Chapter 6
Phytoremediation Applications for Metal-Contaminated Soils Using Terrestrial Plants in Vietnam

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Abstract In the past few decades, the association of economic growth and mining activities has led to an increase in areas of heavy metal-contaminated soils in Vietnam. As a developing country, Vietnam has the limited financial source for environmental restoration, so phytoremediation, a low cost and ecologically sustainable remedial technology, is considered to be a relevant option. To promote the application of phytoremediaton for heavy metal-contaminated soils in Vietnam, there have been several research programs conducted during the last decade. The studies identified two arsenic (As) hyperaccumulators, ***Pteris vittata*** and ***Pityrogramma calomelanos***, and four grasses suitable for treatment of lead (Pb)- and zinc (Zn)-contaminated soils, ***Eleusine indica***, ***Cyperus rotundus, Cynodon dactylon***, and ***Equisetum ramosissimum***, of which *E. indica* was found as Pb hyperaccumulator. All of these species are indigenous and naturally adapted to heavy metal-contaminated habitats. Three plant species, *P. vittata, P. calomelanos*, and *E indica* and one introduced plant species, ***Vetiveria zizanioides***, were subjected to further evaluation of their heavy metal removal potential under greenhouse and field conditions. The results of greenhouse experiments showed that two fern species, *P. vittata and P. calomelanos*, are effective in the accumulation of soil As in roots and fronds; ***E. indica*** can absorb high concentration of both Pb and Zn in roots. Under field conditions, the combination of ***P. vittata, P. calomelanos***, and ***V. zizanioides*** or ***P. vittata, E. indica*** and ***V. zizanioides*** is very effective in treatment of soils contaminated with low or moderate concentration of As and Pb in short time (3 years).

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Through these studies, phytoremediation has been demonstrated to be feasible for the remediation of heavy metal-contaminated soils in Vietnam.

Keywords Mining activity • Heavy metal-contaminated soil • Indigenous hyperaccumulator • Potential species for phytoremediation • Bac Kan and Thai Nguyen provinces

6.1 Introduction

An increasingly industrialized global economy and rapid rise in world population over the last century have led to dramatically elevated releases of anthropogenic chemicals, particularly heavy metals, into the environment [1]. The annual worldwide release of heavy metals reached 22,000 metric ton (t) for cadmium, 939,000 t for copper, 783,000 t for lead, and 1,350,000 t for zinc over recent decades [2]. Sources of heavy metal released into soil environments include mining, smelting of metalliferous, electroplating, gas exhaust, energy and fuel production, fertilizer and pesticide application, sewage sludge treatment, warfare and military training [3]. Hard-rock mining that is the largest producer of heavy metal waste takes place in all of the continents of the world with the exception of Antarctica [4].

Heavy metal-contaminated soils have caused serious problems threatening ecological systems and human health, recently attracted considerable public attention. Several metals, such as Cu and Zn, are essential for biological systems and must be present within a certain concentration range [5], at high concentrations they will become toxic. Other metals, such as Cd, As, Hg, and Pb, have not been found to have any function in plants and animals, and very toxic for biological life even occurred at low concentrations. Metals can act in a deleterious manner by blocking essential functional groups, displacing other metal ions, or modifying the active conformation of biological molecules [6]. Exposure to high levels of these metals can cause adverse effect on human and wildlife [7]. Toxic heavy metals can mutate DNA resulting in carcinogenic effects in animals and human [8, 9]. Lead causes neurological damage in children leading to reduced intelligence, loss of short-term memory, learning disabilities, and coordination problems [7]. The effects of arsenic include cardiovascular problems, skin cancer and other skin effects, peripheral neuropathy [10]. Cadmium accumulates in the kidneys and is responsible for a wide range of kidney diseases [10]. The principal health risks associated with mercury are damage to the nervous system, with such symptoms as uncontrollable shaking, muscle wasting, partial blindness, and deformities in children exposed in the womb [10].

Concentrations of heavy metals that have exceeded safety levels in soil should be treated [11]. There are several methods used for soil remediation, including chemical, physical, and biological techniques. Physical treatments involve removal from contaminated sites (soil excavation), deep burial (landfilling), and capping, while chemical methods use strong acids and chelators to wash polluted soils.

These approaches are expensive, impractical, and at times impossible to carry out, as the volume of contaminated materials is very large. Furthermore, they irreversibly affect soil properties, destroy biodiversity, and may render the soil useless as a medium for plant growth [7]. Recently, phytoremediation that refers to a diverse collection of plant-based technologies using either naturally occurring or genetically engineered plants to clean contaminated environments [12] represents a novel, environmentally friendly, and cost-effective technology and attracts the attention of publics and scientists worldwide.

The idea of using plants to extract metals from contaminated soil was reintroduced and developed by Utsunamyia [13] and Chaney [14] and the first field trial on Zn and Cd phytoextraction was conducted by Baker et al. [15]. Some plants which grow on metalliferous soils have developed the ability to accumulate massive amounts of indigenous metals in their tissues without symptoms of toxicity [15]. Depending on storage sites of heavy metals in plants, phytoremediation technology can be used for containment (phytostabilization) and removal (phytoextraction) purposes [16]. Phytostabilization involves plants to stabilize contaminants by heavy metal retention in roots. Phytoextraction uses plants to absorb metals from soils and translocate them to harvestable shoots where they are collected.

In Vietnam, the increase in mining activities associated with the economic growth has resulted in the increased areas contaminated with heavy metals in recent years. Mining, ore processing, and disposal of tailings provide obvious sources of heavy metal contamination in the mine area and surroundings. The contaminated soils require prompt remediation, and phytoremediation is considered to be one of the best demonstrated available technologies for such purpose [17]. Field applications of phytoremediation have only been reported in developed countries in spite of its cost-effectiveness and environment-friendliness. In most developing countries, it is yet to become commercially available technology possibly due to the inadequate awareness of government and public about its inherent advantages and principles of operation [18]. Since the last decade, therefore, there have been several groups of Vietnamese scientists studying on the use of plant for removal of heavy metals from soils in order to promote the application of phytoremediation. This chapter summarizes the recent research and application related to phytoremediation of heavy metal-contaminated soils in Vietnam, including investigation and selection of native hyperaccumulators of arsenic (As), cadmium (Cd), lead (Pb), and zinc (Zn) naturally grown on heavy metal-contaminated habitats; and evaluation of heavy metal removal potential of selected plants under greenhouse and field conditions.

6.2 Selection of Potential Plants for Heavy Metal Removal from Soils

The selection of plants species for phytoremediation is possibly the most important factor determining the heavy metal removal efficiency. Other aspects such as the ecological and environmental protection should be taken into account as selecting the phytoremediating plants.

The success of phytoextraction is dependent on two important characteristics of plants: the ability to produce large quantities of biomass rapidly and the capacity to accumulate large quantities of environmentally important metals in the shoot tissue [19–22]. Hyperaccumulators have been characterized by high heavy metal accumulating potential, small size, and slow growth, while the common non-hyperaccumulators have low potential for metal bioconcentration that is often traded off by the production of significant biomass [23]. In environmental aspect, most of hyperaccumulators are classified as weedy species that can be invasive and endanger the harmony of ecosystem in the new environments, while some crops are palatable and pose a risk to grazing animals. Therefore, the choice of metal hyperaccumulators or common non-accumulator species for phytoremediation is one of the most debated controversies in the field.

