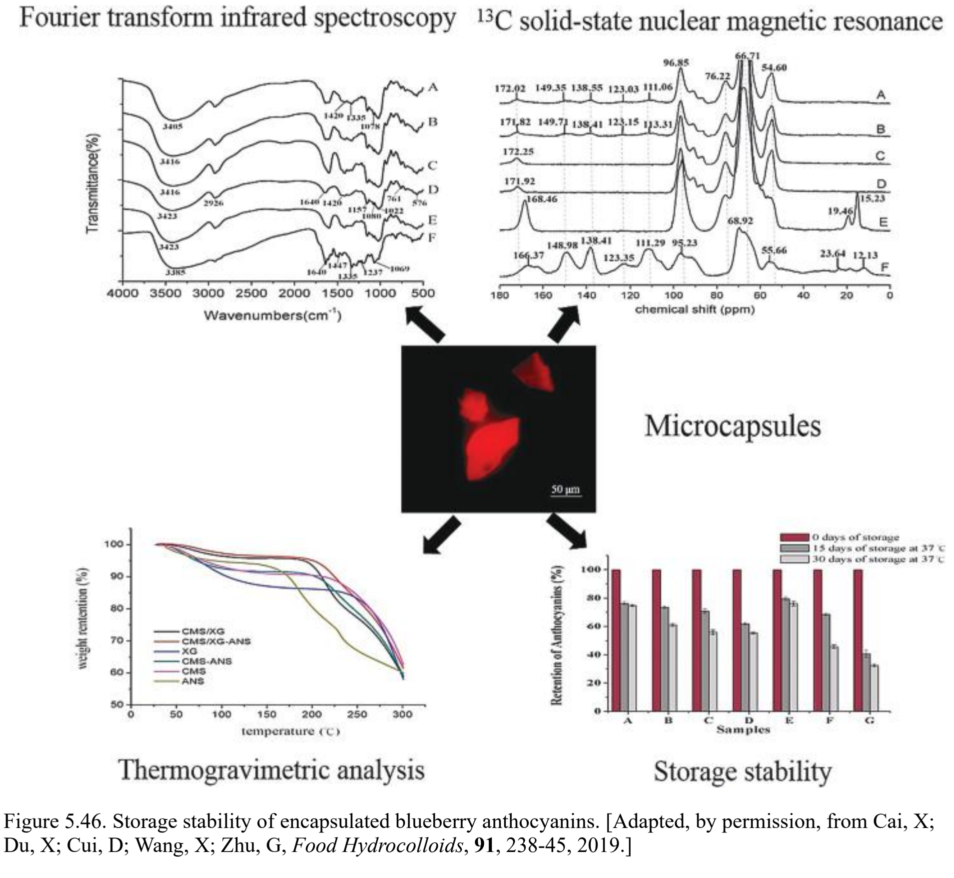


Figure 5.46. Storage stability of encapsulated blueberry anthocyanins. [Adapted, by permission, from Cai, X; Du, X; Cui, D; Wang, X; Zhu, G, *Food Hydrocolloids*, **91**, 238-45, 2019.]

Carboxymethyl starch/xanthan gum combinations microencapsulation had high encapsulation efficiency and thermal stability.[3] Anthocyanin retained 76.11% after the storage (30 d, 37°C) by the microcapsules.[3] Figure 5.46 shows microcapsules and data characterizing storage stability of encapsulated blueberry anthocyanins.[3]

Tea polyphenols are antioxidants with beneficial effects but low oral bioavailability.[4] Debranched corn starch with xanthan gum was used as a carrier for sustained release.[4] Microcapsules with 34% debranching degree presented suitable preparation performance.[4]

References

1 Kang, Y; Li, P; Zeng, X' Chen, X; Xie, T, *Carbohydrate Polym*., **216**, 369-75, 2019.

2 Muhammad, DRA; Doost, MA; Gupta, V; bin Sintang, MD; Dewettinck, K, Food *Hydrocolloids*, **100**, 105377, 2020.

3 Cai, X; Du, X; Cui, D; Wang, X; Zhu, G, *Food Hydrocolloids*, **91**, 238-45, 2019.

4 Hong, Y; Yang, J; Liu, W; Gu, Z; Duan, X, *LWT*, **103**, 325-32, 2019.

INDEX

Numerics

1,1-diphenyl-2-picrylhydrazyl assay 150
1,4-diphenoxybenzene radical 160
2,2,6,6-tetramethylpiperidine 143
2,2-diphenyl-1-picrylhydrazyl scavenging assay 111
2,3-diketo-gulonic acid 46
2,4-di-tert-butylphenol 161, 164
2-mercaptobenzimidazole 62, 203
3,4-diethyl-3,4-diphenyl hexane 138
3,5-di-tert-butyl-4-hydroxycinnamic acid 178
4,5-di-O-caffeoylquinate 134

A

abiotic
  stress 94-95
    tolerance 96
  stressor 94
ABTS$^+$ scavenging activity 110
accelerated
  aging test 143
  wound healing 155
accumulation mechanism 96
acetic acid 54
acid acceptor 120
acrylamide 64
  formation 64
acrylic polyurethane coating 192
acrylonitrile-butadiene rubber 145-146
acrylonitrile-butadiene-styrene 107
activation energy 89, 130, 147-148
active
  biocomposite film 140
  center 206
  edible film 115
  food packaging 141, 143, 161
  free radical 206
  packaging 111, 124, 132, 148, 161, 166, 174, 194
    film 131
adhesion 128
adhesive composition 123
aerial exposure 98
aerobic
  organism 58
  radical 74
aging
  durability 204
  effect 203
  index 206
  phenomena 99
  properties 206
  protection 145
  resistance 204
  stability 130
aglycones isoflavone 67
air
  drying 108
  plasma 159
aircraft 172
alcalase 70
aldehyde quenching 71
alkoxy radical 89, 107
alkyd resin 108
alkyl
  chain length 76
  radical 136
    scavenger 73
allelopathy 60
allergenic effect 118
almond oil 84
Alzheimer's disease 70, 80, 100, 102, 123
amide bond formation 178
amino acid content 184
aminosilane coupling 178
  agent 140
amyloid beta peptide 102
amyloidogenesis 70
anchoring site 190
aneuploid immortal keratinocyte cell 104
anhydride maleic grafted polypropylene 178
aniline pentamer 190
animal 98
  fat 84
anion structure 78

