# 26 Trace Elements in Plants and Soils of Abandoned Mines in Portugal: Significance for Phytomanagement and Biogeochemical Prospecting

*M.N.V. Prasad, J. Pratas, and H. Freitas*

**CONTENTS**



## 26.1 INTRODUCTION

Plant communities that can grow on mine spoils and are capable of accumulating metals in their parts have immense scope for mine reclamation and for biogeochemical exploration. The chemical composition of these plants is usually correlated with the mineral composition of the soil in order to fetch biogeochemical prospecting [1]. Thus, the plant community established on a mine spoil can be useful in mineral exploration as well as in remediation to minimize the impacts of mining [2–4]. Therefore, considering the diversity of plants and their responses in metal-contaminated sites having different levels of metals, it is important to study the composition of the plant communities of abandoned mines or mine spoils, which would serve as a basic approach for initiating steps for mine reclamation and remediation.

Authentic information about plant communities that can grow on metal-contaminated soils is required in large volume to assess this approach for mine reclamation or remediation and also for biogeochemical exploration [5–8]. This study attempts to evaluate plant species and communities that have established on metal laden soils. Plants and soils were analyzed for total Ag, Bi, Cu, Pb, W, and Zn. Patterns of metal accumulation in plant communities were analyzed, indicating their possible application in restoration of mine spoils and tailings. Plants growing in abandoned mine sites usually indicate the mineral composition of the soil. These plant species are tolerant to metals and are able to accumulate or exclude toxic metals. Trace metal-accumulating plants are thus of immense use for biogeochemical prospecting and are invaluable[5,8,9].

Therefore, metal-tolerant perennials and plants with high biomass and bioproductivity are of immense use in phytostabilization and mine restoration [10]. Mining activities leave behind vast amounts of refuse and tailings, which are often very unstable and will become sources of environmental pollution. The direct effects will be loss of cultivated, forest, or grazing land, and the overall loss of production [11]. Air, soil, and water pollution and siltation of rivers are the indirect effects. Both these effects would eventually lead to the loss of biodiversity, amenity, and economic wealth [12].

Reclamation of mine waste with plant communities that are tolerant can fulfill the objectives of stabilization, pollution control, visual improvement, and removal of threats to mankind. The constraints related to plant establishment and amendment of the physical and chemical properties of the toxic metal-mined soils depend upon the choice of appropriate plant species that will be able to grow in such a hostile environment. Thus, the plant community tolerant to trace elements plays a major role in remediation of degraded mine soils. Plants tolerant to toxic levels of trace elements respond by exclusion, indication, or accumulation of metals [13]. Thus, more information about plant communities that can grow on metal-contaminated soils is essential to determine their potential for mine reclamation and biogeochemical exploration [5–8,14,15].

## 26.2 SITE DESCRIPTION

The study area comprises two major segments, namely, the Palão and Pinheiro mines, which belong to the same geological setting. The Palão mines are located about 2 km north of Penamacor (center east of Portugal), 40° 10′ 50″ N; 7° 11′ 20″ W. The mineralization is in the Schist–Graywake complex and is characterized by a vein network of the stockwork type. These thin veins are made of sphalerite, galena, and traces of other sulphides, within a carbonate gangue, barite, and quartz. The principal mining area corresponds to an open pit mine, currently filled with water, slightly elliptic, and more or less 100 × 200 m; the vast majority of the veins are less than 3 cm thick. Very scarce are the Veins larger than 50 cm thick are very scarce and are oriented parallel to the major exploitation axis. From the paragenetic point of view, these mines are considered similar to the Pb–Zn vein mineralizations, with identical paragenesis; some of these date from the upper Cretaceous period.

The Pinheiro segment has the same Schist–Graywake complex, located about 3 km east of Penamacor village, 40° 09′ 05″ N; 7° 07′ 55″ W. It is a vein type mineralization composed of arsenopyrite, ferriferous sphalerite, chalcopyrite, pyrite, and wolframite. By its geological and paragenetic emplacement, the mineralization is part of the hercinic mineralization peribatolitic group with W–Sn of the Central Iberian geotectonic zone. The plant community established on a distinct metal vein mineralization (or distinct paragenesis) in a common geological complex of abandoned mines in central Portugal, namely, Palão, Pinheiro, and Mata da Rainha, which were chosen as study material. Plant samples (aerial parts, leaf, needles, fruit, flower, phyllode, root, seed, twigs, whole plant) belonging to 95 species representing 37 families were collected from the mine sites and analyzed for total As, Bi, Cu, Pb, W, and Zn content.

## 26.3 METHODOLOGY

Several transects were made in the mineralized zones and mine tailings to collect plant samples. On these transects, for every 40 m, soils and plants were collected in a 2-m circle (sampling point) following the methodology suggested by Kovalevskii [7] and Brooks [9].

Mineralized area and mine tailings were chosen as sites for collection of materials. To avoid temporal variations of the different heavy metals by plant species, collection was completed in short duration, i.e., 2 days. Soil samples are always collected from B horizon (not always in the same depth because they are mountain soils with little thickness but variable) to minimize the influence of the organic matter present in superficial horizons and consists of an homogenization of the collection of about 4 points. The soil samples were dried at 80°C and passed through a 100-

mesh sieve. Soil pH was determined in a soil/water suspension with a pH meter. Plant samples were cleaned in abundant freshwater, rinsed with deionized water, and air-dried at room temperature for several days and after crushing. Plants were identified with the help of local herbarium and floras [16,17]. Analytical methods included colorimetry for W [18]; atomic absorption spectrophotometry (Perkin Elmer 2380) for Ag, Co, Cr, Cu, Fe, Mn, Ni, Pb, and Zn; and hydride generation (HGS) for As and Sb [19–21].

Plant samples were cleaned in abundant freshwater and rinsed with distilled water. Dry weights were obtained after oven drying at 60°C for 2 days. Plant samples were analyzed for total Ag, As, Co, Cr, Cu, Ni, Pb, and Zn following the methods stated for soil.

## 26.4 RESULTS AND DISCUSSION

Six metals were analyzed in all soil samples (Table 26.1). High levels of Pb, Zn, As, and W were recorded in the soils. The Pb in the soil was very high, reaching a maximum of 2497.2 ppm in the collected samples. The maximum Zn content in soils was 3599.6 ppm, a level that can be extremely toxic for plants. Maximum concentration of As in soils was 469.5 ppm. Soil content of W was also high, reaching a maximum of 230.7 ppm. The maximum concentrations of Cu and Bi in soils were 356.7 ppm and 2.74 ppm, respectively.

A total of 95 plant species from 37 families were investigated for their ability to accumulate metals in these mine complexes (Table 26.1). Analysis of metals performed in plant material (aerial parts, leaf, needles, fruit, flower, phyllode, root, seed, and twig) indicated that a variable degree of accumulation of metals was present in different plant parts (Table 26.1). The most representative family is Fabaceae with 11 species, followed by Asteraceae with 9 species, Cistaceae with 7, Lamiaceae with 6, Caryophyllaceae with 5, Poaceae with 5, Rosaceae with 5, Scrophulariaceae with 4, Polygonaceae with 4, Fagaceae with 4, Cyperaceae with 3, and the rest with 1 or 2.

Lead concentration in plants was rather high for some species (Figure 26.1), varying from 0.71 ppm in leaves of *Salix atrocinera* and 1.03 ppm in leaves of *Eucalyptus globulus* to 157.8 ppm in roots and 97 ppm in the aerial parts of *Typha dominguensis*. In the aerial parts of another Poacea, *Briza maxima*, lead content of 97.02 ppm was recorded. *Myriophyllum alterniflorum* also showed high content of Pb in the whole plant, with 93.76 ppm (Figure 26.1). This aquatic species also accumulated Zn in the above-ground tissues, demonstrating its capacity to take up toxic metals from soil (Table 26.1). In *Andryala integrifolia*, a frequent species in other mining areas (unpublished data), a content of 77.02 ppm of lead in the above-ground tissue was recorded. This frequent finding of common species in diverse mining areas with distinct paragenesis is worth pointing out because metals and other environmental stress factors play a critical role. Ecological convergence seems clear in this particularly hard environment.