Many researchers have supported for the use of non-accumulator species, while others have promoted the application of natural hyperaccumulators. In the study of Ebbs et al. [23], *Brassica juncea* (also known as Indian mustard) was more effective in removing Zn from soil than *Thlaspi caerulescens* (a well-known Zn hyperaccumulator) although the Zn concentration in its biomass was about one-third the concentration of Zn in *Thlaspi caerulescens*. The advantage is due primarily to the fact that *B. juncea* produces ten times more biomass than *T. caerulescens*. Nevertheless, Chaney et al. [24] analyzed the rate of Zn and Cd removal by non-accumulators crops and came to the remark that these crops could not remove enough metal to support phytoextraction. In addition, the high concentrations of heavy metals at many contaminated sites may cause toxicity to crop species and significant biomass reduction. In support of this, several maize (one of the most productive crops) inbred lines have been identified which can accumulate high levels of Cd [25]. However, these lines were susceptible to Zn toxicity and, therefore, could not be used to cleanup soils at the normal Zn:Cd ratio of 100:1 [24]. In addition, when appropriate disposal is an important regulatory concern, the use of lower biomass producing hyperaccumulator species would be an advantage because less contaminated biomass will have to be handled. Moreover, the use of native plants for phytoremediation is more effective because such plants respond better to the stress conditions at the site than would plants introduced from other environments [26]. Consequently, the selection of native and hyperaccumulators for phytoremediation purposes is one of the most important steps to ensure the success of phytoremediation programs.

In order to select the indigenous hyperaccumulators of heavy metals, there were two investigations conducted at mining sites in Bac Kan and Thai Nguyen province, northern Vietnam, where the most mining activities are done in Vietnam. Soil analyses of mining sites in this region showed that soils have been heavily contaminated with a range of heavy metals, including Mn, Zn, As, Cd, and Pb (Table 6.1). Therefore, the objective of these surveys was to search for hyperaccumulators of Mn, Zn, As, Cd, and Pb.

Table 6.1 Family, species, and number of plant samples around and outside of the mine site

STT	Code name	Family	Species	*n*
1	Age	Asteraceae	*Ageratum houstonianum* Mill.	12
2	Bid	Asteraceae	*Bidens pilosa* L.	6
3	Dip	Athyriaceae	*Diplazium esculentum* (Retz.) Sw.	9
4	Ele	Poaceae	*Eleusine indica* (L.) Gaertn	9
5	Hou	Saururaceae	*Houttuynia cordata* Thunb.	9
6	Kyl	Cyperaceae	*Kyllingia nemoralis*	12
7	Lee	Poaceae	*Leersia hexandra* Sw.	9
8	Lyg	Lygodiaceae	*Lygodium flexuosum* (L.) Sw.	6
9	Nep	Lomariopsidaceae	*Nephrolepis cordifolia* (L.) Presl.	9
10	Pte	Pteridaceae	*Pteris vittata* L.	24
11	Sac	Poaceae	*Saccharum spontaneum* L.	9
12	Sci	Cyperaceae	*Scirpus juncoides* Roxb.	9
13	Sel	Selaginelaceae	*Sellaginella delicatula* (Desv.) Alst	15
14	The	Thelypteridaceae	*Thelypteris noveboracensis*	9
15	Thy	Poaceae	*Thysanolaena latifolia*	12

6.2.1 Bac Kan Province, Northern Vietnam

6.2.1.1 Site Description

The mine site is situated in Cho Don district, Bac Kan province, northern Vietnam (Fig. 6.1). This is one of the biggest Pb–Zn mines in Vietnam. Mining activities started from eighteenth century and still have been active currently [27]. Rainy season starts from April to September, and dry season from October to March. The average rainfall is around 100–600 and 8–22 mm month^{-1} in rainy and dry season, respectively. Humidity is 76–88% and 35–45% in rainy and dry season, respectively [27]. The highest and lowest average temperature is 31–36 °C and 10–11 °C, respectively [27]. The main ore minerals are galena (PbS), sphalerite (ZnS), pyrotin (FeS), pyrite (FeS_2), chalcopyrite ($CuFeS_2$), and arsenopyrite (FeAsS) [27]. In addition, high concentration of Mn was obtained in Pb–Zn ore and in sphalerite which was 9892–20,500 mg kg^{-1} and 0.09–0.23% [28, 29]. High concentrations of Pb, Zn, As, and Mn may result in the leaching of these heavy metals into the surrounding environments via mining activities.

6.2.2 Plant Accumulation and Translocation of Heavy Metals

High concentrations of heavy metals in the soil and water may result in high levels of these elements in the collected plant samples. The concentrations of all heavy metals varied greatly among sites and plant species [30]. The highest concentrations