anionic curcumin 54
anisaldehyde 69
annatto 113
anoxia 98
anserine 70
antagonistic effect 202
Antarctic fish 97
anthocyanidine 44
anthocyanin 44, 134
  content 112
antiapoptotic 44
antiatherosclerotic effect 66
antibacterial activity 195
anticancer
  agent 112
  properties 166
  therapy 60
anti-fibrotic 44
anti-fouling coating 182
antifungal activity 166
anti-inflammatory 44, 76
antimicrobial activity 132
antioxidant 37, 89, 91, 101, 160
  acid chloride 110
  activity 40, 43, 45-46, 48, 52, 55, 57, 59, 65, 67, 77-78, 80, 82, 101, 113-114, 118, 132, 134, 143, 150, 155-156, 161, 166, 168, 174, 181, 183-184, 187, 190, 195, 209
  algae extract 174, 194
  assay 59
  blooming 145, 190
  capacity 61, 112, 124, 132, 189
  concentration 130
    profile 164
  consumption 148
  content 177
  defense
    pathway 102
    system 98
  depletion 137, 152
    thickness 137
  diffusivity 85
  effect 148, 153, 166, 171, 205
  effectiveness 42
  efficacy 63, 66, 181
  efficiency 132, 178
  enzymatic activity 93
  enzyme 58, 89, 181, 195
    activity 95, 200
  functionalized graphene 141
  grafted graphene oxide 173
  hydroperoxide 40
  mechanism 173
  molecule 157
  package 128
  pathway 80
  performance 82
  polymer 133, 196
  potency 77
  potential 155
  properties 90, 183
  reactivity 40
antioxidative
  activity 65, 74
  defense system 58
  function 70
  mechanism 62
antiozonant 122
antiproliferative activity 40
antipsychotic treatment 69
antiradical capacity 44, 148
antiscorching agent 145
antiseptic 81
antisolvent
  extraction process 200
  method 213
antitumor properties 156
apigenin 59, 116
apolipoprotein 123
apoptosis 45, 104
apoptotic death 44
aquaculture 97
aquatic environment 96
arjunolic acid 101
aromatic amine 42
articulating surface 211
ascorbate 45, 66, 90
  concentration 66
  peroxidase 93, 194
  radical 45
ascorbic acid 45-46, 64,84, 90, 100, 111, 116, 132, 150, 195, 213
  antioxidant mechanism 45
  content 113

  derivative 158
  synthesis 45
ascorbyl
  free radical 46
  palmitate 45-46
  6-palmitate 46
asparagine 64
asparagus 84
asphalt 206
  binder 206
astaxanthin 124
asthma pathogenesis 100
atheroma 76
atherosclerosis 66, 76
autocatalytic formation 207
autoclave heating 178
autooxidation 42, 64, 82, 108
  cycle 206
  kinetics 131
  reaction 160
autophagosome 97
avocado treatment 115
azanorbornenes 188
azide group 157

B

bacterial
  adhesion 190
    ability 190
  cellulose 110
  deterioration 134
  growth 85
baking varnish 108
bark extract 192
barrier
  effect 173
  performance 174
  properties 183
bearing 122
  component 211
benzimidazole 50
benzofuranone 48-49
  compound 48
  mechanism of action 48
benzofuranyl radical 48
benzoic acid 85
benzoquinone 51
  imine 42
bilayer film 175
bioaccumulation 96
bioactive glass particles 155
bioactivity 155
bioavailability 76, 109, 200
biochar 95
biocompatibility 85, 134, 189
biocomposite 166
biodegradability 183
biodegradable
  active film 176
  biopolymer 115
biodiesel
  commercialization 64
  fuel 42
  stabilization 43
bioenergetic
  function 52
  status 52
biofilm 190
  formation 124
biological
  antioxidant 86
  damage 59
  source 51
  tissue 213
biomedical
  material 176
  product 118
bionanocomposite 166
biopeptide 70
biophoton emission 100
bioplastic 175-176
biosynthetic pathway 45
bis-(2,4-dicumylphenyl) pentaerythritol diphosphite 107
bisphenol exposure level 101
blend 120, 146
blindness 65
blooming 145, 148, 204
  defect 204
  effect 62
blueberry anthocyanins 213
bond dissociation
  energy 54
  enthalpy 38, 42, 59, 65

bone
  disease 134
  implant 134
bovine casein 70
brain 98, 100
  cell 102
bridge 122
browning 134
buffalo casein 70
building 122
burst release 174
butylhydroxy anisole 135
butylated
  hydroxy anisole 64, 85, 135, 174
  hydroxytoluene 64, 85, 108, 121, 174

C

cable
  covering 182
  insulation 130
  insulator 130
caffeic acid 38-39, 115, 128, 135, 167
caffeine 69
calcitriol 100
cancer 61, 67, 80, 98
  cell 60
  development 103
  risk 45
carbodiimide 173
carbon
  black 164
  dioxide fixation 95
  dot 150
  nanotube 145, 160, 173, 204
carbonyl
  formation 137
  index 140
carboxymethyl
  cellulose 115
  chitosan 134
carcinogenesis
  endpoint 103
  process 103
carcinogenicity 58
cardioprotective 44
cardiovascular disease 61, 67, 76, 80, 98, 100, 190
carnosic acid 135
carnosine 70
carnosol 135
carotene 85, 107, 116, 174, 200
carotenoid 82, 83, 91
  biradical 107
carrageenan 112, 167
  type 112
carrots 84
carvacrol 176, 209
  -loaded nanofibers 209
casein phosphopeptide 70
castor oil 191
catalase 58, 80, 89-91, 98, 100, 181, 194
  activity 97
  performance 90
catalyst deactivation 180
catalytic
  cycle 42
  inhibition 42
    chain 42
cataract 65
cataractogenic sugar xylose 65
catechin 123, 166, 168, 190
cation
  exchange capacity 95
  radical 80
cell
  component 98
  death 93
    pathway 58
  growth gene 103
  proliferation 44, 85
  shape 67
  signaling pathway 102
  stress 52
  viability 104
  volume 67
  -loaded substrate 190
cellular
  antioxidant 51, 58
  damage 80
  dysfunctions 99
  electron transfer molecule 51
  glutathione 98
  level 94
  membrane 51
  metabolism 58