Other species that showed high content of Pb (Figure 26.1) were *Ononis cintrana* (65.69 ppm), *Lotus corniculatus* L. var. *corniculatus* (62.6), *Elatine macropoda* (62.5), *Daphne gnidium* (59.47), *Digitalis thapsi* (55.89), *Dittrichia viscosa* (37.08), *Pterospartum tridentatum* (38.6), *Ludwigia palustris* (35.1), and *Phlomis lychnitis* (29.8).

With respect to As, the aquatic species *Elatine macropoda* showed a remarkable content of As in the above-ground tissues: 531.4 ppm (Figure 26.2). This species also accumulated high levels of Pb (62.5 ppm), Co (127.8 ppm), and Zn (2258.5 ppm) (Table 26.1). The aquatics *Typha dominguensis* and *Myriophyllum alterniflorum*, with 16.97 and 10 ppm of As, respectively, again were among the plants accumulating more As. These two species also showed high content of zinc in the whole plant: 389.7 ppm in *T. dominguensis* and 507.83 ppm in *M. alterniflorum*. Other species that showed high content of As (Figure 26.2) were *Adenocarpus complicatus* (12.9 ppm), *Asparagus acutifolius* (19.62), *Galium palustre* (11.98), and *Lactuca viminea* (11.64).

**TABLE 26.1**
**Trace Metal Composition of Soil and Plant Parts[a] Collected from the Abandoned Mine Complex**

| Plants/family | Plant part | As–S | As–P | Bi–S | Bi–P | Cu–S | Cu–P | Pb–S | Pb–P | W–S | W–P | Zn–S | Zn–P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Fabaceae** | | | | | | | | | | | | | |
| *Genista triacanthos* Brot. | A | 343.8 | 1.26 | 2.74 | 0.003 | 82.9 | 2.9 | 374.1 | 6.8 | <0.1 | <0.01 | 3599.6 | 39.4 |
| *Cytisus striatus* (Hill.) Rothm. | A | 127.20 | 0.49 | 0.82 | 0.007 | 62.21 | 7.74 | 585.01 | 3.69 | 24.77 | 0.011 | 497.59 | 96.45 |
| *C. multiflorus* (L'Hér.) Sweet | A | 79.35 | 0.27 | 0.72 | 0.015 | 40.5 | 9.34 | 288.23 | 3.54 | 1.19 | 0.00 | 165.13 | 105.76 |
| *C. grandiflorus* (Brot.) DC. | A | 81.18 | 0.37 | 0.53 | 0.072 | 49.23 | 11.31 | 797.06 | 3.24 | 1.12 | 0 | 383.91 | 121.19 |
| *Lotus corniculatus* L. var. corniculatus | A | 51.2 | 0.45 | 0.64 | 0.008 | 28.9 | 6.5 | 1631.5 | 62.6 | <0.1 | <0.01 | 589.8 | 139.3 |
| *L. pedunculatus* car. | A | 161.95 | 0.03 | 0.48 | 0.007 | 36.72 | 6.33 | 95.23 | 5.09 | 7.26 | 0.003 | 102.14 | 35.87 |
| *Hymenocarpos lotoides (*L.) Vis. | A | 261.2 | 2.16 | 2.55 | 0.009 | 57.7 | 9.3 | 102.5 | 7.2 | 142.1 | <0.01 | 145.3 | 111.7 |
| *Ononis cintrana* Brot. | A | 49.93 | 0.1 | 0.58 | 0.03 | 33.59 | 12.14 | 1361.2 | 65.69 | 0.075 | 0 | 649.61 | 397.99 |
| *Acacia dealbata* Link | L | 123.25 | 0.76 | 1.26 | 0.023 | 44.88 | 5.88 | 177.95 | 7.67 | 5.50 | 0.004 | 983.89 | 35.85 |
| | T | 123.25 | 0.27 | 1.26 | 0.014 | 44.88 | 2.93 | 177.97 | 3.01 | 5.50 | 0.005 | 983.89 | 39.49 |
| | S | 69.3 | 0.06 | 1.56 | 0.018 | 30.5 | 2.3 | 141.9 | 0.7 | 5.5 | <0.01 | 99.3 | 16.5 |
| *Adenocarpus complicatus* (L.) J. Gay | L | 192.7 | 12.85 | 0.81 | 0.024 | 139.47 | 9.17 | 101.7 | 7.716 | 79.84 | 0.116 | 160.62 | 132.68 |
| | T | 192.7 | 0.15 | 0.81 | 0.031 | 139.47 | 3.84 | 101.78 | 1.68 | 79.84 | 0.06 | 160.62 | 28.75 |
| *Pterospartum tridentatum* (L.) Willk | A | 343.8 | 0.00 | 2.74 | 0.39 | 82.9 | 1.5 | 374.1 | 38.6 | <0.1 | <0.01 | 3599.6 | 284.0 |
| **Asteraceae** | | | | | | | | | | | | | |
| *Helichrysum stoechas* (L.) Moench. | A | 157.8 | 1.50 | 0.97 | 0.05 | 69.87 | 10.13 | 458.68 | 12.18 | 31.80 | 0.04 | 813.67 | 120.14 |
| | L | 149.84 | 0.61 | 0.82 | 0.06 | 72.68 | 10.94 | 349.85 | 8.14 | 38.17 | 0.046 | 557.45 | 120.45 |
| | T | 149.84 | 1.63 | 0.82 | 0.06 | 72.68 | 10.04 | 349.9 | 9.54 | 38.17 | 0.046 | 557.44 | 89.72 |
| *Andryala integrifolia* L. | A | 265.66 | 1.65 | 1.03 | 0.002 | 122.80 | 10.74 | 337.89 | 77.02 | 93.57 | 0.032 | 301.24 | 88.98 |
| *Lactuca viminea* (L.) J. & C.Presl | A | 338 | 11.64 | 1.20 | 0.41 | 150.97 | 9.43 | 86.84 | 12.48 | 124.71 | 0 | 165.14 | 59.21 |
| *Carlina corymbosa* L. subsp. *corymbosa* | A | 163.08 | 0.18 | 1.10 | 0.018 | 41.94 | 8.24 | 521.71 | 11.47 | 20.5 | 0.020 | 769.27 | 84.656 |