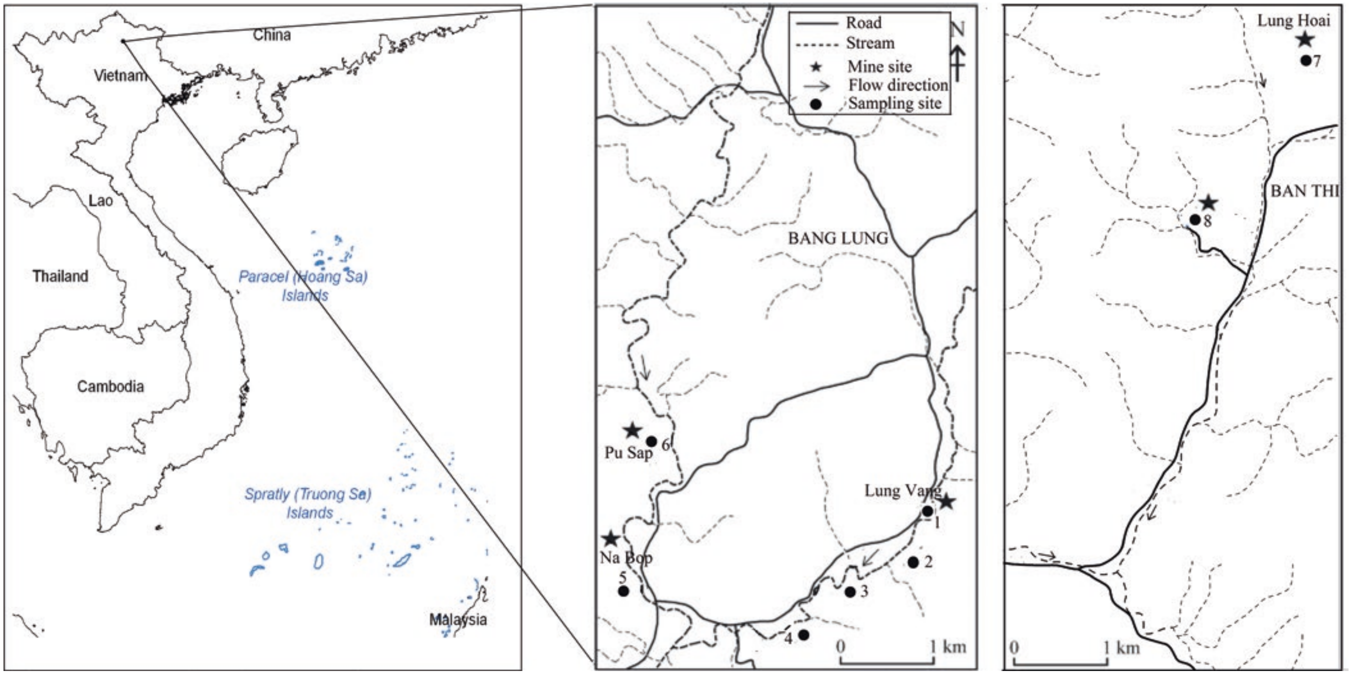

Fig. 6.1 Map showing the location of the Bac Kan sampling sites

of heavy metals (mg kg^{-1}-DW) in the plant root were found in *K. nemoralis* for Mn (2130), *N. cordifolia* for Zn (3780), *P. vittata* for As (861), *L. hexandra* for Cd (13.3), and *A. houstonianum* for Pb (2080); those in the shoot were found in *K. nemoralis* for Mn (1990), *N. cordifolia* for Zn (1710), *P. vittata* for As (2300), *A. houstonianum* for Cd (19.0), and *E. indica* for Pb (2010) (Tables 6.2 and 6.3). Among all plant species in the present study, highest concentrations of Mn, Zn, and As in the root and shoot were observed in *K. nemoralis, N. cordifolia*, and *P. vittata*, respectively.

Almost all collected plant species accumulated higher concentrations of Zn, As, and Pb than their toxicity threshold levels in plants. The concentrations of Mn, Zn, As, Cd, and Pb in the shoot of *A. houstonianum*, *E. indica*, and *H. cordata* were within and above the toxic levels for plant species (Tables 6.3 and 6.4). In addition, all plant species can adapt very well with the soil that highly contaminated with multiple heavy metals (Table 6.4). These results may indicate that plant species growing on the site contaminated with heavy metals were tolerant of these metals.

P. vittata showed great potential for accumulating As in the shoot (Table 6.2). The concentrations of As in the shoot of *P. vittata* L. were significantly higher than those in other plant species. Concentrations of As in the root were significantly higher than those in *B. pilosa*, *D. esculentum*, *K. nemoralis*, *L. flexuosum*, *S. spontaneum,* and *T. noveboracensis*. Mn concentrations in root of *P. vittata* were significantly higher than those in *B. pilosa*, *L. flexuosum*, and *S. spontaneum.* However, those in the shoot were significantly lower than those in *H. cordata* and *K. nemoralis*. Cd concentrations in the root of this species were lower than those in *H. cordata* and *S. juncoides*.

E. indica accumulated the highest concentration of Pb in the shoot among 15 collected plant species (Table 6.2). Pb concentration in *E. Indica* roots was higher than in roots of *B. pilosa* L., *K. nemoralis*, *L. flexuosum*, *N. cordifolia*, *S. spontaneum*, and *S. delicatula.* Concentrations of the heavy metals in the root and shoot of *E. indica* were significantly higher than those in *L. flexuosum*, those of As were significantly higher than those in *D. esculentum*, *K. nemoralis*, *L. flexuosum*, and *T. noveboracensis*. Cd concentrations in the root and shoot were significantly higher than those in *B. pilosa*, *L. flexuosum*, *S. spontaneum*, and *T. latifolia*.

6.2.3 Potential Plant Species for Phytoremediation of Contaminated Soils

The typical characteristics of an ideal plant species for phytoremediation are as follows: (1) a hyperaccumulator of metals which in aboveground tissues; (2) a high and fast-growing biomass and be repulsive to herbivores to avoid the escape of accumulated metals to the food chain; (3) BCF and TF values higher than 1; (4) a widely distributed, highly branched root system; (5) easy to cultivate and a wide geographic distribution; and (6) relatively easy to harvest [31, 32].

Table 6.2 Concentrations (mg kg^{-1}-DW) of Mn, Zn, and As in plant growing in and outside of the mine ($N = 6–24$)

		Mn		Zn		As	
No	Code name	Root	Shoot	Root	Shoot	Root	Shoot
1	Age	565 (85.2; 371–704)	555 (94.3; 238–1030)	514 (28.9; 197–1130)	563 (37.8; 152–1210)	272 (4.72; 162–350)	204 (15.9; 203–209)
2	Bid	130 (96; 115–155)	213 (142; 196–238)	191 (123; 149–265)	216 (112; 178–286)	183 (32.2; 156–213)	440 (34.5; 285–528)
3	Dip	1600 (221; 1190–2010)	215 (80.4; 81.7–349)	574 (56.2;544–604)	176 (26.3; 98–255)	82.5 (3.69; 73.3–91.7)	17.2 (19.0; 10.2–24.2)
4	Ele	385 (102; 142–628)	139 (90.4; 130–147)	1159 (57.6; 178–2140)	372 (41.9; 119–625)	339 (4.77; 230–448)	364 (1.55; 204–524)
5	Hou	987 (193; 941–1030)	710 (307; 434–985)	537 (53.8; 465–609)	319 (50.5; 234–404)	416 (2.99; 284–548)	240 (0.78; 197–283)
6	Kyl	1150 (210; 418–2130)	1440 (303; 1120–1990)	453 (76.0; 267–795)	239 (63.0; 173–284)	103 (0.99; 84.8–119)	57.2 (0.78; 29.6–97.5)
7	Lee	326 (277; 300–352)	147 (113; 118–176)	638 (138; 433–844)	170 (158; 142–197)	368 (43.5; 278–458)	191 (41.8; 182–199)
8	Lyg	119 (82.6; 97.2–149)	204 (84.7; 187–225)	38.1 (26.3; 31.3–43.8)	71.5 (21.7; 53.6–96.1)	20.1 (0.83; 16.3–23.1)	18.6 (13.4; 14.7–21.5)
9	Nep	614 (187; 566–662)	299 (156; 240–357)	2690 (183; 1590–3780)	1322 (158; 934–1710)	299 (52.0; 259–340)	176 (39.0; 158–193)
10	Pte	634 (254; 177–1200)	165 (98.1;65.0–358)	1150 (110; 247–3710)	388 (80.6; 155–1430)	464 (135; 291–861)	**1180** (149; 251–2300)
11	Sac	138 (134; 129–146)	112 (120; 75.0–150)	455 (123; 179–731)	167 (74.3; 106–237)	185 (54.0; 173–197)	174 (32.6; 166–182)
12	Sci	574 (183; 215–933)	301 (135; 225–376)	204 (126; 165–242)	73.0 (41.7; 59–87)	469 (0.83; 237–700)	190 (13.4; 183–197)
13	Sel	476 (153; 148–717)	278 (207; 117–430)	341 (89.3; 222–438)	246 (131; 206–278)	250 (87.7; 91–362)	89.3 (69.6; 78–164)
14	The	446 (131; 217–676)	212 (141; 159–365)	874 (93.4; 300–1450)	325 (112; 168–581)	48.2 (39.5; 42.1–54.3)	33.1 (25.5; 29.8–56.5)
15	Thy	304 (289; 110–532)	155 (118; 112–212)	233 (126; 196–288)	161 (94.6; 117–190)	333 (18.3; 172–480)	128 (16.9; 63.1–184)