  proliferation signaling 102
  reactive
    oxygen species 102, 181
    sulfur species 181
cellulose 109
  acetate 111
  membrane 117
  nanocrystal 110
  nanofiber 109
  nanowhisker 110
  nitrate 117
cerebral
  ischemia 190
  malaria 98
chain
  breaking reaction 90
  end 192
  extension 190
  mobility 143
  reaction 89-90
  scission 140, 148, 191-192, 211
  -breaking antioxidant 84, 159
chelation therapy 56
chemical
  oxidation 204
  reaction 115
  stabilizer 89
  structure 44
chemiluminescence 148
  emission 207
chilling 45
  injury 195
    symptom 195
  stress 95
chitosan 110, 113-114, 134, 141, 156, 166, 183, 194, 210
  derivative 113
  nanocomposite 141
  sodium montmorillonite clay 141
chlorine derivatives 151
chlorogenic acid 69, 76, 115
chlorophyll 83, 95
chloroplast 93
  ultrastructure 95
cholesterol 76, 98, 100
  domain formation 76
choline 65
chromaticity protection 161
chronic inflammation 100
chrysin 59
cinnamon 102
  bark extract 213
  polyphenol 213
ciprofloxacin hydrochloride 155
citral 82
citric acid 195
click chemistry 157
clinical studies 69
clove
  bud essential oil 209
  essential oil 111, 124
  oil 143, 195
coating
  composition 114
  thickness 192
cocoa 132
coconut shell lignin 177
coefficient of friction 118-119
coenzyme
  Q 65
  Q10 51
coil coating 165
cold
  exposure 97
  storage 194-195
  tolerance 97
collagen 40
  peptide 115
colloidal particle 150
colored product 131
compression molding 211
conducting polymer 183, 190
conductive nanocomposite 183
conformation 184
conformer 45
conjugated
  double bond system 108
  link 78
  polyene system 82
  triene structure 84
connective tissue 158
conservation 81
contact environment 152
controlled drug release 123

conversion 42
coplanarity 44
copper naphthenate 108
corrosion inhibitor 196
cosmetic 45
cosmetics 45
coumarin 57
covalent bond 184, 192
critical
  electron density 42
  gene 102
crop productivity 95
crosslink density 128, 143
crosslinked
  polyethylene 164
    network 165
crosslinking 72, 118, 128, 140, 163
  agent 198
  density 143
  efficiency 211
crystallinity 143, 178, 194
  degree 143
crystallite size 211
crystallizable length 140
crystallization 190
  temperature 178
cultured lenses 65
curculigoside 104
curcumin 54, 56, 65, 123, 134, 140, 157, 212
  derivative 55
  encapsulation 55
  loading capacity 55
  pyrazole 54
  structure 55
cyanoacrylate 123
cyclic
  olefin copolymer 118
  sulfide 187
cyclical regenerative process 65
cyclodextrin 110, 156
cycloolefin copolymer 85
cypermethrin 97
cytoplasm 92
cytoprotective
  effect 188
  mechanism 52
cytosol 93
cytotoxic effect 104
cytotoxicity 45, 58, 69, 100, 123

D

daidzein 66
deactivating singlet oxygen species 72
dealcoholized red wine 76
decomposition product 128
defense
  mechanism 98
  system 90, 93
degassing 180
degradation
  mechanism 189
  rate 131, 198
  temperature 137
degradative chain scission 198
dehydratase 92
dehydration 98
dehydroascorbic
  acid 46
  lactone ring 46
  palmitate 46
denaturation 55
Denisov cycle 42-43
depletion rate 153
depressurization 180
deprotonated curcumin 54
deprotonation 45
detoxifying/defensive proteins 58
dextran sulfate 157
dextrin 183
diabetes 82, 100
diarylamine 42
Diels-Alder addition 108
dietary
  exposure 96
  supplement 82
differential scanning calorimetry 171
differentiation 90
diffusion 132, 148
  coefficient 148
diffusivity 140
dihydroxy dimer 86
dilaurylthiodipropionate 133
dimerization 48
  product 48
dipeptide 70

diphenylamine 205
direct
  radical scavenger 70, 90
  scavenging 91
  transfer 80
discoloration 48, 74, 154, 192, 197, 202, 207
discrete membrane bilayer domain 76
disease progression 101
disproportionation 48
dissipative rubber 150
dissociation
  energy 171
  enthalpy 37
dissolved oxygen 81
disulfide 79
DNA
  damage 80, 91
  repair mechanism 102
  scission 70
dopant acid 150
doped lead titanate 128
dose 112
  level 75
double
  emulsion solvent evaporation technique 125
  -bond content 203
DPPH
  inhibition 143
  method 148
  radical
    scavenging
      assay 140
      capacity assay 112
drier 108
drought 45, 58, 94-95
drug delivery
  stent 116
  system 111
ductility 175
dwell time 147
dysprosium 128

E

edaravone 65
edible
  coating 115
  film 115
egg white protein nanoparticle 55
elastin 40
electric insulation 127
electrical
  conductivity 115
  insulating properties 140
  signal propagation 190
electrically
  excitable cell 190
  insulating layer 128
electroactive polyurethane 190
electrochemical cycling 183
electrohydrodynamic atomization 134
electrolyte leakage 95
electromagnetic frequency 102
electron 89
  beam
    irradiated 211
    irradiation 184
  density 55
  leakage 100
  transfer 51, 80, 82, 183
    enthalpy 37, 39
  withdrawing character 54
  -donating
    group 40
    substituent 48, 65
  -proton transfer 37
  -withdrawing group 65
electronic properties 60
electrospinning 111, 156, 200
electrospun fiber 174
  material 156
  nanofiber 111, 194
  nanofibrous membrane 195
electrostatic interactions 184
eleostearic acid 108
elevated temperature 147
ellagic acid 104
elongation at break 143
emeraldine base 150
emulsion interface 157
enamel 108
encapsulated blueberry anthocyanins 214
encapsulating material 115
encapsulation
  efficiency 109, 111, 113, 115, 124-125, 174, 214

  matrix 111
end-group oxidation 207
endogenous antioxidant system 56
endoplasmic reticulum 90
energy
  metabolism 100
  transfer 43
enol form 54
environmental
  constraints 95
  contamination 93
  pollution 96
  stress cracking 164
  toxicant 100
enzymatic
  activity 98
  antioxidant 98
  hydrolysis 71, 184
  oxidation 42
enzyme 89
  dysfunction 92
  inhibitor 40
epicatechin 76
epichlorohydrin 127
epigallocatechin gallate 64, 115
epithelial cell 91, 104, 189
epoxidized natural rubber 155
epoxy resin 127
equol 66
erythrocyte 69, 189
erythrocyte hemolysis 188
ESR spectroscopy 86
essential oil 209
ester bond 110
esterification 195
etherification 195
ethyl cellulose 124, 125
ethylenediaminetetraacetic acid 128
ethylene-propylene
  diene
    monomer 50
    terpolymer 128
  rubber 130
ethylene-vinyl acetate copolymer 131
ethylene-vinyl alcohol copolymer 132-133
ethylidene norbornene 130
eugenol 85, 111, 143, 166, 209-210
  microcapsule 209
eukaryotic cell 97
  compartment 90
excess energy dissipation 82
excessive reactive oxygen species 80
excited state 50
exogenous
  application 93
  ascorbate 2-phosphate 47
  source 103
exposure time 143, 147
external lubricant 121
extracellular space 93
extreme environmental conditions 58