| *Tolpis barbata* (L.) Gaertner | A | 272.25 | 0.60 | 1.61 | | 48.11 | 13.66 | 99.01 | 14.50 | 71.69 | 0 | 125.26 | 170.76 |
| *Crepis capillaris* (L.) Wallr. | A | 263.6 | 0.39 | 0.98 | 0.06 | 121.94 | 9.30 | 88.87 | 11.48 | 96.84 | 0 | 148.61 | 114.48 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Chondrilla juncea* L. | A | 71.7 | 0.03 | 1.98 | <0.001 | 130.6 | 12.3 | 577.4 | 6.0 | 0.1 | <0.01 | 118.4 | 59.6 |
| *Dittrichia viscosa* (L.) W. Greuter | A | 7.0 | 1.27 | 0.16 | 0.07 | 32.3 | 18.6 | 32.2 | 11.1 | 1.9 | <0.01 | 47.6 | 104.6 |
| | L | 104.83 | 0.74 | 0.92 | 0.033 | 43.54 | 18.99 | 436.48 | 37.08 | 0.50 | 0.005 | 1150.0 | 179.38 |
| | T | 137.56 | 0.63 | 1.16 | 0.004 | 47.28 | 6.47 | 571.2 | 5.65 | 0.049 | 0.002 | 1517.5 | 53.40 |
| *Phagnalon saxatile* (L.) Cass. | A | 469.5 | 7.60 | 0.40 | <0.001 | 356.7 | 9.1 | 62.5 | 4.6 | 230.7 | 0.13 | 244.9 | 117.9 |
| **Fagaceae** | | | | | | | | | | | | | |
| *Quercus coccifera* L. | L | 9.63 | 0.21 | 0.21 | 0.01 | 28.82 | 2.61 | 33.64 | 2.61 | 1.95 | 0.00 | 70.03 | 20.40 |
| | T | 9.63 | 0.11 | 0.21 | 0.012 | 28.81 | 3.36 | 33.64 | 3.19 | 1.95 | 0 | 70.03 | 15.21 |
| *Q. ilex* L. subsp. *ballota* (Desf.) Samp. | L | 338 | 0.31 | 1.20 | 0.005 | 150.97 | 4.785 | 86.84 | 2.44 | 124.71 | 0.031 | 165.14 | 65.83 |
| | T | 338 | 0.32 | 1.20 | 0.005 | 150.97 | 4.68 | 86.84 | 3.62 | 124.71 | 0.11 | 165.14 | 38.41 |
| *Q. pyrenaica* Willd. | L | 38.32 | 0.31 | 0.43 | 0.005 | 26.95 | 14.85 | 287.89 | 2.99 | 0.45 | 0 | 322.42 | 85.58 |
| | T | 38.32 | 0.44 | 0.43 | 0.003 | 26.95 | 6.57 | 287.89 | 3.86 | 0.45 | 0 | 322.42 | 70.04 |
| *Q. suber* L. | L | 160.93 | 0.38 | 0.74 | 0.019 | 80.39 | 5.057 | 581.02 | 3.81 | 42.49 | 0.021 | 288.36 | 57.65 |
| | T | 160.93 | 0.26 | 0.74 | 0.06 | 80.39 | 6.21 | 581.02 | 4.45 | 42.49 | 7.32 | 288.36 | 65.64 |
| **Ericaceae** | | | | | | | | | | | | | |
| *Erica australis* L. | A | 8.73 | 0.08 | 0.17 | 0.007 | 33.25 | 3.071 | 30.74 | 1.73 | 3.03 | 0.001 | 52.58 | 7.12 |
| *Calluna vulgaris* (L.) Hull. | A | 10.68 | 0.36 | 0.21 | 0.017 | 30.78 | 3.39 | 33.22 | 1.29 | 2.77 | 0.007 | 51.74 | 10.66 |
| *Erica umbellata* L. | A | 11.02 | 0.23 | 0.22 | 0.020 | 30.64 | 3.50 | 33.30 | 3.43 | 2.85 | 0.002 | 52.11 | 10.88 |
| *E. lusitanica* Rudolphi | T | 9.3 | 0.42 | 0.15 | 0.007 | 33.3 | 38.3 | 40.8 | 4.9 | 1.3 | 0.03 | 41.6 | 125.9 |
| *E. lusitanica* Rudolphi | A | 39.31 | 0.25 | 0.85 | 0.008 | 31.92 | 23.45 | 91.33 | 10.28 | 3.39 | 0.016 | 70.44 | 102.6 |
| **Cistaceae** | | | | | | | | | | | | | |
| *Cistus psilosepalus* Sweet | L | 116.7 | 0.5 | 0.9 | 0.0 | 48.0 | 9.5 | 623.3 | 6.9 | 20.1 | 0.1 | 290.1 | 189.5 |
| | T | 116.70 | 0.42 | 0.92 | 0.018 | 47.98 | 3.072 | 623.32 | 3.79 | 20.06 | 0.026 | 290.09 | 98.65 |
| *Xolantha guttata* (L.) Raf. | A | 338 | 1.48 | 1.20 | 0.07 | 150.97 | 8.99 | 86.84 | 10.51 | 124.71 | 0.041 | 165.14 | 80.98 |
| *Cistus ladanifer* L. | L | 60.34 | 0.796 | 0.39 | 0.02 | 47.89 | 5.14 | 208.85 | 7.64 | 13.18 | 0.03 | 313.6 | 134.15 |
| | F | 16.1 | 0.14 | 0.14 | 0.009 | 22.8 | 5.1 | 133.9 | 2.3 | <0.1 | <0.01 | 243.9 | 41.0 |
| | FR | 10.78 | 0.43 | 0.21 | 0.039 | 31.26 | 5.03 | 33.59 | 2.58 | 2.75 | 0.005 | 54.28 | 32.59 |
| | T | 60.34 | 0.46 | 0.39 | 0.018 | 47.89 | 2.85 | 208.85 | 11.64 | 13.18 | 0.033 | 313.6 | 72.77 |
| *C. salvifolius* L. | A | 7.0 | 0.65 | 0.16 | 0.027 | 32.3 | 3.1 | 32.2 | 2.6 | 1.9 | <0.01 | 47.6 | 28.9 |
| | L | 71.41 | 0.48 | 0.43 | 0.019 | 30.33 | 7.98 | 483.62 | 10.58 | 0.98 | 0.00 | 229.98 | 198.00 |
| | T | 71.41 | 0.44 | 0.43 | 0.016 | 30.33 | 4.066 | 483.62 | 17.13 | 0.98 | 0.003 | 229.98 | 84.21 |
| *C. crispus* L. | A | 9.819 | 0.42 | 0.17 | 0.01 | 34.54 | 2.98 | 34.21 | 6.26 | 2.63 | 0.012 | 43.13 | 30.60 |
| | L | 109.56 | 0.93 | 0.71 | 0.017 | 65.02 | 8.84 | 550.17 | 14.16 | 26.12 | 0.042 | 504.13 | 222.06 |

