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LAND POLLUTION (G HETTIARACHCHI, SECTION EDITOR)

Trace Elements in Soils around Coal Mines: Current Scenario, Impact and Available Techniques for Management

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Abstract The present paper reviewed the average concentrations of trace elements in soils near coal mine areas from various cities/countries to provide a current global summary of this issue. The contamination of soils was assessed by using global reference materials and various contamination indices. The results show that the average concentrations of trace elements varied widely: As (0.5–38.3 mg/kg), Mn (86–3, 700 mg/kg), Zn (1.5–296 mg/kg), Cu (0.5–110 mg/kg), Cr (17.5–954 mg/kg), Ni (4.3–390 mg/kg), Pb (0.5–433 mg/kg), Cd (0.02–4.48 mg/kg), and Hg (0.02–0.69 mg/kg). Most of these values are higher than the average world background soils and upper continental crust (UCC). The geo-accumulation (I_{geo}) and contamination factor (CF) indices show that the contamination levels of Ni and Pb are higher than other elements. The potential ecological risk index (E_i) suggests a high risk from Cd, especially in the Tabagi River watershed in Brazil and Ledo coal mines in India, and Hg, especially in Oltu (Turkey). The degree of contamination index (C_d) reveals that the soils from Barapukuria (Bangladesh), Ledo (India), Ptolemais-Amynteon (Greece), and the Tibagi River (Brazil) have a higher degree of contamination than other sites. To control soil contamination, effective monitoring and legislative measures must be taken immediately. For the long term, various physical, chemical, and biological methods should be implemented. Although the selection of suitable methods is site-specific based on the extent and nature of contamination, in general, phytoremediation seems to be more beneficial and cost-effective than physical/chemical techniques.

Keywords Soil · Trace elements · Contamination · Pollution index · Remediation

This article is part of the Topical Collection on *Land Pollution*

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Introduction

Coal is the most abundant fossil fuel on the earth and supplies about 75 % of the total fuel resources [1]. It is the major source of energy production, contributing over 40 % of the world's electricity generation (Figs. 1 and 2), and is used heavily in the steel industry [2]. China is the biggest coal-producing country, contributing nearly 45 % of the world's total coal output, followed by the USA and India, contributing 14.5 % and 6.8 %, respectively, of the world's total coal production [3]. Coal production has important economic and social benefits; however, it generates large amounts of coal mine spoils, and waste rocks which oxidize under atmospheric conditions and release metal-rich effluents to the surrounding environment. This causes serious problems to surrounding water-soil bodies [4–6]. Soils are the major sink for trace elements released into the environment because of their high metal-scavenging potential [7]. This, in turn, degrades the chemical and microbiological quality of soil [8•, 9–11, 12•], and subsequently creates a threat to humans and the ecosystem through direct contact with contaminated soils and the food chain because trace elements can be transferred from soil to plants and impact on

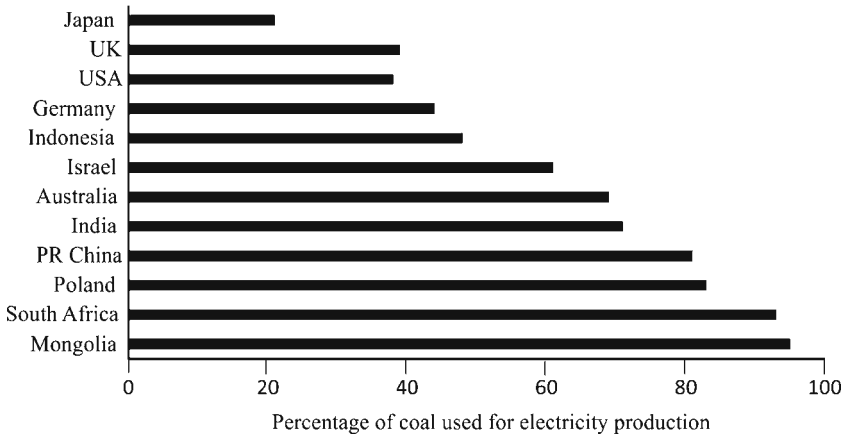

Fig. 1 Percentage of coal used for electricity production worldwide [2]