Table 6.3 Concentrations (mg kg^{-1}-DW) of Cd and Pb in plant growing in and outside of the mine ($N = 6–24$)

No	Code name	Cd		Pb	
		Root	Shoot	Root	Shoot
1	Age	6.72 (0.50; 3.35–12.6)[a]	7.52 (0.56; 1.35–19.0)	1299 (11.8; 770–2080)	844 (4.87; 631–1070)
2	Bid	1.41 (0.75; 1.23–2.14)	0.60 (0.36; 0.52–0.75)	411 (74.1; 297–485)	505 (58.5; 378–563)
3	Dip	10.9 (0.71; 8.98–12.8)	0.71 (0.17; 0.70–0.72)	1307 (37.5; 949–1670)	200 (8.90; 154–246)
4	Ele	6.55 (0.75; 3.75–9.35)	5.14 (0.34; 2.93–7.34)	1840 (65.1;1810–1870)	**1300** (15.3; 595–2010)
5	Hou	12.3 (0.15; 11.1–135)	9.22 (0.08; 8.99–9.46)	843 (11.1; 606–1080)	**1060** (5.11; 999–1130)
6	Kyl	4.17 (0.15; 2.95–4.91)	2.18 (0.08; 1.70–2.53)	556 (21.0; 281–712)	386 (17.0; 116–702)
7	Lee	11.3 (0.54; 9.44–13.3)	0.77 (0.36; 0.56–0.97)	1910 (17.0; 1880–1940)	357 (8.79; 211–503)
8	Lyg	0.31 (0.12; 0.25–0.42)	0.18 (0.04; 0.12–0.24)	43.4 (8.29; 28.7–52.4)	9.42 (1.03; 8.44–10.1)
9	Nep	7.72 (0.64; 7.24–8.20)	8.68 (0.35; 7.95–9.41)	366 (63.7; 276–456)	501 (74.3; 492–510)
10	Pte	5.25 (0.48; 0.94–10.6)	0.72 (0.24; 0.37–0.99)	1070 (234; 453–1840)	544 (83.5; 92.0–781)
11	Sac	0.47 (0.38; 0.37–0.58)	0.25 (0.20; 0.25–0.38)	563 (42.0; 438–688)	807 (65.8; 781–832)
12	Sci	14.8 (0.12; 11.8–17.7)	5.27 (0.06; 4.58–5.97)	1650 (8.29; 1520–1780)	793 (1.03; 721–864)
13	Sel	2.59 (0.57; 2.40–2.79)	2.20 (0.35; 0.57–3.50)	359 (13.7; 234–613)	408 (6.86; 142–865)
14	The	2.22 (0.35; 2.16–2.28)	0.74 (0.27; 0.73–0.75)	865 (78.2; 842–888)	411 (89.9; 191–631)
15	Thy	0.70 (0.34; 0.47–0.85)	0.51 (0.15; 0.25–0.70)	667 (118; 474–886)	367 (23.5; 242–511)

[a] Average (reference, min–max)

Table 6.4 Concentrations (mg kg^{-1}) of heavy metals in the soil in and outside of the mine area

Site	Mn	Zn	As	Cd	Pb
1	**9270** ± 350	**7150** ± 1420	2290 ± 440	70.2 ± 15.1	8780 ± 790
2	4940 ± 290	5780 ± 1790	**5630** ± 2910	**93.7** ± 18.0	**9090** ± 1940
3	3620 ± 810	1720 ± 370	2450 ± 660	17.2 ± 5.24	4360 ± 1200
4	1730 ± 220	1570 ± 390	489 ± 307	3.71 ± 1.79	3360 ± 910
5	2410 ± 1010	1470 ± 130	2130 ± 810	4.72 ± 2.22	2470 ± 580
6	4010 ± 850	2010 ± 740	1550 ± 220	25.1 ± 9.7	3340 ± 720
7	3210 ± 770	4620 ± 840	538 ± 301	37.0 ± 25.3	4180 ± 960
8	4270 ± 260	6210 ± 300	858 ± 66	75.2 ± 5.7	8290 ± 710
Reference	817 ± 167	88.8 ± 2.5	4.77 ± 0.24	1.00 ± 0.05	70.8 ± 21.3

Values present means ± standard deviations ($N = 3–9$)

Table 6.5 Bioconcentration factors of plant growing around the mine

Code	Mn	Zn	As	Cd	Pb
Age	0.11 ± 0.08[a]	0.17 ± 0.08	0.09 ± 0.05	0.28 ± 0.12	0.12 ± 0.03
Bid	0.11 ± 0.08	0.11 ± 0.08	0.35 ± 0.15	0.12 ± 0.11	0.39 ± 0.22
Dip	0.12 ± 0.10	0.13 ± 0.07	0.05 ± 0.03	0.29 ± 0.19	0.06 ± 0.02
Ele	0.07 ± 0.04	0.08 ± 0.01	0.43 ± 0.39	0.63 ± 0.45	0.46 ± 0.28
Hou	0.76 ± 0.34	0.73 ± 0.59	0.12 ± 0.04	**2.00** ± 1.87	0.38 ± 0.05
Kyl	0.22 ± 0.01	0.11 ± 0.02	0.01 ± 0.01	0.14 ± 0.03	0.04 ± 0.02
Lee	0.45 ± 0.19	0.27 ± 0.16	0.52 ± 0.42	0.07 ± 0.08	0.19 ± 0.11
Lyg	0.21 ± 0.13	0.78 ± 0.30	0.36 ± 0.11	0.19 ± 0.07	0.02 ± 0.02
Nep	0.07 ± 0.03	0.26 ± 0.11	0.40 ± 0.26	0.61 ± 0.67	0.24 ± 0.02
Pte	0.10 ± 0.15	0.20 ± 0.15	**1.19** ± 0.50	0.10 ± 0.11	0.11 ± 0.06
Sac	0.04 ± 0.01	0.07 ± 0.07	0.12 ± 0.03	0.02 ± 0.01	0.26 ± 0.02
Sci	0.10 ± 0.03	0.04 ± 0.01	0.15 ± 0.01	0.58 ± 0.47	0.28 ± 0.13
Sel	0.18 ± 0.22	0.26 ± 0.27	0.23 ± 0.23	0.31 ± 0.30	0.09 ± 0.08
The	0.05 ± 0.03	0.08 ± 0.04	0.12 ± 0.13	0.13 ± 0.05	0.09 ± 0.05
Thy	0.06 ± 0.03	0.05 ± 0.03	0.11 ± 0.06	0.05 ± 0.08	0.08 ± 0.03
Average	0.18	0.22	0.28	0.37	0.19

[a]Mean ± standard deviation

Hyperaccumulators are defined as plants with leaves able to accumulate at least 100 mg kg^{-1}of Cd; 1000 mg kg^{-1}of As or Pb; or 10,000 mg kg^{-1} of Mn or Zn (dry weight) when grown in a metal-rich environment [33–35]. Among all plant species, hyperaccumulation levels (mg kg^{-1}-DW) were obtained in *P. vittata* (1180) for As (Table 6.2), in *E. indica* (1300) and *H. cordata* (1060) for Pb (Tables 6.2 and 6.3). Of which, *P. vittata* has been reported as a well-known hyperaccumulator of As [36]. *A. houstonianum* and *E. indica* have been reported to hyperaccumulate Pb [32, 37]. *H. cordata* is a hyperaccumulator of As (1140 mg kg^{-1}-DW); however, to the best of our knowledge, no previous study has reported the hyperaccumulation of Pb in *H. cordata*.