## TABLE 26.1
**Trace Metal Composition of Soil and Plant Parts[a] Collected from the Abandoned Mine Complex** (continued)

| Plants/family | Plant part | As–S | As–P | Bi–S | Bi–P | Cu–S | Cu–P | Pb–S | Pb–P | W–S | W–P | Zn–S | Zn–P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Cistus monspeliensis* L. | L | 74.91 | 0.71 | 0.46 | 0 | 23.44 | 8.90 | 154.22 | 7.09 | 0 | 0 | 133.50 | 104.11 |
| | T | 74.91 | 0.84 | 0.46 | 0.004 | 23.44 | 3.17 | 154.21 | 5.30 | 0 | 0 | 133.50 | 52.51 |
| *Halimium ocymoides* (Lam.) Willk | T | 109.56 | 0.72 | 0.70 | 0.011 | 65.02 | 4.75 | 550.17 | 24.61 | 26.12 | 0.012 | 504.13 | 105.89 |
| | A | 10.36 | 0.22 | 0.22 | 0.005 | 30.74 | 3.31 | 32.84 | 3.39 | 2.82 | 0.006 | 51.97 | 30.87 |
| **Rosaceae** | | | | | | | | | | | | | |
| *Sanguisorba verrucosa* (Link) Ces. | A | 92.06 | 1.04 | 0.78 | 0.016 | 31.15 | 6.54 | 475.39 | 8.18 | 28.41 | 0.138 | 280.38 | 65.70 |
| *Pyrus bourgaeana* Decne | L | 20.2 | 0.15 | 0.21 | 0.027 | 28.7 | 22.9 | 179.8 | 6.4 | <0.1 | <0.01 | 306.4 | 121.2 |
| | T | 20.2 | 0.09 | 0.21 | 0.021 | 28.7 | 8.2 | 179.8 | 6.3 | <0.1 | <0.01 | 306.4 | 61.1 |
| *Rubus ulmifolius* Schott | L | 110.51 | 0.32 | 0.65 | 0.015 | 60.29 | 8.22 | 435.13 | 6.03 | 27.043 | 0.008 | 244.91 | 56.68 |
| | T | 110.52 | 0.30 | 0.65 | 0.014 | 60.29 | 6.52 | 435.13 | 3.79 | 27.043 | 0.002 | 244.91 | 59.10 |
| *Rosa canina* L. | L | 266.23 | 0.10 | 0.44 | 0.01 | 140.8 | 5.13 | 100.24 | 4.78 | 77.3 | 0 | 156.2 | 35.36 |
| | T | 266.23 | 0.048 | 0.44 | 0.022 | 140.85 | 7.25 | 100.24 | 8.18 | 77.35 | 0.011 | 156.22 | 40.47 |
| *Crataegus monogyna* Jacq. | L | 119.52 | 0.59 | 0.64 | 0.003 | 60.37 | 10.02 | 351.62 | 7.40 | 34.25 | 0.009 | 296.66 | 65.71 |
| | T | 119.52 | 0.39 | 0.64 | 0.003 | 60.37 | 6.02 | 351.69 | 4.20 | 34.25 | 0.010 | 296.66 | 93.51 |
| **Hypolepidaceae** | | | | | | | | | | | | | |
| *Pteridium aquilinum* (L.) Kuhn subsp. *aquilinum* | A | 226.90 | 0.19 | 1.16 | 0.002 | 102.46 | 7.045 | 406.78 | 5.52 | 75.91 | 0.003 | 236.92 | 285.27 |
| **Polygonaceae** | | | | | | | | | | | | | |
| *Rumex crispus* L. | A | 40.6 | 5.51 | 0.28 | 0.009 | 34.9 | 4.7 | 94.9 | 4.0 | 13.2 | 0.02 | 99.0 | 25.9 |
| *R. acetosella* L. subsp. *angiocarpus* Murb. | A | 45.91 | 0.43 | 0.46 | 0.054 | 31.88 | 6.30 | 863.20 | 15.92 | 6.613 | 0 | 344.42 | 123.7 |
| *R. induratus* Boiss. & Reuter | A | 213.26 | 1.13 | 0.80 | 0.015 | 102.63 | 6.19 | 86.29 | 14.04 | 75.86 | 0.16 | 138.24 | 35.05 |
| *Polygonum minus* Hudson | A | 51.2 | 0.92 | 0.64 | <0.001 | 28.9 | 4.9 | 1631.5 | 45.8 | <0.1 | <0.01 | 589.8 | 313.8 |
| **Caryophyllaceae** | | | | | | | | | | | | | |
| *Spergularia purpurea* (Pers.) G. Don. fil. | A | 135.5 | 0.45 | 1.02 | 0.010 | 88.35 | 12.85 | 2497.2 | 20.88 | 2.80 | 0 | 846.01 | 1057.7 |
| *Petrorhagia nanteuillii* (Burnat) P.W. Ball & Heywood | A | 376.4 | 3.35 | 0.54 | 0.092 | 197.63 | 2.97 | 79.02 | 6.96 | 116.02 | 0.028 | 175.08 | 27.75 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Silene scabriflora* Brot. subsp. *scabriflora* | A | 26.19 | 0.45 | 0.31 | 0.02 | 26.14 | 6.37 | 135.86 | 5.74 | 0 | 0 | 233.49 | 138.26 |
| *Ortegia hispanica* Loefl. ex. L. | A | 261.2 | 0.43 | 2.55 | 0.003 | 57.7 | 13.7 | 102.5 | 4.4 | 142.1 | <0.01 | 145.3 | 168.6 |
| *Saponaria officinalis* L. | A | 39.3 | 5.59 | 0.48 | 0.009 | 31.2 | 5.1 | 100.9 | 7.3 | 3.3 | 0.01 | 137.6 | 41.2 |
| **Boraginaceae** | | | | | | | | | | | | | |
| *Echium plantagineum* L. | A | 20.1 | 0.31 | 0.21 | 0.014 | 20.6 | 8.8 | 248.5 | 6.1 | <0.1 | <0.01 | 243.5 | 158.6 |
| **Athyriaceae** | | | | | | | | | | | | | |
| *Athyrium felix-femina* (L.) Roth. | A | 69.3 | 0.14 | 1.56 | 0.002 | 30.5 | 7.4 | 141.9 | 16.2 | 5.5 | <0.01 | 99.3 | 31.7 |
| **Aristolochiaceae** | | | | | | | | | | | | | |
| *Aristolochia longa* L. | A | 32.45 | 0.33 | 0.39 | 0.007 | 26.82 | 11.64 | 509.76 | 10.04 | 0 | 0 | 322.5 | 204.90 |
| **Scrophulariaceae** | | | | | | | | | | | | | |
| *Digitalis purpurea* L. subsp. purpurea | A | 42.97 | 0.94 | 0.74 | 0.024 | 27.45 | 9.13 | 163.79 | 5.32 | 2.93 | 0.016 | 160.16 | 154.50 |
| *D. thapsi* L. | A | 338 | 0.49 | 1.20 | 0.037 | 150.97 | 6.717 | 86.84 | 55.89 | 124.71 | 0.037 | 165.14 | 172.19 |
| *Linaria aeruginea* (Gouan) Cav. | A | 20.24 | 0.62 | 0.23 | 0.055 | 26.02 | 6.38 | 394.19 | 10.44 | 0.90 | 0 | 243.69 | 119.71 |
| *Anarrhinum bellidifolium* (L.) Willd. | A | 338 | 0.90 | 1.20 | 0.01 | 150.97 | 5.72 | 86.84 | 3.93 | 124.71 | 0.013 | 165.14 | 39.88 |
| **Pinaceae** | | | | | | | | | | | | | |
| *Pinus pinaster* Aiton | N | 115.4 | 1.6 | 0.6 | 0.1 | 69.8 | 2.5 | 447.6 | 2.9 | 32.2 | 0.0 | 524.6 | 56.7 |
| | T | 95.6 | 0.1 | 0.5 | 0.0 | 63.0 | 3.4 | 370.8 | 4.0 | 26.8 | 0.0 | 436.6 | 32.3 |
| **Apiaceae** | | | | | | | | | | | | | |
| *Oenanthe crocata* L. | A | 131.85 | 0.14 | 0.98 | 0.039 | 68.03 | 25.41 | 255.95 | 15.47 | 4.87 | 0.002 | 107.57 | 69.68 |
| *Eryngium campestre* L. | A | 48.7 | 0.03 | 0.53 | 0.004 | 38.3 | 4.1 | 1091.0 | 4.9 | 0.1 | <0.01 | 709.5 | 17.9 |
| **Oleaceae** | | | | | | | | | | | | | |
| *Olea europaea* L. | L | 131.76 | 0.6 | 0.50 | 0.023 | 92.18 | 5.59 | 171.16 | 4.29 | 46.14 | 0.02 | 338.37 | 41.00 |
| | T | 131.76 | 0.24 | 0.50 | 0.012 | 92.18 | 3.92 | 171.16 | 4.68 | 46.14 | 0.003 | 338.37 | 48.72 |
| *Fraxinus angustifolia* Vahl | L | 115.6 | 0.05 | 1.02 | 0.00 | 33.63 | 7.81 | 118.57 | 6.73 | 6.36 | 0 | 100.73 | 116.87 |
| | T | 115.62 | 0.13 | 1.02 | 0.009 | 33.63 | 7.20 | 118.57 | 7.85 | 6.36 | 0.002 | 100.73 | 117.63 |
| **Valerianceae** | | | | | | | | | | | | | |
| *Centranthus calcitrapae* (L.) Dufresne | A | 338.0 | 0.3 | 1.2 | 0.0 | 151.0 | 10.1 | 86.8 | 12.8 | 124.7 | 0.0 | 165.1 | 34.1 |
| **Thymelaeaceae** | | | | | | | | | | | | | |
| *Daphne gnidium* L. | L | 134.51 | 0.50 | 0.83 | 0.517 | 80.53 | 11.54 | 668.86 | 59.47 | 34.77 | 0.039 | 311.86 | 261.20 |