crop growth and food safety [10, 11, 13]. Thus, research on soil contamination around coal mine sites is receiving increasing attention in restoration of soil ecosystems and their sustainable use. There are several methods that have been widely used for evaluating trace element contamination in soils. The most commonly used pollution indices are: single element indices such as the geo-accumulation index (I_{geo}), the enrichment factor (*EF*), the contamination factor (*CF*), and ecological risk (E_i); and multi-element indices such as the pollution load index (*PIL*), the degree of contamination (C_d), and Nemerow integrated pollution index (*NIPI*) [8•, 14–16]. Although each index has limitations, the combination of these approaches can be a good option for providing a more comprehensive and accurate assessment of trace element contamination. In the last few decades, several individual studies have been carried out investigating this issue around coal mines worldwide [8•, 17, 18]. However, to date there has been no comprehensive review on these studies.

In the present paper, we review data on total concentrations of trace elements in soils nearby coal mines from various countries and evaluate their contamination status using global reference/background values and various contamination indices. This review thus provides a global scenario of soil contamination around coal mines. In addition, we discuss various physical/chemical/biological techniques available for remediation of metal-contaminated soils, which can be helpful for the selection of suitable strategies to employ for contaminated sites. The limitation of this review is that it is based on the availability of online literature and may not fully represent soil pollution in the vicinity of coal mines around the world. Furthermore, it is recognized that methodologies vary across these studies. However, these factors do not significantly affect the general assessment results because the research methods used are quite similar and are widely accepted by the scientific community.

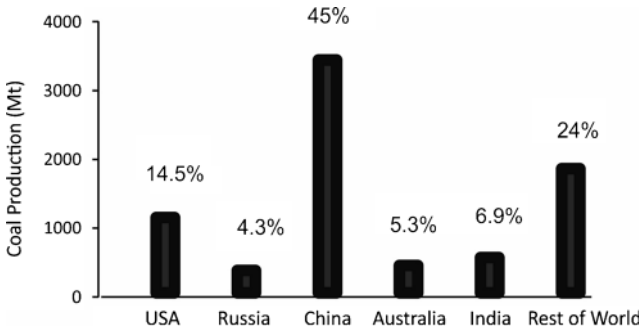

Fig. 2 Coal production (Mt) in the year 2011 worldwide; the percentage at the top of each bar represents the individual contribution relative to total production [3]

Calculation of Pollution Indices

Contamination Factor (*CF*)

Contamination factor (*CF*) was employed to assess the pollution potential of individual elements in soils. This is calculated using the following equation (Eq. 1) [19].

$$CF = \frac{C_{metal}}{C_{control}} \quad (1)$$

where C_{metal} and $C_{control}$ are concentrations of metals in contaminated and background samples, respectively. In this study, world background soil was used as the control value. The level of contamination is classified according to the *CF* values given in Table 1 [19].

Geo-accumulation Index (I_{geo})

The geo-accumulation index (I_{geo}) was introduced by Muller [20] to evaluate trace element contamination in sediments, and it is now widely used to determine soil contamination [21]. I_{geo} is calculated as follows (Eq. 2):

$$I_{geo} = log_2 \left(\frac{C_{metal}}{1.5\ C_{metal(control)}} \right) \quad (2)$$

Table 1 Classification according to contamination factor (*CF*) for soils [19]

CF value	Contamination level
CF < 1	Low
1 ≤ CF < 3	Moderate
3 ≤ CF < 6	Considerable
CF ≥ 6	Very high

where C_{metal} is the concentration of the metal in the studied sample and $C_{metal(control)}$ is the geochemical background value (world background soil). The factor 1.5 is the correction factor used to minimize the effect of possible variations in the background or control values which may be attributed to terrigenous effects [22]. The six classes of I_{geo} index values are given in Table 2 [20].

Degree of Contamination (C_{deg})

The sum of contamination factors for all elements for a particular sampling site represents the contamination degree (C_{deg}). This is calculated using the following equation (Eq. 3) [19]:

$$C_{deg} = \sum_{i=1}^{n} CF \tag{3}$$

where n is the number of analyzed pollutants, and *CF* is the contamination factor. The classification of "C_{deg}" is given in Table 3.