Bioconcentration factor (BCF) values of Mn, Zn, As, Cd, and Pb of 15 plant species varied within 0.04–0.76, 0.04–0.78, 0.01–1.19, 0.02–2.00, and 0.02–0.46, respectively (Table 6.5). BCF values of plants for Mn, Zn, and As at the uncontaminated site were significantly higher than those at the mine site. This is possibly due to low concentrations of heavy metals in associated soils outside of mining area (Table 6.4). BCF values of Mn and Zn were correlated ($p < 0.05$). BCF values higher than 1 were only observed in *H. cordata* (2.00) and *P. vittata* (1.19) for Cd and As, respectively. This result reflected high accumulation capacity of heavy metals by these species. Most BCF values were found to be lower than 1. This is possibly due to the existence of heavy metals in various geochemical forms in soils (water-soluble, exchangeable, bound to carbonate, bound to Fe-Mn oxide, bound to organic matter, and residual forms) [38–40]. In addition, the possible source of heavy metals was derived from a sulfide deposit, consequently, these heavy metals are assumed to partially exist as sulfides. The occurrence of heavy metals in sulfides,

Table 6.6 Translocation factors of plant growing around the mine

Code	Mn	Zn	As	Cd	Pb
Age	0.97 ± 0.08[a]	**1.15** ± 0.08	0.84 ± 0.05	0.81 ± 0.12	0.75 ± 0.23
Bid	**1.64** ± 0.08	**1.14** ± 0.08	**2.41** ± 0.15	0.43 ± 0.11	**1.23** ± 0.22
Dip	0.12 ± 0.10	0.31 ± 0.07	0.22 ± 0.03	0.07 ± 0.09	0.18 ± 0.02
Ele	0.57 ± 0.04	0.48 ± 0.01	**1.03** ± 0.39	0.78 ± 0.75	0.70 ± 0.28
Hou	0.73 ± 0.34	0.58 ± 0.59	0.61 ± 0.04	0.76 ± 0.87	**1.35** ± 0.35
Kyl	**1.65** ± 0.01	0.63 ± 0.02	0.54 ± 0.11	0.53 ± 0.03	0.63 ± 0.22
Lee	0.46 ± 0.19	0.28 ± 0.16	0.54 ± 0.42	0.07 ± 0.08	0.19 ± 0.11
Lyg	**1.72** ± 0.13	**1.88** ± 0.30	0.78 ± 0.11	0.58 ± 0.07	0.22 ± 0.09
Nep	0.50 ± 0.03	0.52 ± 0.11	0.59 ± 0.26	**1.12** ± 0.67	**3.46** ± 0.62
Pte	0.27 ± 0.15	0.45 ± 0.25	**2.98** ± 0.50	0.29 ± 0.11	0.43 ± 0.16
Sac	0.80 ± 0.01	0.43 ± 0.07	0.94 ± 0.23	0.51 ± 0.11	**1.50** ± 0.42
Sci	0.72 ± 0.03	0.39 ± 0.12	0.54 ± 0.11	0.36 ± 0.27	0.48 ± 0.13
Sel	0.63 ± 0.22	0.75 ± 0.37	0.43 ± 0.23	0.85 ± 0.40	0.99 ± 0.28
The	0.41 ± 0.03	0.31 ± 0.04	0.64 ± 0.13	0.33 ± 0.15	0.48 ± 0.15
Thy	0.65 ± 0.03	0.70 ± 0.03	0.39 ± 0.16	0.70 ± 0.28	0.54 ± 0.23
Aver	0.18	0.22	0.28	0.37	0.19

[a] Mean ± standard deviation

combined with the fact that the poor structure of soil developed in mine tailings may reduce metal availability to root over short periods of time [41].

Translocation factor (TF) values of Mn, Zn, As, Cd, and Pb in 15 plant species varied within 0.12–1.72, 0.28–1.88, 0.22–2.98, 0.07–1.12, and 0.18–3.46, respectively (Table 6.6). It is noted that most TF values of heavy metals in this study were lower than 1. This is in line with the result reported by Stoltz and Greger [42] that most of the plant species growing on mine tailings have a restricted translocation of metals and As to the shoot. The restriction of upward movement from root to shoot can be considered as one of the tolerance mechanisms [43]. The average TF values of Mn, Zn, As, Cd, and Pb of plants growing at the uncontaminated site were 0.28, 0.50, 3.53, 0.30, and 0.41, respectively. The TF value of Cd was significantly lower than that of Mn, As, and Pb. TF values of plants for Mn, Zn, and As at the uncontaminated site were significantly higher than those at the mine site. The translocation of Mn from root to shoot in *D. esculentum*, *P. vittata*, and *T. noveboracensis* was significantly lower than that in other species. TF values of As in *B. pilosa*, *E. indica*, and *P. vittata* were significantly higher than those in other plants. Significantly higher TF values of Pb in *B. pilosa*, *H. cordata*, *N. cordifolia*, and *S. spontaneum* than those in other species were also observed. *B. pilosa* showed the high capacity to translocate multiple heavy metals from the root to the shoot (Table 6.6).

Among all plants collected in the present study, *P. vittata* is the most widely distributed species. The results of the present study were in agreement with the previous study that *P. vittata* L. is an efficient As hyperaccumulator [36]. The highest concentrations of As, Pb, Zn, Mn, and Cd in shoot of *P. vittata* L. were 358, 1430, 2300, 0.99, and 784 mg kg^{-1}-DW, respectively. TF values exceeded 1 were obtained for As. In addition, *P. vittata* L. has considerable biomass, grows fast, and propagate easily [36, 44, 45]. Therefore, this plant has high potential for phytoremediation of multi-metals, especially for As [44, 45], Zn and As [46], Cd and As [47], and multiple heavy metal-contaminated soils [32].

Of the three Pb hyperaccumulators identified in this study, *E. indica* (L.) accumulated highest concentrations of Pb in the shoot. *H. cordata* had the highest translocating factor of Pb from root to shoot (TF = 1.35). TF values of *E. indica* and *A. houstonianum* and BCF values of all Pb hyperaccumulators were lower than 1. This study was conducted to assess the phytoremediation potential of plants growing on a site contaminated with heavy metals. Results of this research indicated that among 15 plant species being collected, *P. vittata* L. is a good candidate for phytoremediation of As; *A. houstonianum*, *E. indica*, and *H. cordata* are potential species for phytoremediation of Pb. Further studies are required to confirm the phytoremediation potential of those plant species through greenhouse and field experiments as well as to establish the agronomic requirements and management practices in order to investigate their whole phytoremediation possibilities.