**TABLE 26.1**
**Trace Metal Composition of Soil and Plant Parts[a] Collected from the Abandoned Mine Complex** (continued)

| Plants/family | Plant part | As–S | As–P | Bi–S | Bi–P | Cu–S | Cu–P | Pb–S | Pb–P | W–S | W–P | Zn–S | Zn–P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Dioscoreaceae** | **T** | **134.51** | **0.36** | **0.83** | **0.22** | **80.53** | **13.64** | **668.86** | **7.38** | **34.77** | **0.005** | **311.86** | **149.64** |
| *Tamus communis* L. | A | 29.11 | 0.49 | 0.35 | 0.052 | 24.88 | 10.20 | 113.87 | 7.56 | 0 | 0 | 197.02 | 110.3 |
| **Lamiaceae** | | | | | | | | | | | | | |
| *Mentha pulegium* L. | A | 43.2 | 0.52 | 0.27 | 0.016 | 31.08 | 9.79 | 118.82 | 6.11 | 6.61 | 0 | 108.75 | 34.95 |
| *Mentha suaveolens* Ehrh. | A | 83.08 | 0.39 | 0.57 | 0.007 | 30.52 | 11.30 | 137.42 | 7.10 | 3.89 | 0.024 | 133.87 | 324.50 |
| *Origanum virens* Hoffmanns & Link | A | 16.1 | 0.61 | 0.14 | 0.005 | 22.8 | 10.3 | 133.9 | 5.2 | <0.1 | <0.01 | 243.9 | 62.7 |
| *Phlomis lychnitis* L. | A | 469.5 | 0.32 | 0.40 | 0.098 | 356.7 | 14.0 | 62.5 | 29.8 | 230.7 | 0.37 | 244.9 | 710.3 |
| *Clinopodium vulgare* L. | A | 26.12 | 0.54 | 0.30 | 0.036 | 26.13 | 10.82 | 135.86 | 14.66 | 0 | 0 | 233.49 | 263.72 |
| *Lavandula stoechas* L. subsp. *pedunculata* (Miller) Samp. ex. Rozeira | A | 159.00 | 0.73 | 0.89 | 0.00 | 74.70 | 10.60 | 704.98 | 11.97 | 31.88 | 0.07 | 644.8 | 347.19 |
| *Teucrium scorodonia* L. | A | 124.27 | 0.18 | 0.82 | 0.008 | 32.59 | 9.25 | 139.09 | 4.35 | 2.25 | 0 | 170.34 | 112.35 |
| | E | 9.99 | 0.30 | 0.20 | 0.018 | 31.65 | 4.79 | 33.19 | 3.68 | 2.82 | 0.034 | 47.640 | 45.95 |
| | FL | 146.77 | 0.26 | 0.82 | 0.015 | 68.95 | 17.47 | 650.75 | 9.65 | 29.43 | 0.059 | 595.2 | 206.98 |
| | T | 146.77 | 0.39 | 0.82 | 0.014 | 68.95 | 5.47 | 650.75 | 8.85 | 29.43 | 0.01 | 595.24 | 329.4 |
| *L. stoechas* L. subsp. *stoechas* | A | 9.99 | 0.24 | 0.20 | 0.044 | 31.65 | 3.07 | 33.19 | 2.20 | 2.827 | 0.006 | 47.640 | 36.72 |
| *Origanum virens* Hoffmanns & Link | A | 16.1 | 0.61 | 0.14 | 0.005 | 22.8 | 10.3 | 133.9 | 5.2 | <0.1 | <0.01 | 243.9 | 62.7 |
| **Cyperaceae** | | | | | | | | | | | | | |
| *Eleocharis multicaulis* (Sm.) Desv. | A | 123.26 | 0.14 | 0.41 | 0.004 | 33.58 | 2.99 | 111.05 | 3.79 | 4.84 | 0.038 | 107.59 | 25.46 |
| *Cyperus fuscus* L. | A | 102.27 | 0.07 | 0.42 | 0.010 | 32.98 | 4.66 | 108.58 | 3.77 | 4.47 | 0 | 115.10 | 68.70 |
| *Scirpus holoschoenus* L. | A | 93.14 | 0.30 | 0.79 | 0.002 | 58.99 | 3.55 | 1207.1 | 5.13 | 3.45 | 0.006 | 1020.0 | 123.18 |
| **Juncaceae** | | | | | | | | | | | | | |
| *Juncus inflexus* L. | A | 40.6 | 1.53 | 0.28 | 0.013 | 34.9 | 7.0 | 94.9 | 6.0 | 13.2 | 0.02 | 99.0 | 74.7 |
| *J. heterophyllus* Dufour | A | 39.3 | 1.64 | 0.48 | 0.011 | 31.2 | 14.1 | 100.9 | 5.2 | 3.3 | <0.01 | 137.6 | 399.3 |
| **Liliaceae** | | | | | | | | | | | | | |
| *Ruscus aculeatus* L. | P | 42.3 | 0.44 | 0.57 | 0.004 | 26.9 | 3.0 | 93.8 | 3.3 | <0.1 | <0.01 | 150.1 | 134.9 |
| *Asparagus acutifolius* L. | A | 376.4 | 19.62 | 0.54 | 0.05 | 197.63 | 3.14 | 79.02 | 10.32 | 116.02 | 0.038 | 175.05 | 37.03 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Rutaceae** | | | | | | | | | | | | | |
| *Ruta montana* L. | A | 469.5 | 0.05 | 0.40 | 0.012 | 356.7 | 3.6 | 62.5 | 5.4 | 230.7 | 0.02 | 244.9 | 13.6 |
| **Haloragaceae** | | | | | | | | | | | | | |
| *Myriophyllum alterniflorum* DC. | W | 46.91 | 9.94 | 0.51 | 0.020 | 29.06 | 9.309 | 876.66 | 93.76 | 0.83 | 0.06 | 358.95 | 507.83 |
| **Lythraceae** | | | | | | | | | | | | | |
| *Lythrum hyssopifolia* L. | A | 39.95 | 0.56 | 0.38 | 0.023 | 33.03 | 11.29 | 97.93 | 9.29 | 8.28 | 0.045 | 118.32 | 879.87 |
| **Callitichaceae** | | | | | | | | | | | | | |
| *Callitriche stagnalis* (L.) Scop | A | 39.3 | 531.4 | 0.48 | <0.001 | 31.2 | 127.8 | 100.9 | 62.5 | 3.3 | 0.42 | 137.6 | 2258.5 |
| **Rubiaceae** | | | | | | | | | | | | | |
| *Galium palustre* L. | A | 39.3 | 11.98 | 0.48 | 0.140 | 31.2 | 60.7 | 100.9 | 12.8 | 3.3 | <0.01 | 137.6 | 1726.0 |
| **Typhaceae** | | | | | | | | | | | | | |
| *Typha dominguensis* (Pers.) Steudel | L | 51.2 | 0.27 | 0.64 | 0.005 | 28.9 | 3.2 | 1631.5 | 7.5 | <0.1 | <0.01 | 589.8 | 82.0 |
| | F | 51.2 | 0.12 | 0.64 | 0.011 | 28.9 | 2.3 | 1631.5 | 8.2 | <0.1 | <0.01 | 589.8 | 66.8 |
| | AL | 51.2 | 0.20 | 0.64 | 0.013 | 28.9 | 5.1 | 1631.5 | 4.0 | <0.1 | <0.01 | 589.8 | 39.3 |
| | R | 51.2 | 16.97 | 0.64 | 0.021 | 28.9 | 7.9 | 1631.5 | 157.8 | <0.1 | 0.15 | 589.8 | 389.7 |
| *Briza maxima* L. | A | 272.25 | 0.02 | 1.61 | 0.19 | 48.11 | 6.46 | 99.01 | 97.02 | 71.69 | 0.06 | 125.26 | 36.21 |
| *Arrhenatherum elatius* (L.) J. & C. Presl. | A | 272.25 | 0.22 | 1.61 | 0.035 | 48.11 | 3.71 | 99.01 | 8.37 | 71.69 | 0 | 125.26 | 29.88 |
| *Avena sterilis* L. | A | 272.25 | 0.20 | 1.61 | 0.086 | 48.11 | 5.13 | 99.01 | 5.60 | 71.69 | 0.39 | 125.26 | 40.96 |
| *Agrostis curtisii* Kerguélen | A | 10.49 | 0.61 | 0.22 | 0.007 | 30.30 | 1.994 | 39.18 | 2.03 | 1.66 | 0.009 | 81.12 | 20.31 |
| **Onagraceae** | | | | | | | | | | | | | |
| *Ludwigia palustris* (L.) Elliott | A | 322.6 | 1.9 | 1.2 | 0.1 | 69.8 | 53.5 | 196.5 | 35.1 | 4.7 | 0.0 | 242.9 | 1131.0 |
| **Dipsacaceae** | | | | | | | | | | | | | |
| *Pterocephalus diandrus* Lag. | A | 261.2 | 1.08 | 2.55 | 0.003 | 57.7 | 8.6 | 102.5 | 3.9 | 142.1 | <0.01 | 145.3 | 138.4 |
| **Ranunculaceae** | | | | | | | | | | | | | |
| *Ranunculus peltatus* Schrank | A | 45.9 | 3.07 | 0.26 | 0.016 | 27.3 | 5.0 | 142.7 | 13.1 | <0.1 | 0.04 | 118.5 | 29.0 |
| **Myrtaceae** | **A** | **42.3** | **0.40** | **0.57** | **0.005** | **26.9** | **1.5** | **93.8** | **1.9** | **<0.1** | **<0.01** | **150.1** | **67.1** |
| *Eucalyptus globulus* Labill | L | 6.27 | 0.023 | 0.15 | 0.013 | 31.67 | 2.69 | 27.25 | 1.03 | 3.35 | 0.02 | 73.40 | 2.92 |