Modified Degree of Contamination (mC_d)

The modified degree of contamination index (mC_d) is the sum of all the contamination factors for a given set of pollutants by the number of analyzed pollutants. This is a modified form of the Hakanson equation [23] and was calculated as follows (Eq. 4):

$$mC_d = \frac{\sum_{i=1}^{n} CF}{n} \tag{4}$$

where n is the number of analyzed pollutants and *CF* is the contamination factor, which is calculated based on Eq. 1. The classification of mC_d values is given in Table 4 [23].

Pollution Load Index (*PLI*)

Pollution load index (*PLI*) is used to determine the total metal contamination in soils [24]. This index is the geometric mean of the contamination factor (*CF*) of different trace metals present in the study area. *PLI* is expressed as:

$$PLI = \sqrt[n]{CF_1 \times CF_2 \times CF_3 \ldots\ldots \times CF_n} \tag{5}$$

Table 2 Index of geoaccumulation (I_{geo}) for contamination levels in soil [20]

Class	Value	Soil quality
0	$I_{geo} \le 0$	Uncontaminated
1	$0 < I_{geo} < 1$	Uncontaminated/moderately contaminated
2	$1 < I_{geo} < 2$	Moderately contaminated
3	$2 < I_{geo} < 3$	Moderately/strongly contaminated
4	$3 < I_{geo} < 4$	Strongly contaminated
5	$4 < I_{geo} < 5$	Strongly/extremely contaminated
6	$5 < I_{geo}$	Extremely contaminated

where n is the number of metals and *CF* is the contamination factor. A *PLI* value >1 indicates soil is polluted whereas a *PLI* value <1 indicates no pollution [14].

Nemerow Integrated Pollution Index (*NIPI*)

A Nemerow integrated index (*NIPI*) was applied to determine the quality of the soil environment [25] and is defined as follows (Eq. 6):

$$NIPI = \sqrt{\frac{PI_{avg}^2 + PI_{max}^2}{2}} \tag{6}$$

where $PI = C$, and PI_{avg}^2 and PI_{max}^2 are the maximum and average *PI* value of each metal, respectively. The quality of soil was classified into five grades according to the *NIPI* index (Table 5) [25].

Ecological Risk Factor

An ecological risk factor (E_i) quantitatively expresses the potential ecological risk of a single contaminant. This can be calculated using the equation [19]:

$$E_i = T_f \times CF \tag{7}$$

where T_f is the toxic response for a given element, and *CF* is the contamination factor, which is calculated based on Eq. 1. The toxic-response factors for common trace elements such as Pb, Cd, As, Cu, and Zn were 5, 30, 10, 5, and 1, respectively. The terminology used to describe the risk factor is given in Table 6.

Table 3 Different degrees of contamination (C_{deg}) for soils [19]

Class	Degree of contamination level
$C_{deg} < 8$	Low degree of contamination
$8 \le C_{deg} < 16$	Moderate degree of contamination
$16 \le C_{deg} < 32$	Considerable degree of contamination
$C_{deg} > 32$	Very high degree of contamination

Table 4 Different classes of modified degree of contamination (mC_d) values for soils [23]

Class	Degree of contamination level
$mC_d < 1.5$	Nil to very low degree of contamination
$1.5 \leq mC_d < 2$	Low degree of contamination
$2 \leq mC_d < 4$	Moderate degree of contamination
$4 \leq mC_d < 8$	High degree of contamination
$8 \leq mC_d < 16$	Very high degree of contamination
$16 \leq mC_d < 32$	Extremely high degree of contamination
$16 \leq mC_d < 32$	Ultra high degree of contamination

Potential Ecological Risk Index (*RI*)

The potential ecological risk index (*RI*) was introduced in the same way as the degree of contamination, and was defined as the sum of all risk factors for metals in soils. This is defined as follows (Eq. 8):

$$RI = \sum_{i=1}^{n} E_i \tag{8}$$

where E_i is the single index of ecological risk factor, and n is the number of the trace element species. The classification of potential ecological risk and the relevant terminology are listed in Table 7 [19].