F

fast release 209
fat content 85
fatigue
  crack propagation resistance 212
  resistance 212
  strength 211
fatty food 115
Fenton reaction 72, 189
ferric ion 56
ferrous ion 56
ferulic acid 38-40, 64, 132, 156
  planar structure 40
fiber 168
fibroblast 40, 85
Fick's
  behavior 174
  second law 175
film formulation 206
first-order kinetics 154
fisetin 59
fish 96
  gelatin 134
flavohemoglobin 58
flavon 130
flavonoid 59-60, 65, 82, 116, 130, 132, 155, 200
  anion 59
  prooxidant properties 61
flax fiber 137
flaxseed oil 85
flood 58
flooding 95

fluorescent emission 47
fluoride toxicity 95
foaming agent 121
folic acid 116
food 40
  industry 56
  intake 96
  oxidation process 144
  packaging 133, 140, 176, 183
  preservative 134
  processing 45
  product 66, 78, 196
  protection 174
  quality 70
  shelf-life 194
  supplement 114
  system 45
formyl species generation 116
Fourier transform infrared spectroscopy 198
  imaging 171
free
  amino acid 70
  radical 45, 54, 59, 70, 82, 85, 89, 117, 136, 191, 206
    assay 63
    chain mechanism 84
    diffusion 76
    formation 130
    generation 40, 69
    mitochondrial damage 51
    overproduction 57
    polymerization reaction 188
    scavenger 40, 69, 101
    scavenging 70
      activity 55, 188
      capacity 150
      mechanism 175
      rate 188
    source 80
    trapping 144
  volume 154
freezer storage 178
freezing exposure 98
fresh meat 111
freshwater 96
  fish 97
fried potatoes 82
fumed nanosilica 140
functional food 124
functionalized
  graphene 62
  mesoporous silica 85
furfural 206, 213

G

gadolinium 128
galangin 59
gallic acid 38-40, 76, 110, 157, 168, 190
gap-junctional communication 82
gastric
  cancer 91
  carcinogenesis 92
  pH 213
gastrointestinal fluid 114
gelatin 134
  matrix 114
gelation 133
gelling property 184
genetic mutation 92
genistein 66
geomembrane 137
geothermal environment 182
geranial 110
geranyl acetate 110
germination 84
glass transition temperature 111, 177, 208
glucosides isoflavone 67
glucuronic acid 213
glutathione 46, 58, 65, 70, 90, 150
  peroxidase 58, 89-90, 98, 100
    activity 98
glutathione S-transferase 93, 98
glycidylation 127
glycosylation 44
glyphosate 93
graftable antioxidant 73, 137, 163
grafted
  antioxidant 203
  graphene oxide 147
  hydrocarbon adduct 143
grafting efficiency 73, 137
grape 77
  juice 76
graphene oxide 62-63, 98, 173, 204, 211
  surface 147

green
  coffee seed 69
  tea extract 132, 148, 178
growth 94
  capacity 94
  habit 94
  reduction 95
  regulator 95
guava 82
  fruit 200
gum arabic 111

H

halloysite nanotube 148, 204
hardening process 108
hardness 143
harmful reactive oxygen species 213
haze 154
HCl elimination 198
health
  benefit 67
  effect 61
healthcare 109
heart failure 101
heavy metal 95
hemodialysis
  membrane 188
  therapy 189
hemodialyzer membrane 189
herbicide 93
hesperidin 130
high impact polystyrene 186
Higuchi kinetics 45
hindered
  amine 62, 137, 212
    light stabilizer 198
    liquid stabilizer 43
  light stabilizer 143
  nitroxy radical 148
  phenol 62, 137-138, 198
    antioxidant 133, 147
  piperidine 65
histidine 70
homeostasis breakdown 51
HOMO
  and LUMO levels 50
  energy level 55
  value 54
homocarnosine 70
homolysis 42
honey content 195
hose production 120
hot pressing 140
hotmelt adhesive 108
Huisgen cycloaddition 157
human
  cancer 103
  endometrium 101
  erythrocyte 181
  immune function 82
  skin 100
hybrid
  antioxidant 204
  fibrous mat 156
hybridized antioxidant 161
hydrodynamic diameter 150
hydrogel composite 110
hydrogen
  atom 84
    transfer 37, 40, 54, 72, 77, 86
      mechanism 39, 59
  bond 112
    intra-molecular 39
  bonding 48, 110, 147, 168
  donating ability 43, 49
  donation 48
    kinetics 49
  peroxide 45, 56, 58, 80, 85, 89, 91, 93, 95, 100, 189, 201
  transfer 42, 82
hydrogenated phospholipid 46
hydro-lipophilic properties 45
hydrolysis 74, 161
  degree 70
hydrolytic chain scission 148
hydroperoxide 45, 74, 89-90, 136, 207
  decomposer 177
  evolution 131
hydroperoxyl radical 90
hydrophilic 194
  nature 40
  polymer 201
  simulant 195
hydrophilicity 124, 155

hydrophobic 190
  polymer 85
  tail 51
hydrophobicity 43
hydroquinone 51-52, 64, 108
hydrotalcite 120
hydrothermal
  degradation 182
  oxidation 182
hydroxide decomposer 147
hydroxy
  benzimidazole derivative 50
  telechelic polybutadiene 153
hydroxycinnamic acid 40
hydroxyl
  functional group 40, 48, 57, 78, 107, 131
  radical 58, 72, 80, 89, 93, 189, 213
    scavenging 209
      assay 112
      effect 213
hydroxylamine 65
hydroxymorin 130
hydroxyrutin 130
hydroxytyrosol 124-125
hyperbranched polyglycerol nanoparticle 198
hypertension 82
hypochlorous acid 90
hypoxia 98