6.3 Selection of Indigenous Plants Suitable for Phytoremediation in Thai Nguyen Province

The study was performed at four mining sites located at two districts of Thai Nguyen province, northern Vietnam: Tan Long (Zn/Pb mine) and Trai Cau (Fe mine) site in Dong Hy district, Ha Thuong (Ti/Sn mine) and Yen Lang (coal mine) in Dai Tu district. Soil samples were collected at the same place with plant samples (Figs. 6.2 and 6.3)

This research was conducted to determine soil concentrations of As, Pb, Cd, and Zn at four mining sites of Thai Nguyen province as well as to identify indigenous potential plants for phytoremediation. Total 33 indigenous plants and 12 soil in situ plant samples in these areas were collected for heavy metal analysis. The soils of surveyed mining areas contained 181.2–6754.3 mg kg^{-1} As, 235.5–4337.2 mg kg^{-1} Pb, 0.8–419 mg kg^{-1} Cd, and 361.8–17565.1 mg kg^{-1} Zn depending on the characteristics of each mining site. As compared to the upper limit of As (15 mg kg^{-1}), Cd (1.5 mg kg^{-1}), Pb (70 mg kg^{-1}), and Zn (200 mg kg^{-1}) for industrial soil in Vietnam [48], these soils are much higher than standard values.

The collected 33 plant species can grow at the mine tailings or in the soils affected by mining waste. The heavy metal concentrations in their roots and shoots of these plant species were evaluated. In the total of these selected plants, only six potential indigenous plant species of Thai Nguyen province was presented in the Table 6.7. The results showed that two ferns, *Pteris vittata* and *Pityrogramma calomelanos* were capable of accumulating high arsenic concentrations. As concentrations in shoot and root of *P. vittata* were 5877 and 2643 mg kg^{-1}, respectively, while these values of *P. calomelanos* were 2426 and 2256 mg kg^{-1}. Remarkably, a large

Fig. 6.2 Location of survey areas in Thai Nguyen province

Fig. 6.3 Some sampling sites in Bac Kan and Thai Nguyen

Table 6.7 Heavy metal concentration in shoots and roots of six potential indigenous plant species of Thai Nguyen province

	As (mg kg^{-1})		Pb (mg kg^{-1})		Cd (mg kg^{-1})		Zn (mg kg^{-1})	
Plant species	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root
Pteris vittata L.	**5876.5 ± 99.6**	**2642.5 ± 72.3**	9.4 ± 1.4	10.2 ± 1.7	0.4 ± 0.1	1.3 ± 0.3	152.3 ± 12.7	220.5 ± 23.5
Cynodondactylon L.	44.1 ± 3.5	765.5 ± 23.2	538.5 ± 25.2	**4579.6 ± 88.5**	4.4 ± 0.7	34.6 ± 4.8	**912.8 ± 42.5**	15.6 ± 3.8
Eleusine indica L.	25.2 ± 2.8	236.0 ± 15.1	664.5 ± 45	**4638.2 ± 210.4**	9.3 ± 1.3	26.5 ± 2.5	**4346.8 ± 157.9**	**3108.7 ± 213.5**
Equisetum ramosissimum (Vauch)	28.2 ± 2.6	34.3 ± 4.1	455.2 ± 32.6	**1025.7 ± 65.8**	9.2 ± 1.5	29.0 ± 3.6	**1346.2 ± 130.2**	**3756.9 ± 145.7**
Cyperus rotundus L.	19.9 ± 1.7	37.7 ± 3.6	**941.3 ± 35.2**	**1560.2 ± 113.5**	7.2 ± 2.1	9.5 ± 2.4	**1201.4 ± 147.3**	**2194.4 ± 155.7**
Pityrogramma calomelanos L.	**2426.3 ± 104.5**	**2256.0 ± 123.4**	49.9 ± 5.6	85.4 ± 7.4	1.0 ± 0.3	1.1 ± 0.5	368.6 ± 15.7	230.8 ± 24.6

Values are mean ± standard deviation of three replicates amount of As from roots of these ferns transported to shoot, facilitating its removal from the soil. Many research results have reported that they are two As hyperaccumulating ferns [28, 29, 32, 36, 49–51]. None of the collected plant species had high Cd accumulating ability.

Zn accumulating ability in some investigated plant species was quite high. *E. ramosissimum*, *C. rotundus*, and *E. indica* can accumulate Zn in their shoots with 1346, 1201, and 4347 mg kg^{-1}, respectively, and in their roots with 3757, 2194, and 3109 mg kg^{-1} Zn, respectively. As indigent plants, they can easily adapt to the local conditions being also potential for phytoremediation.

Our findings in Thai Nguyen province indicate that two ferns *P. vittata* and *P. calomelanos* are suitable for As treatment in the mining soil of Ha Thuong, Dai Tu, district (Table 6.7). Four grasses, *E. indica*, *C. dactylon*, *C. rotundus*, and *E. ramosissimum* are potential for Pb, Zn removal from soils. Some research results reported that *E. indica* is Pb hyperaccumulator [32, 37].

6.4 Some Research Results in Greenhouse Experiment of Potential Plant Species

Based on the screening results, three species, namely, *P. vittata*, *P. calomelanos*, and *E. indica* were selected with an introduced plant *Vetiveria zizanioides* and a crop plant *Brassica juncea* for evaluation under greenhouse conditions.

6.4.1 Pteris vittata *and* Pityrogramma calomelanos

The obtained results from greenhouse experiments showed that *Pteris vittata* and *Pityrogramma calomelanos* can grow in the mining soil containing 15,146 ppm As. Although they are As hyperaccumulators, the plants still also have the ability to accumulate Cd, Pb, and Zn. *Pteris vittata* and *Pityrogramma calomelanos* can tolerate 5000 and 4000 mg kg^{-1} Pb (concentration of Pb was established by adding $Pb(NO_3)_2$ in the garden soil); 1200 and 300 mg kg^{-1} Cd (concentration of Cd was established by adding $Cd(NO_3)_2$ in the garden soil), respectively. The highest level of As accumulation in *Pteris vittata* and *Pityrogramma calomelanos* are 6042 and 4034 mg kg^{-1} (in the fronds); 3756 and 2256 (in the roots), respectively. Concentration of As, Cd, Pb, and Zn in *Pteris vittata* were comparable to those found by An et al. [46] and Ha et al. [32]. From 3 to 4 months after growing there is appropriate time for harvesting plant biomass if applied in practical processing (Fig. 6.4).

Fig. 6.4 Pot experiments of potential plant species

6.4.2 Eleusine indica

Eleusine indica can be used for remediating the soil contaminated with Pb and Zn. The results of the survey showed that this plant can grow in the waste area of lead, zinc processing factory. Analyzing Pb and Zn concentration in soil and plants showed that if soil contained 4316.9 mg kg^{-1} Pb, there would be 664.5 and 4638.2 mg kg^{-1} Pb in shoots and roots of the plant, respectively; if soil contained 1000 mg kg^{-1} Zn, there would be 761.6 and 2011.3 mg kg^{-1} in shoots and roots, respectively. *Eleusine indica* could grow well at the concentration of Pb and Zn (in the form of $Pb(NO_3)_2$ and $Zn(NO_3)_2$), respectively. Other studies have found *Eleusine indica* (L.) higher accumulating Pb in the shoots [32, 37].