**TABLE 26.1**
**Trace Metal Composition of Soil and Plant Parts[a] Collected from the Abandoned Mine Complex** (continued)

| Plants/family | Plant part | As–S | As–P | Bi–S | Bi–P | Cu–S | Cu–P | Pb–S | Pb–P | W–S | W–P | Zn–S | Zn–P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Betulaceae** | | | | | | | | | | | | | |
| *Alnus glutinosa* (L.) Gaertner | L | 54.95 | 0.014 | 0.92 | 0.013 | 32.70 | 11.90 | 118.42 | 6.006 | 9.34 | 0.036 | 99.17 | 64.71 |
| | T | 54.95 | 0.00 | 0.92 | 0.006 | 32.70 | 5.55 | 118.42 | 1.76 | 9.34 | | 99.17 | 38.07 |
| **Caprifoliaceae** | | | | | | | | | | | | | |
| *Lonicera periclymenum* L. | L | 20.2 | 0.96 | 0.21 | 0.004 | 28.7 | 7.8 | 179.8 | 4.8 | <0.1 | <0.01 | 306.4 | 290.5 |
| | T | 20.2 | 0.67 | 0.21 | <0.001 | 28.7 | 5.8 | 179.8 | 4.2 | <0.1 | <0.01 | 306.4 | 290.4 |
| **Salicaceae** | | | | | | | | | | | | | |
| *Salix salvifolia Brot*. | L | 103.60 | 0.65 | 0.51 | 0.014 | 33.38 | 5.14 | 480.72 | 2.72 | 4.47 | 0.005 | 232.94 | 117.50 |
| | T | 103.60 | 0.32 | 0.51 | 0.0120 | 33.38 | 3.87 | 480.72 | 1.83 | 4.47 | 0.001 | 232.94 | 122.25 |
| *S. atrocinerea* Brot. | L | 10.68 | 0.24 | 0.21 | 0.014 | 30.78 | 2.61 | 33.22 | 0.71 | 2.77 | 0.009 | 51.74 | 22.71 |
| | T | 40.6 | 0.65 | 0.28 | 0.007 | 34.9 | 6.2 | 94.9 | 3.4 | 13.2 | 0.03 | 99.0 | 328.5 |

2[a]mg $kg^{-1}$.
*Notes*: A = aerial parts; F = fruit; FL = flower; L = leaf; N = needles; P = phyllaode; R = root; S = seed; T = twig; W = whole plant; P = suffixing element in plant; S = suffixing element in soil.

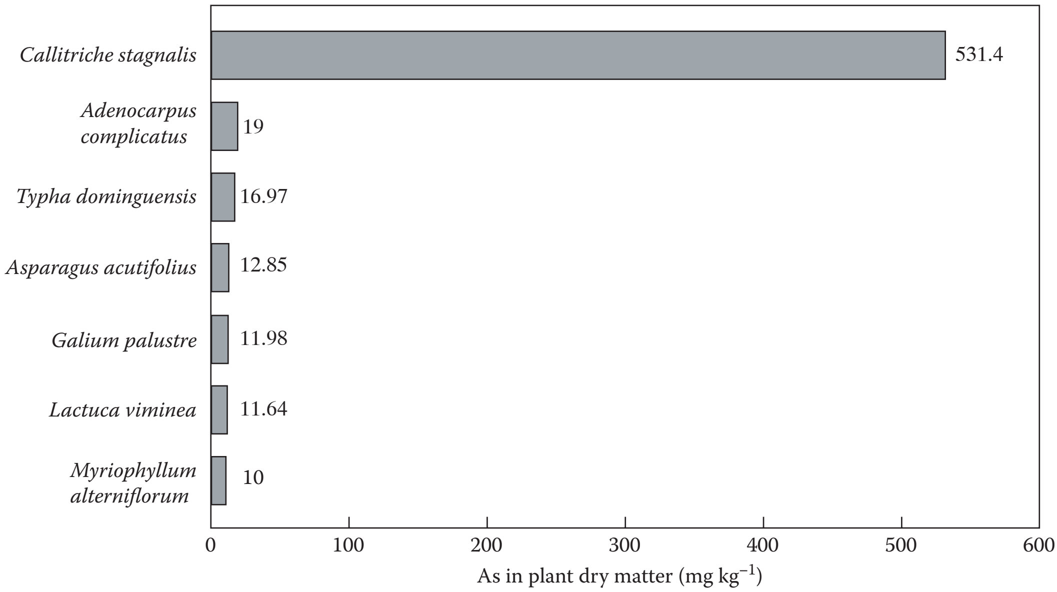


**FIGURE 26.1** Accumulation of lead (in mg kg$^{-1}$ dry weight) in plant species from the Palão, Pinheiro, and Mata da Rainha mine complex.

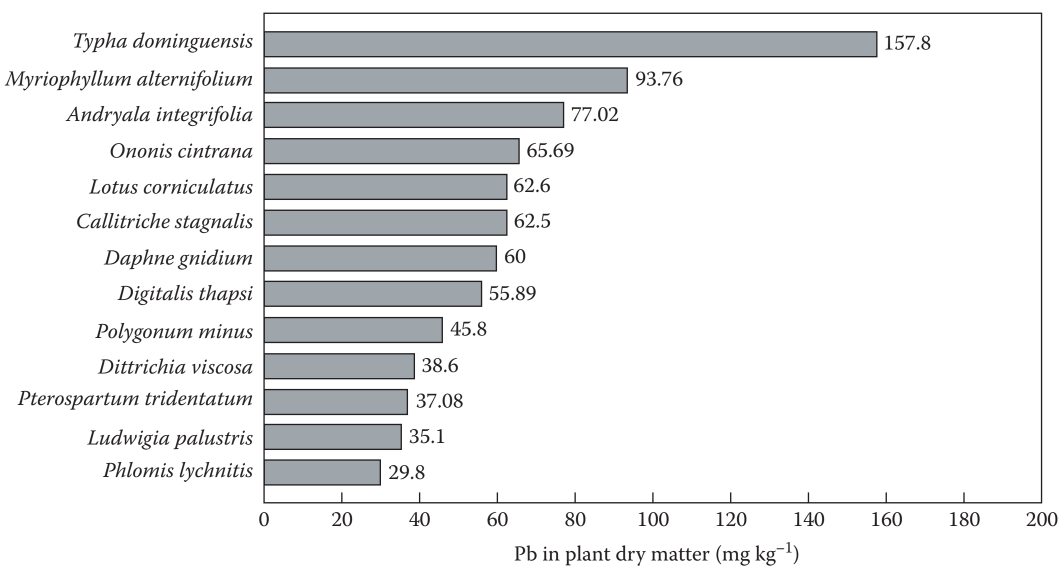


**FIGURE 26.2** Accumulation of arsenic (in mg kg$^{-1}$ dry weight) in plant species of the Palão, Pinheiro, and Mata da Rainha mine complex.