I

iminostilbene 205
immersion phase transformation method 188
immune cell 90
impact strength 192
implant 134, 137
  bearing component 212
  lifespan 211
  manufacturing 211
in-cage disproportionation 42
indole derivative 80
indolic nitrogen 80
indolinonic hydroxylamine 65
indolyl radical 80
induced effect 78
induction period 43, 136, 171
inert solvent 159
infected plant 91
inflammation 92, 100
inflammatory
  cytokines 101
  gene expression 102
  mediator 98
  response 76
  signaling 101
inhibited oxidation 159
inhibition 172
  chain 42
  cycle 42
  process 153
  reaction 148
inhibitor 42
initial stabilizer concentration 153
initiation step 130
instability 109
insulating elastomeric compound 128
insulation 182
insulin 100
interaction 209
intermolecular hydrogen bond 195
internal
  lubricant 121
  wall 85
interphase boundary 207
intestinal pH 213
intracellular
  antioxidant capacity 102
  content 47, 90
  organelles 102
  reactive oxygen species 92, 100
  substance 97
intramolecular
  hydrogen bond 48, 78
  proton transfer 50
  stabilization 45
intumescent thermoplastic elastomer 120
ion leakage 195
ionic metal 72
ionization
  enthalpy 59
  potential 37-38
ionizing radiation 191
irradiation 128
irradiation dose 184
isoflavone 66
  consumption 66

isoform 90
isotactic polypropylene 159
isoxazole 54
iteroparity 94

J

jack pine surface 192
jacket 182
jasmonate 95
  mechanisms 96
jasmonic acid 95
jasmonyl-isolucine 95
joint
  arthroplasty 211
  implant 212

K

kaempferol 59
keratinocyte 40, 46, 85
ketolactone 45
kidney 97
  damage 100
killing rate 156
krill oil 114

L

laccase 190
lactic acid bacteria 90
lactose 113
laser flash photolysis 49
layer-by-layer coating 157
layered double hydroxide 74, 161
LDL cholesterol oxidation 70
leaching 152
lead exposure 96
leaf growth 95
lecithin 209
LED reflection plate 149
lemongrass oil 110
lens opacification 65
lifespan 94, 99
lifetime 152
light
  emitting diode 204
  screening 60
  stress 95
lignan pinoresinol 102
lignanamide 68
lignin 137, 155, 178, 194-195
  fraction 192
limiting oxygen index 160
limonene 82
linalool 82
lipid 90, 92, 95
  alkoxyl radical 76
  deterioration 58
  oxidation 66, 78, 82, 85, 132, 161, 209
  packing order 76
  peroxidation 66, 69, 76, 84, 91-93, 95, 97, 100, 188, 195, 200
    inhibition 188
  peroxyl radical 66
  radical 46
lipoperoxidation 132
lipophilic antioxidant 189
lipophilicity 76
lipoprotein 100
  oxidation 66
liposomal peroxidation 70
liposome 181
liquid chromatography 72, 153
liquid siloxane 159
liver 97
  injury 100
  necrosis 100
living thing 89
loading
  capacity 109
  efficiency 145
long chain branching formation 140
longevity 212
lubricant 187
lutein 117
  nanocrystal 117
luteolin 59
lymphoid tumor cell 44

M

macromolecular stabilizer 131
macrophage 104
macroradical 211
  intermediate 143
magnetic powder 172
Maillard
  chemistry 71
  reaction 113, 134
maize starch 45
malondialdehyde 95, 98, 100, 132

- malonedialdehyde 100
- malvin 44
- mandarin 195
- mangiferin 200
- mango leaves 200
- mass
  - loss 115
  - spectrometry detection 72
- master regulator 95
- matrix encapsulation 134
- maze effect 74
- meat product 132
- medical
  - application 208
  - device 116, 212
- melt
  - blending 118, 166
  - compounding 178
  - extrusion 140
  - mixing 110
  - processing 147, 175
  - stabilizer 65
  - stabilizing
    - action 86
    - effect 87
    - efficiency 74
  - viscosity 108, 147
- melting point 212
- membrane 183
  - aging 189
  - lifetime 189
  - peroxidation 52
  - process 189
- mesoporous
  - molecular sieve 140
  - silica 85
    - nanoparticle 203
- metabolic syndrome 114
- metabolically demanding activity 94
- metabolism 99
- metabolite 93
- metal 45
  - chelating 46, 56, 71
  - chelator 40
  - complexation 80
  - deactivator 120, 202
  - induced-neurodegenerative disease 56
  - ion 90
  - prooxidant 70
- metalworking fluid 187
- methionine sulfoxide reductase 70
- methoxy group 78
- methyl
  - jasmonate 95
  - linoleate 72
- micellar media 59
- micellization 60
- Michael-type addition reaction 166
- microaerophilic bacterium 91
- microbial pathogen 58
- microcrystalline cellulose 110
- microemulsion 46
- microencapsulation 174, 214
- microwave radiation 178
- migration 102, 118
  - resistance 204
- milk protein 70
- minced meat 148
- mitochondria 90, 93
- mitochondrial
  - inner membrane 52
  - level 98
  - membrane potential 52
  - origin 51
  - protein 70
  - reactive oxygen species 102
  - respiratory chain 51-52, 100
  - superoxide production 51
- mitochondrion 93
- mobile
  - free radical 159
  - phone 102
- modulating factor 103
- molding 154
  - composition 120
- molecular
  - damage 90
  - mass 141
  - oxygen 89, 107, 159
  - volume 174
  - weight 70, 140, 178, 207
    - reduction 176
    - regulator 192
- mononuclear iron protein 92

montmorillonite 111, 166
morin 59
moringa extract 115
mulberry polyphenolic extract 112
multilayer
  antioxidant packaging 82
  film 134-135, 161
  food packaging 85
multilayered microparticle 85
multiwalled carbon nanotube 137, 211
mutation 102
myopathy 100
myricetin 59

N

N,N'-diaryl-p-phenylene diamines 122
N,N-substituted p-phenylene diamine 145
nanocomposite 110
nanodiamond 211
nanoemulsion 46
nanoencapsulation 115
nanofiber 209
nanofibril 109, 183
nanofibrillated cellulose 183
nanofibrous scaffold 155
nanohybrid 150
nanorod-polyaniline 144
nanoscale carrier 109
nanosilica-immobilized antioxidant 140, 178
naringenin 101, 128, 134, 200
natural
  aging 145
  citrus extract 161
  rubber 62, 120, 128, 203
  rubber vulcanizate 203
  spruce bark extract 168
neodymium actylacetonate 205
nephropathies 82
neral 110
nerve tissue regeneration 155
neurodegenerative disease 100
neurohormonal activation 101
neuro-inflammation 98, 102
neurotoxic free radical production 69
neutral
  compound 77
  curcumin 54
nitric oxide 58, 90
  level 100
nitrite reductase 58
nitrogen atom 42
nitrosative burst response 58
nitroxide 42
  radical 42
nitroxyl radical 65
non-protein thiol 93
norbornene comonomer 118
normal cellular function 58
Nrf2 activators 102
nuclear
  accumulation 90
  facility 145
  power plant 130
nucleating agent 121
nucleation 178
nucleic acid 93, 95
  oxidation 100
nutraceutical 111, 114, 125
  compound 174
nutrient
  balance 95
  deficiency 97
nutritional quality 78