6.4.3 Vetiveria zizanioides

In mining soil contaminated with Pb from 1400.5 to 2530.1 mg kg^{-1}, *Vetiveria zizanioides* still grew well after 90-days treatment. Some characteristics of plant growing on Pb-contaminated soil such as height, root length, biomass, and the chlorophyll concentration increased more than those on control soil (soil without Pb). Pb concentration analysis in soil after this experiment showed that the Pb extraction effect from the contaminated soil by *Vetiveria zizanioides* could reach from 87% to 92.6%. However, the average Pb accumulation in its shoots and roots were not high being only 24 and 349 mg kg^{-1}, respectively. This species also can accumulate As and Cd taken from soil. Many of our further experimental results confirmed feasibility of using *Vetiveria zizanioides* as phytostabilization agent for Pb, Cd, and As in contaminated soils. Some research results also reported that Vetiver grass has the ability to accumulate wide range of heavy metals [52–55].

6.4.4 Brassica juncea

As, Pb, and Cd accumulations of *Brassica juncea* were quite high. All three heavy metals can be accumulated in roots more than in the shoots. In trace concentration, heavy metals can stimulate plant growth, but at higher concentrations (Cd > 25 mg kg^{-1}, As > 200 mg kg^{-1}, and Pb > 2000 mg kg^{-1}) they inhibited plant growth. Pb accumulation in shoots and roots of *Brassica juncea* grown on 2000 mg kg^{-1}Pb soils were 1325 and 2546.2 mg kg^{-1}, respectively. The concentration of Pb accumulated in *Brassica juncea* shoots in this study was similar to that reported in study of Lombi et al. [56] and Jae et al. [57]. When cultivated on soils containing 25 mg kg^{-1} As and Cd, concentration in shoots and roots were 185.6 and 228.9 mg kg^{-1} for As, 185.6 and 228.9 mg kg^{-1} for Cd, respectively. *Brassica juncea* can be used to remove As, Pb, and Cd concentration in contaminated soil but it should be noted that this plant is also a popular green vegetable. Therefore, the use of this plant species for phytoremediation is limited due to the risk of poisoning human through consumption of its heavy metal-contaminated leaves.

6.5 Field Evaluation of Heavy Metal Accumulating Potential of the Selected Terrestrial Plants

6.5.1 Study at Ha Thuong and Tan Long Mines, Thai Nguyen Province

The field study was performed at Ha Thuong and Tan Long mine site. Selection of the experimental sites was based on three criteria: (1) areas affected by mining activities, containing high concentration of heavy metals As, Pb, Cd, and Zn; (2) potential of indigenous plants for phytoremediation; (3) local conditions suitable for operation model.

6.5.2 Ha Thuong Field Experimental Site

The analysis of soils collected at Ha Thuong Ti/Sn mine site showed very high concentration of As (4521 mg kg^{-1}), moderate concentration of Pb and Zn (235 and 463 mg kg^{-1}, respectively), low concentration of Cd (4.5 mg kg^{-1}), and low pH (2.3). Concentration of As, Cd, Pb, and Zn in the polluted soils was301.4, 3, 3.4, and 2.3 times higher than the permitted standards for agricultural soils, respectively (Table 6.8). At this site, there is no plant species survived, except *Pityrogramma calomelanos*. The source of soil contamination is from tin mining wastewater discharged daily into the drain near this site. Spreading of contaminants has often occurred in rainy season, when the whole area is totally submerged in water for several hours or longer with frequency of 3–5 times per year.

Table 6.8 Soil characteristics of Ha Thuong area before and after growing *P. vittata, P. calomelanos*, and *V. zizanioides*

Times	As (mg kg^{-1})	Cd (mg kg^{-1})	Pb (mg kg^{-1})	Zn (mg kg^{-1})	pH (KCl)	OM (%)	CEC (cmolkg^{-1})
S0 (0 month)	4521 ± 324	4.5 ± 0.9	235 ± 67	463 ± 85	2.3 ± 0.8	0.21 ± 0.13	3.1 ± 0.6
S1 (8 months)	2317 ± 389	2.3 ± 0.7	115 ± 51	216 ± 37	6.7 ± 0.8	1.8 ± 0.5	11.1 ± 1.3
S2 (12 months)	2011 ± 215	1.8 ± 0.8	70 ± 12	191 ± 21	7.2 ± 0.6	2.3 ± 0.6	10.3 ± 0.8
S3 (24 months)	1360 ± 180	0.8 ± 0.5	25 ± 8	112 ± 34	7.3 ± 0.5	3.6 ± 0.7	12.1 ± 2.1
S4 (36 months)	956 ± 87	0.3 ± 0.1	9 ± 2	60 ± 12	7.2 ± 0.4	4.1 ± 0.5	11.8 ± 3.2

Note: *OM* organic matter, *CEC* cation exchangeable capacity; $n = 5$, values are presented in mean ± standard deviation. Allowable limits of As, Cd, Pb, and Zn in agricultural soil recommended by the Vietnam National Technical Regulation are 15, 1.5, 70, and 200 mg kg^{-1}dw, respectively

The experimental area at Ha Thuong mine site is 700 m^2. Before experiment started, several plant species (*Sesbania sesban, Reynoutria japonica, Senna alata*) had been planted in this area for creating a favorable environment, and CaO had been added to raise soil pH to 7. Three plant species (*Pteris vittata, Pityrogramma calomelanos*, and *Vetiveria zizanioides*) were tested at this site. Concentration of heavy metals and As over 3-year period is presented in Table 6.8 (Fig. 6.5).

6.5.3 Tan Long Field Experimental Site

Soils at Tan Long experimental site contained very high concentration of Pb and Zn (3470 and 3191 mg kg^{-1}, respectively), moderate concentration of As (213 mg kg^{-1}), low concentration of Cd (52 mg kg^{-1}), and high pH value of 8.2. At this site, *Pteris vittata* was found the most popular, while other species, such as *Pityrogramma calomelanos,* was also detected but with less number as compared to Ha Thuong site.

Tan Long experimental site has an area of 740 m^2. Vetiver and elephant grass were cultivated around the experimental site to control erosion and leaching. Three plant species were used at this site, including *Pteris vittata, Vetiveria zizanioides*, and *Eleusine indica*.

Concentrations of As, Cd, Pb, and Zn (mg kg^{-1} dw) in the soils at Ha Thuong and Tan Long experimental site were determined at 0, 8, 12, 24, and 36 months after cultivation of selected plants (Tables 6.8 and 6.9). To increase the efficiency of phytoremediation, mycorrhiza fungi, EDTA, phosphorous, and organic fertilizers were applied at two experimental sites. In general, soil concentrations of heavy metals and As were markedly reduced over 3 years at both experimental sites. Particularly, soils contaminated with low or moderate concentration of heavy metal and As (Cd, Pb, and Zn at Ha Thuong site, As and Cd at Tan Long site) were effectively remediated to contain the level of heavy metals that are below the limits of Vietnam National Technical Regulation. It should be noted that the removal effectiveness of the heavy metals from the soil depends on the plant species; plant biomass; the added of mycorrhiza fungi, EDTA, P, organic fertilizers; plant–microorganisms relationship and soil leaching (Fig. 6.6).