## 26.5 CONCLUSIONS

It is worth pointing out that the species from the most representative families are typical Mediterranean species, which are well adapted to environmental stress conditions — namely, water stress and very poor and tiny soils, and are represented in the investigated samples. Tolerance to high levels of metals in the soil is the important aspect for application in phytoremediation. It is also advantageous when the plant community can tolerate other environmental stress factors as mentioned earlier. The investigated plant species are present in metal-enriched soils and therefore manage to control the uptake of heavy metals and also cope with very poor nutritional substrates.This study gave important insights for remediation of contaminated soils. The investigated plant community was established on abandoned mines.

The plant diversity observed in this study includes a number of functional groups of plants (semiaquatic, legumes, grasses, and tree species) (Table 26.1) in response to single stress factors or a combination of them. The reclamation of such mines may include metal accumulators belonging to these functional groups to initiate plant successions in such a hostile environment, eventually leading to restoration of the ecosystem [24,25]. The use of legumes may enrich the soil nutrient content and the combined used of perennials and annuals can provide different inputs in terms of organic matter and nutrient recycling, thus contributing in distinct ways to the development of the soil.

Establishing plant communities with tolerance to toxic metals is an approach that would successfully reclaim mines or minimize the hazards of environment [26–31]. The success of any phytoremediation technique depends upon the identification of suitable plant species that hyperaccumulate trace metals and produce a large amount of biomass, using established crop production and management practices. Restoration of abandoned mines by phytostabilization, soil ammendments, and rhizosphere biotechnology facilitates phytoremediation technology and is supported by promising research findings.

In conclusion, studies on plants that accumulate/hyperaccumulate toxic trace elements have significant environmental and biogeochemical implications (Figure 26.3). The emerging phytoremediation technologies aimed at metals in the environment would derive great sources of knowledge and information on this category of plants for the benefit of man and biosphere.

In order to establish the vegetative groundcover on the surface mined sites, the two most important factors influencing species selection are the soil properties and the tolerance levels of the selected plants. Three categories of plants have been noted to possess the reclamation potential

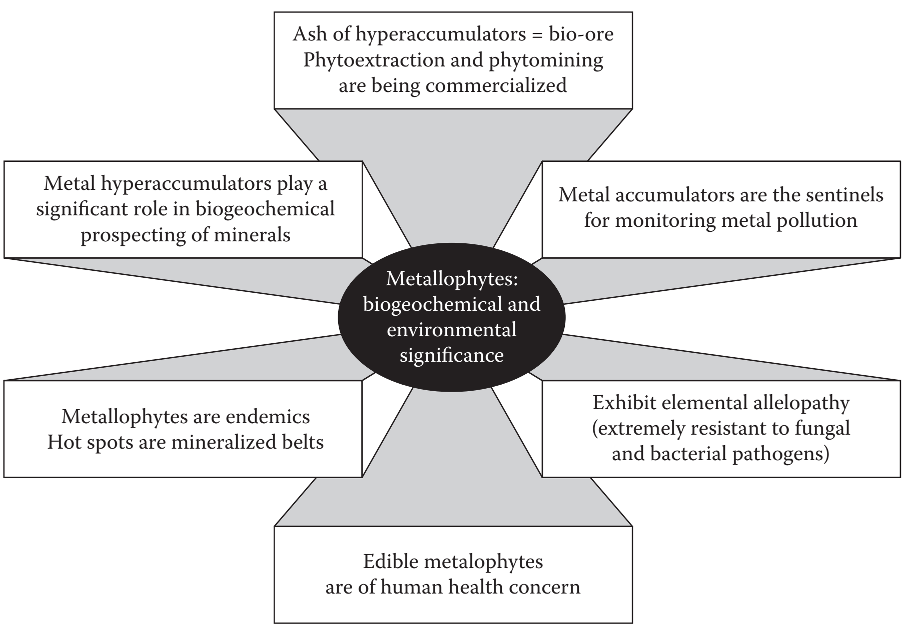


**FIGURE 26.3** Plants that accumulate metals (metallophytes) have a major role in mine restoration and also serve as sentinels of mineral exploration (biogeochemical prospecting). The environmental and biogeochemical significance of the metal-tolerant plants is depicted in this figure.

for mine areas. They are grasses, forbs, and trees. Grasses (Poaceae) produce large amounts of biomass and are adapted to initiate regrowth rapidly. Grasses have fibrous root systems that hold soil in place, thereby controlling erosion.

Forbs (herbaceous flowering plants) are generally used in mine revegetation in conjunction with grasses. Forbs usually have broad leaves, flowers, and a branching taproot system. Forbs can be further classified as *legumes* and *non-legumes*. Legumes are especially important for revegetating mined lands because they are capable of using nitrogen from the air to meet their N nutrition requirements, and they can transfer this "fixed" N to other components of the plant/soil system. Nonleguminous forbs are also broad-leaved plants with showy flowers. The establishment of trees and shrubs on mined lands is the final stage of reclamation [22,32,33].

The identified assemblage of plants (Table 26.1) consists of the preceding three categories and is well adapted to the metal toxicity [34]. Phytostabilization of mining sites is a well established environmental compliance using plant species that adapt different strategies, such as metal tolerance, metal accumulation, and metal exclusion [11,23,35–40]. This type of approach requires increasing information about plant communities growing on different kinds of abandoned mine sites in order to take advantage of their potential for phytostabilization of abandoned mines.

The physicochemical properties of the metal-contaminated soils tend to inhibit soil-forming processes and plant growth. In addition to elevated metal concentrations, other adverse factors include absence of topsoil; periodic sheet erosion; drought; surface mobility; compaction; wide temperature fluctuations; absence of soil-forming fine materials; and shortage of essential nutrients [41,42]. The mine-degraded soils usually have low concentrations of important nutrients like K, P, and N [43]. Toxic metals can also adversely affect the number, diversity, and activity of soil organisms, inhibiting soil organic matter decomposition and N mineralization processes. The chemical form of the potential toxic metal, the presence of other chemicals that may aggravate or ameliorate metal toxicity, the prevailing pH, and the poor nutrient status of the trace element-contaminated soil will affect the way in which plants respond to the toxic metal.

Substrate pH affects plant growth mainly through its effect on the solubility of chemicals, including toxic metals and nutrients. Three important factors may affect the bioavailability of metals: (1) soil capacity: pH cation exchange, capacity, organic matter, amount and type of clay, ion interactions, oxides of Fe and Mn, and redox potential; and (2) plant capacity, such as species, cultivar, age of plant part, and 3 plant–metal interaction [44].

Phytoremediation of heavy metal-contaminated soils basically includes phytostabilization and phytoextraction. Some soils are so heavily contaminated that removal of metals using plants would take an unrealistic amount of time. The normal practice is to choose drought-resistant, fast growing crops or fodder that can grow in metal-contaminated and nutrient-deficient soils.