O

octyl gallate 123
odorous substance 81
oil 46
  extraction 69
oligochitosan 190
olive 65
  oil oxidative deterioration 134
omega-3 fatty acid 111
one-electron oxidized radical 55
open wound 155
ophthalmic application 192
optimal depth 76
oral
  administration 98
  bioavailability 214
  supplementation 98
orange peel extract 134
oregano essential oil 132
organ level 94

organic
  carbon storage 95
  phenol 57
  phosphite 111
organismal dysfunction 99
organizational level 94
organophosphite 177
organophosphonite 160
oryzanol 69
over-expression 95
oxalic acid bisbenzylidene hydrazide 120
oxidant 89
oxidation 37, 46, 108
  index 137
  induction time 128, 141, 143, 147, 178, 204
  inhibiting effect 171
    efficiency 50
  potential 80
  process 118
  product 118
  promoter 42
  stability 64, 131
  therapy 60
  wear 211
oxidative
  barrier 56
  damage 45, 61, 85
  degradation 136
  deterioration 71
  DNA repair gene 103
  induction 182
    time 137
      onset 177
  inhibition 112
  modification 70
  polymerization 150
  process 42
  property 112
  rancidity 71
  stability 143, 156, 211
    index 85
    of cheese 69
  state 58
  status 97
  stress 46, 51, 58-59, 69, 76, 80, 90, 92-93, 95-98, 100-104, 181, 189
    level 104
    mechanism 96
    status 101
    -related disease 90
  transformation
    mechanism 79
    product 79, 86
oxidizable substrate 82
oxidizing
  species 90
  treatment 191
oxoferryl porphyrin 89
oxygen 89
  aging 128
  atmosphere 131
  barrier 133
  consumption 148
  deprivation 98
  diffusion 183
  mobility 169
  permeability 209
  permeation effect 171
  pressure 154
  radical absorbance capacity 70
  reaction 89
  scavenging functional groups 133
  uptake 130
oxylipin 95
ozone 83, 89
  attack 122
  exposure 83
  resistance 170
  stress 45

P

packaged product 142
packaging 87, 122
  film 134
  material 111, 115
palmitoyl residue 46
papain 70
paraffin oil 172
paraphenylene diamine 170
Parkinson's disease 98, 100
particle size 55
pathogen 76, 94
  strain 190
pathogenic cell 90

pathological
  condition 90
  reaction 102
pathology 76
pathophysiology 70, 104
pavement temperature 206
peanuts 84
pelargonidin 44
pentamethylbenzofuranol 123
penta-O-galloyl glucose 200
pepsin 70
peptide 70
perfluoropolyether 165
peripheral nerve repair 155
permeability 154
peroxidase 90, 194
peroxidative reaction 76
peroxide 47, 206
  decomposing 130
  decomposition 43
  index 132
  value 69
  -initiated crosslinking 143
peroxidolytic antioxidant 79
peroxiredoxin 90, 98
peroxisome 90, 93
peroxy
  free radical 211
    scavenging activity 124
  radical 42-43, 56, 66, 76, 84, 97, 136, 148, 211
peroxynitrite 90
petunia plant 91
pH 55, 184
  value 112
phagocytic cell 58
pharmaceutical 45
  compound 124
  formulation 118
  industry 109, 148
  product 78, 196
  storage 118
pharmacological preparation 56
phenolic
  antioxidant 37, 43, 72, 90, 174, 212
  diterpene 135
  glycoside 104
  group 190
  hydrogen
    atom 84
    donor 182
  hydroxyl 59
  macromolecular antioxidant 198
  phosphite 177
    antioxidant 75
  radical 40
    disproportionation 48
  stabilizer 178
phenothiazine 65, 205
phenoxy radical 59, 77
phenyl-b-naphthyl amine 204
phenylenediamine 172
phosphate 74, 136
  ester 138
phosphine 74
phosphite 74, 87, 107, 126, 131, 136, 161, 198, 206
  antioxidant 119, 143
phosphonite 74, 202
  antioxidant 119
phosphopeptides 70
phosphorus antioxidant 197
photoantioxidant activity 79
photocatalytic activity 179
photochemistry 37
photon emission 100
photooxidation 42, 207
photooxidative
  degradation 148
  stabilization 202
photophysics 37
photoprotection 82, 94
photosynthesis 95
photosynthetic
  organism 84
  pigment 95
phthalocyanine complex 137
physical
  aging 154
  migration 152
  quenching 82
physiological concentration 90
physiologically safe limit 92
phytoalexin 77

phytosteryl lipoate 69
pigment 95
  oxidation 132
pineapple 113
pipe 121, 137, 151, 163
piperidine 65
  -based compound 143
piracetam 101
plant 58, 76, 82, 96
  defense 94
    mechanism 95
  extract 188
  growth 91, 95
  pigment 91
  tissue 95
plasma
  lipid oxidation products 66
  membrane potential 52
plastic deformation 212
plasticizing effect 111, 177
platelet adhesion 188
plumbing system 164
polar environment 54
polarity 174
polarizability 60
pollination 60
pollution 46
poly(2-hydroxyethyl methacrylate) 168
poly(3-hydroxybutyrate) 166
poly(butyl cyanoacrylate) 123
poly(ε-caprolactone) 155-156
poly(ethylene terephthalate) 87, 161
poly(ethylene-co- chlorotrifluoroethylene) 126
poly(lactic acid) 174
  film 174
poly(N-vinyl pyrrolidone) 200
poly(p-phenylene sulfide) 182
poly(propylene glycol) 181
poly(styrene-co-butadiene) 203
poly(vinyl alcohol) 110, 194
poly(vinyl butyrate) 197
poly(vinyl chloride) 198
  chlorinated 121
polyamide 147-148, 197
  11 148
  6 147
polyaniline 124, 150, 204
  nanofiber 150
polybutadiene 153
polybutylene 151
polycaprolactone 115
polycarbonate 154
polychloroprene 122
polycondensate polymer 148
polydimethylsiloxane 124, 159
polydispersity 178
polydispersivity 113
polyetheretherketone 160
  /poly(ether imide) 160
polyethylene 72-74, 118
  chlorinated 120
  crystallization 120
  film 119
  high-density 85, 120, 136, 137
  linear low-density 7, 143
  low-density 85, 139, 140
  silane-crosslinkable 163
  ultra-high molecular weight 211-212
polyhydric alcohol 87
polyhydroxybutyrate 167
polyimide 169
  hollow fiber membrane 169
  nanofiltration membrane 169
polyisobutylene 170
polyisoprene 171
  rubber matrix 171
polyketone 173
  composite 62
  matrix 173
polylysine 157
polymer
  chain 136, 206
  discoloration 87
  powder coating 173
  tube 152
polymeric material 43
polymerization phase 118
polymethylmethacrylate 75, 177
polymorphism 103
polymorphonuclear neutrophil 104
polyol 191, 192
polyolefin thermoset 143