6.6 The Uptake Capacity for Heavy Metals of *Vetiveria zizanioides* at Field Conditions

Khanh Son landfill site is located above hill area of Lien Chieu District, Da Nang City. This area was the municipal solid wastes dumping site of Da Nang City since 1992, and closed in 2006. The studied site was selected at a dumping area inside the landfill where the solid wastes were kept for 2 years, covered with 0.5 m of surface soil. The solid wastes were already decomposed and mixed. The second experimental site was selected at waste disposal point with an area of 1500 m^2

Fig. 6.5 Ha Thuong experimental site before and after growing *Pteris vittata, Pityrogramma calomelanos*, *and Vetiveria zizanioides*

located in residential area of Hoa Minh ward, Lien Chieu district, Danang city. The studied site was the place used for holding and recycling the second-hand cars. Vetiver grass was cultivated at a density of 20 seedlings.m^{-2} for both experimental sites. Heavy metal concentrations in shoot (stem and leaves) of vetiver were determined at 3, 6, and 12 months after cultivation of vetiver.

Heavy metal concentrations accumulated in vetiver shoot were gradually diminished with time (Table 6.10). The highest concentration of Zn, Cu, and Pb in stems and leaves of Vetiver grown at Khanh Son landfill were 342.4, 30.3, and 5.6 mg kg^{-1}, respectively. At Hoa Minh waste landfill, vetiver accumulated the highest Zn and Pb concentration of 36.4 and 6.4 mg kg^{-1}, respectively. The concentrations of Zn, Cu, and Pb in shoot of vetiver grown at field condition were higher than those of vetiver grown under greenhouse condition. The concentration of heavy metals in stem and leaf of Vetiver was highest after 3 months of transplanting at both Khanh Son and Hoa Minh areas. After 12 months of growth, the amount of Zn accumulated by vetiver was 0.9 gm^{-2} $year^{-1}$ and 1.5 gm^{-2} $year^{-1}$ at Khanh Son landfill and Hoa Minh waste disposal site, respectively (Table 6.11).

In terms of physical–chemical characteristics and the concentration of heavy metals in soil, the obtained results showed that the contents of organic matter (OM) and total nitrogen (N_{ts}) increased at both experimental sites after the experiment was completed. The amount of organic matter increased from 9% to 13% and the total nitrogen increased from 23% to 68% at the end of experiment compared with those

Table 6.9 Soil characteristics of Tan Long area before after growing *P. vittata*, *V. zizanioides* and *E. indica*

Times	As (mg kg^{-1})	Cd (mg kg^{-1})	Pb (mg kg^{-1})	Zn (mg kg^{-1})	pH (KCl)	OM (%)[a]	CEC (cmol$_c$kg^{-1})[b]
S0 (0 month)	213 ± 54	52 ± 11	3470 ± 123	3191 ± 231	8.2 ± 1.3	0.6 ± 0.2	4.3 ± 0.5
S1 (8 months)	127 ± 23	31.2 ± 1.9	2135 ± 121	2365 ± 237	7.6 ± 0.7	3.8 ± 0.7	15.7 ± 2.4
S2 (12 months)	93 ± 16	22.5 ± 2.8	1924 ± 202	2132 ± 131	7.8 ± 0.5	3.3 ± 0.6	16.5 ± 2.8
S3 (24 months)	47 ± 9	10.2 ± 1.5	1367 ± 185	1512 ± 214	7.9 ± 0.4	4.6 ± 0.8	17.1 ± 3.1
S4 (36 months)	16 ± 7	5.7 ± 1.3	954 ± 96	1034 ± 123	7.7 ± 0.6	5.1 ± 0.6	16.8 ± 5.3

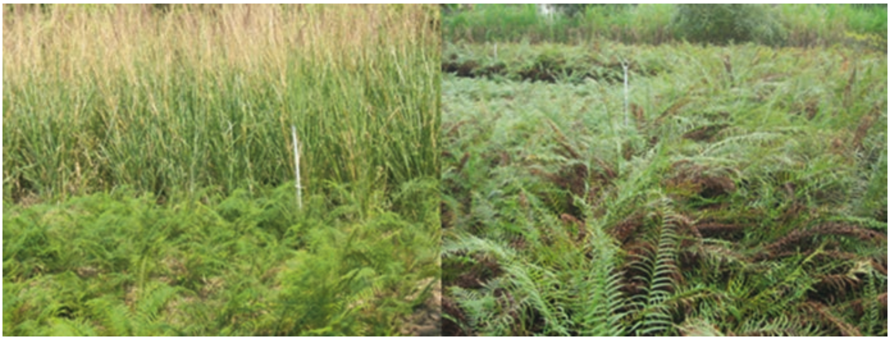

Fig. 6.6 Phytoremediation in Tan Long mining site

Table 6.10 Concentrations of heavy metals (ppm) in aerial parts (stems and leaves) of Vetiver

Places	Heavy metal	Periods of experiment		
		3 months	6 months	12 months
Khanh Son Landfill	Zn	342.4 ± 3.4	305.4 ± 6.5	287.5 ± 7.1
	Cu	30.2 ± 0.9	27.37 ± 1.8	23.2 ± 2.8
	Pb	5.6 ± 0.5	5.76 ± 0.3	4.1 ± 0.1
Hoa Minh waste disposal site	Zn	336.4 ± 3.9	321.6 ± 0.9	310.5 ± 3.7
	Pb	6.4 ± 0.1	6.3 ± 0.1	5.6 ± 0.2

Table 6.11 The amount of studied-heavy metals per 1 m^2 after 12 months at the field conditions

Places	Amount of heavy metals (g/m^2)		
	Zn	Cu	Pb
Khanh Son Landfill	0.931	0.075	0.013
Waste disposal site at Hoa Minh	1.469	–	0.026

at the beginning of experiment. In contrast, the contents of bioavailable phosphorus in both areas reduced from 12% to 23%. In addition, the amount of bioavailable potassium in the soil at Khanh Son increased 31%, whereas this amount at Hoa Minh reduced 5%. These results were also consistent with the results reported in the study of Phien and Tam [58]. Significantly, the amount of heavy metals in soils at the end of experiment was lower than that at the beginning of experiment. The reduction for Zn, Pb, and Cu were 13–16%, 7–12%, and 17%, respectively.

6.7 Conclusion

Mining activities in Vietnam have resulted in large areas of land contaminated with high concentrations of heavy metals and As. The contaminated soils require immediate remediation to control adverse effect of contaminants on human and environment.

Among several available remedial technologies, phytoremediation is the most appropriate because the technology is simple, cost-effective, and environmentally friendly. Several research programs have been conducted since the last decade in order to search for indigenous hyperaccumulators of As, Cd, Pb, and Zn and evaluate the selected plant species for phytoremediation purpose under greenhouse and field conditions.

Among plant species being collected in Bac Kan and Thai Nguyen, *P. vittata* and *P. calomelanos* are good candidates for phytoremediation of As. *A. houstonianum*, *E. indica, H. cordata*, *C. dactylon*, *C. rotundus*, and *E. ramosissimum* are potential species for phytoremediation of Pb and Zn. The mixed cultivation of *P. vittata, V. zizanioides*, and *E. indica* at Tan Long mine site, and *P. vittata, P. calomelanos*, and *V. zizanioides* at Ha Thuong mine site together with application of mycorrhiza fungi, EDTA, phosphorous, and organic fertilizers, showed very promising results. Concentrations of As, Pb, and Zn were significantly reduced over 3-year period. It can be concluded that the mixed cultivation of the selected plants can be used to remediate As-, Pb-, and Zn-contaminated soils.

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