## REFERENCES


1. Kabata–Pendias, A., *Trace Elements in Soil and Plants*. CRC Press, Boca Raton, FL, 2001, 432.
2. Ross, S.M., Ed., *Toxic Metals in Soil and Plant Systems*. Wiley, Chichester, U.K., 1994.
3. Siegel, R.R., *Environmental Geochemistry of Potentially Toxic Metals*. Springer–Verlag, Heidelberg, 2002, 218.
4. Sengupta, M., *Environmental Impacts of Mining: Monitoring, Restoration and Control*. Lewis Publishers, Boca Raton, FL, 1993.
5. Badri, M. and Springuel, I., Biogeochemical prospecting in the southeastern desert of Egypt, *J. Arid Environ.,* 28, 257, 1994.
6. Fletcher, W.K., Analytical methods in geochemical prospecting, in *Handbook of Exploration Geochemistry*, Govett, G.J.S., Ed., vol. 1. Elsevier, Amsterdam, 1981, 255, 1.
7. Kovalevskii, A.L., *Biogeochemical Exploration for Mineral Deposits*. Oxonian Press PVT, New Dehli, 1979, 136.

8. McInnes, B.I.A. et al., Biogeochemical exploration for gold in tropical rain forest regions of Papua, New Guinea, *J. Geochem. Exploration,* 57, 227, 1996.
9. Brooks, R.R., *Biological Methods of Prospecting for Minerals*. Wiley-Interscience, New York, 1983, 313.
10. Hooper, D.U. and Vitousek, P.M., The effects of plant composition and diversity on ecosystem processes, *Science*, 277, 1302, 1997.
11. Wong, M.H., Ecological restoration of mine degraded soils, with emphasis on metal contaminated soils, *Chemosphere*, 50, 775, 2003.
12. Bradshaw, A.D., Understanding the fundamentals of succession, in Miles, J. and Walton, D.H. (Eds.), *Primary Succession on Land*. Blackwell, Oxford. 1993.
13. Baker, A.J.M., Accumulators and excluders: strategies in the response of plants to trace metals, *J. Plant Nutr.*, 3, 643, 1981.
14. Pratas, J. et al. Plants growing in abandoned mines of Portugal are useful for biogeochemical exploration of arsenic, antimony, tungsten and mine reclamation, *J. Geochemical Exploration,* 85, 99, 2005.
15. Levinson, A., *Introduction to Exploration Geochemistry.* Applied Publishing Ltd, Calgary, 1994, 612.
16. Franco, J.A., *Nova Flora de Portugal Continente e Açores* Vol. I *Lycopodiaceae — Umbelliferae*. Lisboa, 1971, 555.
17. Franco, J.A., *Nova Flora de Portugal Continente e Açores*, Vol. II *Clethraceae — Compositae*. Lisboa, 659, 1984.
18. Quin, B.F. and Brooks, R.R., The rapid determination of tungsten in soils, rocks and vegetation, *Anal. Chim. Acta*, 58, 301, 1972.
19. Aslin, G.E.M., The determination of arsenic and antimony in geological materials by flameless atomic absorption spectrometry, *J. Geochem. Explor.*, 6, 321, 1976.
20. Van Loon, J.C., *Selected Methods of Trace Metal Analysis: Biological and Environmental Samples*. John Wiley & Sons, London, 1985, 355.
21. Vijan, P.N. et al., A semiautomated method for the determination of arsenic in soil and vegetation by gas-phase sampling and atomic absorption spectrometry, *Anal. Chim. Acta*, 82, 329, 1976.
22. Hooper, D.U. and Vitousek, P.M., Effect of plant composition and diversity on nutrient cycling, *Ecol. Monogr.*, 68, 121, 1998.
23. Tsao, D. (Ed.), *Phytoremediation*. Springer–Verlag, Heidelberg, 206, 2003.
24. Vangronsveld, J. and Cunningham, S.D. *Metal-Contaminated Soils:* in Situ *in Activation and Phytorestoration*. Springer–Verlag, Berlin, 265, 1998.
25. Wenzel, W.W., Lombi, E., and Adriano, D.C., Biogeochemical processes in the rhizosphere: role in phytoremediation of metal-polluted soils, in *Heavy Metal Stress in Plants — from Molecules to Ecosystems*, Prasad, M.N.V. and Hagemeyer, J., Eds. Springer–Verlag, Berlin, 1999, 271.
26. Markert, B., *Plants as Biomonitors: Indicators for Heavy Metals in the Terrestrial Environment*. 1993, VCH Publishers.
27. Palmer, E.F., Warwick, F., and Keller, W., Brassicaceae (Cruciferae) family, plant biotechnology and phytoremediation, *Int. J. Phytoremediation*, 3, 245, 2001.
28. Prasad, M.N.V., *Metals in the Environment — Analysis by Biodiversity.* Marcel Dekker Inc., 2001, New York, 504.
29. Prasad, M.N.V., and K. Strzalka *Physiology and Biochemistry of Metal Toxicity and Tolerance in Plants*. Kluwer Academic Publishers, Dordrecht, 460, 2002.
30. Prasad, M.N.V., Phytoremediation of metals and radionuclides in the environment: the case for natural hyperaccumulators, metal transporters, soil-amending chelators and transgenic plants, in M.N.V. Prasad (Ed.), *Heavy Metal Stress Inlants: from Biomolecules to Ecosystems*. Springer–Verlag, Heidelberg, 2nd ed., 2003, 345–392.
31. Prasad, M.N.V. and Freitas, H., Feasible biotechnological and bioremediation strategies for serpentine soils and mine spoils, *Electron. J. Biotechnol.,* 1999, 2, 35. http://Ejb.Ucv.Cl Or Http://Www.Ejb.Org.
32. Berry, C.R., Growth and heavy metal accumulation in pine seedlings grown with sewage sludge, *J. Environ. Qual.*, 14, 415, 1995.
33. Bending, N.A.D. and Moffat, A.J., Tree performance on mine spoils in the South Wales coalfield, *J. Appl. Ecol.*, 36, 784, 1999.
34. Pulford, I.D. and Watson, C., Phytoremediation of heavy metal-contaminated land by trees — a review, *Environ. Int.*, 29, 529, 2003.

35. Dahmani–Muller, H., van Oort, F., Gélie, B., and Balabane, M., Strategies of heavy metal uptake by three plant species growing near a metal smelter, *Environ. Pollut.*, 109, 231–238, 2000.
36. Shu, W.S. et al., Use of vetiver and other three grasses for revegetation of Pb/Zn mine tailings at Lechang, Guangdong Province: field experiment, in *2nd Int. Vetiver Conf.*, Bangkok, Thailand, 2000.
37. Tang, S.R. et al., The uptake of copper by plants dominantly growing on copper mining spoils along the Yangtze River, the People's Republic of China, *Plant Soil*, 209, 225, 1999.
38. Tang, S.R. et al., Heavy metal uptake by metal-tolerant *Elsholtzia haichowensis* and *Commelina communis* from China, *Commun. Soil Sci. Plant Anal.*, 32, 895, 2001.
39. Yang, Z.Y. et al., Germination, growth and nodulation of *Sesbania rostrata* grown in Pb/Zn mine tailings, *Environ. Manage.*, 21, 617, 1997.
40. Zhang, Z.Q. et al., Soil seed bank as an input of seed source in revegetation of lead/zinc mine tailings, *Restor. Ecol.*, 9, 1, 2001.
41. Wong, J.W.C. et al., Phytostabilization of mimicked cadmium-contaminated soil with lime amendment, in *Proc. 5th Int. Conf. Biogeochem. Trace Elements*, Vienna, 1999.
42. Wong, M.H. et al., Current approaches to managing and remediating metal contaminated soils in China, in *Proc. 5th Int. Conf. Biogeochem. Trace Elements*, Vienna, Austria, 1999.
43. Huenneke, L.F. et al., Effects of soil resources on plant invasion and community structure in Californian serpentine grassland, *Ecology*, 71, 2, 478, 1990.
44. Adriano, D.C., *Trace Elements in Terrestrial Environments: Biogeochemistry Bioavailability and Risks of Metals*. 2nd ed., Springer–Verlag, New York, 866, 2001.