polyphenol 69, 76, 81, 134, 169, 181, 194, 209, 213
  dose 76
  oxidase 91, 194
  radical 66
polyphenolic
  antioxidant 118
  compound 155
polypropylene 48, 65, 79, 86-87, 131-132, 137, 178
  chain 178
  film 111
  stability 179
  surface 178
polypyrrole 183
polysaccharide 169
polysorbate 85
polystyrene 186
polysulfide 187
polysulfone 188-189
  chain 189
polyunsaturated
  acid 84
  fatty acid 71, 84
polyurethane 153, 190-192
  film 191
  foam 192
polyvinylpyrrolidone 150
pomegranate
  extract 104
  phenolics 104
pore size 85
post-irradiation oxidative stability 137
potable water pipe 163
potential energy surface 50
poultry 85
preform 212
pressure-sensitive adhesive 208
preventive effect 101
primary
  antioxidant 64, 72, 136, 141, 173, 206
  trapped radical 212
printing equipment 132
probiotic product 98
processing aid 121
procyanidin 113
proinflammatory cytokines 100
proliferation 90, 102
proline 70
prooxidant 70
prooxidant
  activity 86
  effect 85
propagating step 107
propagation 84
propagative cycle 84
propyl gallate 85, 116, 174
prosthetic implant 211
pro-survival protein 102
protease specificity 70
protective
  atmosphere 183
  bandage 208
  effect 113
  effectiveness 195
  mechanism 83
protein 91-93, 95, 184
  carbonylation 91
  leakage 65
  oxidation 85, 200
  synthesis 91
  -polyphenol conjugate 184
proteinaceous component 90
protocatechuic acid 190
proton
  affinity 37, 39
    value 59
  dissociation enthalpy 37-38
  -coupled electron transfer 72
pseudo-Fickian diffusion 110
pseudoisoeugenol 69
punicalagin 104
pyrogallol 64
pyruvate acid 213

Q

quantum chemical calculation 59
quenching process 91
quercetin 59, 101, 109, 111, 123, 132, 155, 174, 198, 200
quinic acid 134
quinine epoxide 84
quinone
  group 51
  structure 78

  /hydroquinone ratio 51

R

radical 89
  adduct formation 54
  cation 59
    deprotonation 59
  chain-breaking antioxidant 207
  polymerization 128
  scavenger 177
  scavenging 37, 51, 71, 137, 173, 206
    ability 150
    activity 39, 115
  species 39
  -radical disproportionation 86
radiofrequency electromagnetic field 102
rapanone 51
rate determining step 42
reacetylated chitosan 113
reaction
  mechanism 54
  rate 87
  time 134
  with ozone 43
reactive
  oxygen species 45-46, 52, 58, 80, 91-93, 95-97, 100, 104, 117, 181, 195
    generation 58, 102, 104
  pendant group 196
  sulfur species 80, 181
reclaimed natural rubber 146
red
  grape skin 44
  meat 85, 144
  wine 44, 76-77
redox
  active nature 183
  cycle 65
  modulation 98
  reaction 136
  signaling 90
reduced
  glutathione 97
  graphene 141
reductase inhibitor 100
regeneration 42, 46
reinforcing efficiency 203
relaxation time 154
release
  kinetics 132, 174
  mechanism 195
release
  profile 175
  study 213
renal failure 114
repair pathway 103
reproduction 93
reproductive
  experience 99
  fitness 94
reservoir system 148
residual free radical 211
resorcinol 108
respiration rate 115
resveratrol 77-78, 91, 113, 143, 148, 181
  release 114
reversible transition 159
riboflavin 130
rice
  bran oil 69
  protein 184
  varieties 76
ring-opening polymerization 155, 175
rosemary 194
  extract 135, 209
rosmarinic acid 115, 135, 174
  ester 76
rotamer 40
rotational interaction 82
routine tool 97
rubber 120
  composite 62
  vulcanization 51
rutin 134

S

safe level 93
safety
  glass 197
    laminate 197
  tire 172
safflower seedling 95
sage leaves extract 82
salicylic acid 38-39, 93, 194, 200
salinity 58, 95
  stress 90-91

salt 45
sandalwood essential oil 69
saponin 82
sardine 132
scavenger enzyme activity 40
scavenging
  affinity 70
  assay 190
  effect 115
  mechanism 183
Schwann cell 155
seal 145
seawater 96
secondary
  antioxidant 136, 141, 173
  aromatic amine 43
  oxidation 85
seed
  development 95
  polyphenol extract 179
  storage 84
seedless grapes 194
selenium 101, 128
  antioxidant 80
self
  -catalysis effect 74
  -healing composite hydrogel 109
  -maintenance 93
semelparity 94
semipermeable barrier 114
semiquinone 78
senescence 95
sensoric properties 45
separation membrane 149
sequential proton loss electron transfer 37, 40, 54, 59, 72, 77
  mechanism 39
serum catalase activity 98
service life 136, 154
sesquiterpene 82
shear viscosity 168
sheath material 130
shelf-life 114, 157
shikimic acid 76
shrimp shell waste 184
side chain 153
signaling
  entities 80, 181
  system 89
silibinin 188
  content 188
silica 85
silica-like layer 159
silicone rubber 120, 172
siloxane additive 118
silver nanoparticle 111, 198
single electron transfer 54, 59, 72, 80
  followed by proton transfer 59
singlet oxygen 82, 90-91, 93, 95
  oxidation 84
  quenching 46, 82
sink 92
skin 46, 85
  cell 85
  damage 158
  layer 148
  mask 113
  penetration 148
  repair 85
  wound closure 85
sodium
  alginate 69
  ascorbyl phosphate 45
  bisulfite 116
  metabisulfite 116
  sulfite 116
soil structure 95
solar
  cell 204
    encapsulant 131
  radiation 156
sol-gel route 155
solid
  lipid nanoparticle 194
  propellant rocket motor 128
solubility 148, 197, 209
soy 66
  isoflavone 66-67
  protein 185
  sauce 185
soybean 84
  oil 43
  products 67

spandex 192
spin 89
spirodimer 86
spray-drying 115
squalene 211
stabilization
  effect 211
  energy calculation 160
starch 150, 209
  derivatives 209
statin 100-101
steric
  hindrance 48, 178
  stabilizer 150
sterically hindered
  phenolic antioxidant 192
  piperidine 192
sterilization 122
  dose 128
stilbene derivative 77
stoichiometric factor 42
storability tolerance 195
storage 142
  stability 214
stratum corneum 148
stress condition 91
stressed cell 93
stressor 94
styrene
  -butadiene
    block copolymer 202
    rubber 203, 205
    -styrene triblock copolymer 206
  -ethylene-butylene-styrene triblock copolymer 207
  -isoprene-styrene block copolymer 208
subcellular degradation 97
sub-lethal concentration 58
submersible power cable 128
sulfur
  antioxidant 80
  dioxide 81
  -containing compound 91
sunflower 84
  oil oxidation 210
sunlight 46
sunscreen 100
supercritical
  assisted atomization 200
  carbon dioxide impregnation 143, 161
  emulsion extraction 174
    technology 124
superoxide 90
  anion 58, 100
    radical 56
  dismutase 58, 80, 89-90, 93, 97-98, 100, 181, 194
    level 188
    mimetic 116
  radical 95
    scavenging 209
surface
  layer 118
  oxidation 85
  roughness 190
  topography 190
sustained release 174, 200, 204
sweet cherry 155
swelling 209
synergism 131, 177
synergist 84
synergistic
  activity 43
  antioxidant 50, 128
  effect 72, 171, 202, 207, 212
  interaction 64, 90
  mixture 64
syringic acid 168

T

tannic acid 109, 127, 134, 213
tannin 82
  wine seed extract 179
target gene 90
tau phosphorylation 70
tea
  catechin 76
  polyphenol 134, 214
temperature 97
  degradation shift 137
terpenoid 82
  component 82
tert-butyl hydroquinone 64, 85, 174
tertiary
  amine 42

  butyl catechol 108
TGA measurement 160
therapeutic
  agent 65
  target 70
therapy 102
thermal
  aging 108
    resistance 120
  conductivity 204
  degradation temperature 147
  oxidation 130, 143, 153, 171
    stability 140, 173, 178
  processability 140
  resistivity 160
  shock 189
  stability 56, 62, 127, 140, 150, 154, 166, 184, 190, 214
  stabilization 43
  stress 95
thermodynamically favorable pathway 77
thermooxidation 107, 160
  rate 160
  temperature 136
thermooxidative
  aging resistance 50, 62
  degradation 107, 128, 130, 147
  stability 177-178, 192
  treatment 198
thermoplastic starch 143
thiazoline 79
thiodialkylpropionate 127
thiodiethylenepropionate 127
thioether 43
thioglycerol 116
thioglycolic acid 116
thiol 43
thioredoxin system 58
thiosynergist 206
thymol 111, 148, 175-176
timing belt 129
tire 205
tissue
  damage 97
  deformation 192
tobacco substitute 135
tocopherol 46, 69, 76, 84-85, 90, 115, 118, 123, 133, 140-142, 156, 161, 174, 180, 189-192, 194, 206, 211
  acetate 85
  activity 84
  concentration profile 212
  diffusion 212
  hydroperoxydienone 84
  quinone 189
  radical 46, 84, 90
tocopherylquinone 84
tocotrienol 69
toluene 164
  2,4-diisocyanate 153
tomato 84
  plant 95
torque 140
total
  antioxidant
    capacity 100
    status 101
  knee
    arthroplasty 211
    replacement 211
toxic
  effect 96
  oxidation product 78
toxicity 97
traditional medicine 82, 102
transcription factor 90, 94
transcriptional activation 90
transesterification reaction 166
transfersome 85
trans-ferulic acid 134
transformation product 211
transgenic plant 95
transient translation repression 91
transition metal ion 76
translation
  activity 91
  repression 91
transparency 154, 197, 209
triacylglycerol 100
triazine derivative 179
triazinone 171
triazole linkage 157
triethyl citrate 111

trimer 86
tripeptide 70
triphenylphosphite 133
triplet state 89
tris-(2,4-di-tert-butylphenyl)phosphite 173
tris-(nonylphenyl)phosphite 133
triterpene 82
triterpenoid 82
trypsin 70
tryptophan 70, 72
tubing 164
tumor necrosis 100
tung oil 108
turbidity 197
two-electron
  peroxide reduction 71
  transfer 51
tyrosine 70

U

ubiquinol 52
ubiquinone 46, 51
ultrasound exposure 104
ultraviolet
  irradiation 100
  radiation 76
unpaired electron 89
unsaturated
  alkyd resin 108
  fatty acid 66
up-regulation 102
UV irradiation 189

V

vanillic acid 168
vasodilator 44
vesicle 85
vinyltriethoxysilane 143
virgin wine seeds wastes 179
visible light transmission 134
vision 82
volatility 197
vulcanization accelerator 145

W

water
  affinity 209
  content 95
  habitat 96
  production plant 189
  solubility 109
waterborne polyurethane 190
watermelon seed protein 184
waterproofing
  composite 124
  membrane 120
wear 212
  degradation 211
weathering
  test 141
  time 192
weight
  change 153
  loss 75, 160, 177
wheat straw 194
  lignin 192
wheeled combat vehicle 172
whitening agent 201
winemaking 81
winery effluent 169
wire and cable 141
wood 192
wound dressing 115
  material 195

X

xanthan gum 213-214
xanthone 130
xenobiotic 98
xylan 110
xylene 91

Y

yeast cell 90-91
  microcarrier 56
yellowing resistance 192
yellowness index 154

Z

zebrafish 97
zein
  nanoparticle 113
  structure 114
zeta-potential 55
zinc
  dialkyldithiophosphate 206
  dibutyldithiocarbamate 206, 208
  dimethacrylate 50, 128
  dithiocarbamate 202
  oxide 192

ChemTec Publishing

ISBN 978-1-927885-59-8
90000
9 781927 885598