Results and Discussion

Trace Element Content in Soils around Coal Mines

The concentrations of trace elements in soils nearby coal fields from various countries are given in Table 8 [26–46, 47•, 48–57]. In order to facilitate a comparative analysis, world background soils [58, 59], upper crustal abundance value (UCC) [60], and other reference soils (China, the USA, Spain, and Brazil) were used [61–64]. The degree of contamination of individual metals was determined with the help of *CF* and I_{geo} (Tables 3 and 9). Although some authors have considered the local background soils as the reference for calculation of pollution indices, such background values vary from place to place and are less suitable for a global assessment. As such, global reference materials, such as world background soil [58, 59], have been used. Concentration data and contamination status of each metal are discussed below.

Table 5 Different classes of Nemerow integrated pollution index (*NIPI*) values of soils [25]

Class	Degree of contamination level
$NIPI \leq 0.7$	Non-pollution
$0.7 < NIPI \leq 1$	Warning line of pollution
$1 < NIPI \leq 2$	Low level of pollution
$2 < NIPI \leq 3$	Moderate level of contamination
$NIPI > 3$	High level of pollution

Table 6 The ecological risk coefficient (E_i) of soils [19]

Value	Pollution degree
$E_i < 40$	Low
$40 \leq E_i < 80$	Moderate
$80 \leq E_i < 160$	Considerable
$160 \leq E_i < 320$	High
$E_i \geq 320$	Very high

Arsenic (As)

Arsenic is considered a class 'A' human carcinogen element in the USA [67], and therefore has generated considerable global attention to the environment and public health. The average As concentrations in surface soil in the vicinity of coal mines varied widely from 0.5 to 38.3 mg/kg, and most of these values were higher than the respective values of UCC (Table 1). Concentrations in soils from Dingji (China), Barapukuria (Bangladesh), Ptolemais (Greece), Douro (Portugal), and Tula (Russia) exceeded those from world background soils, and also exceeded the values in US baseline soil [62], China reference soils [61], and the threshold value (12 mg/kg) set by CCME (Canadian Council of Ministers of the Environment). The highest average As value in soil was found at Douro coalfield in Portugal, which was the only site that exceeded the threshold value (29 mg/kg) for clean soil recommended by the Dutch Ministry, suggesting the need for prompt remediation of As contamination. The main source of As in soils is its parent material, but As accumulation in urban environments is most likely due to combustion of fossil fuels, particularly coal and mining activities [68].

The I_{geo} value of As was lower compared to other metals, and ranges from −5.9 to 1.16 (Table 3). The maximum value, 1.16, was from Douro coalfield,

Table 7 The potential ecological risk coefficient (RI) of soils [19]

Value	Risk potential
$RI < 50$	Low
$50 \leq RI < 100$	Moderate
$100 \leq RI < 200$	High
$RI \geq 200$	Significantly very high

Table 8 Average concentrations (mg/kg) of trace elements in coal-mine soils from various countries compared with global reference values and other reference soils

Location	Soil type	No.	As	Mn	Zn	Cu	Cr	Ni	Pb	Cd	Hg	Reference
Antaibao, China	Reclaimed soil	-	-	-	-	31.16	59.4	-	9.72	0.09	0.1	[26]
Fushun, China	Reclaimed soil	3	-	142.3	46.3	16.23	42.77	-	-	0.42	-	[27]
Heidaigou, China	Reclaimed soil	-	-	-	56.2	18.06	73.8	27.88	12.36	0.09	0.03	[28]
Laohutai, China	Reclaimed soil	-	-	-	65.6	34.33	72.49	-	-	0.02	-	[27]
Pindingshan, China	Reclaimed soil	-	-	-	39.9	38.99	594.1	19.2	61	1.3	-	[29]
Pingshuo, China	Reclaimed soil	-	-	-	-	-	40.92	-	23	0.21	0.02	[30]
Xuzhou, China	Reclaimed soil	-	-	-	130.9	52.3	73.4	-	47.4	3.2	0.03	[31]
Huainan, China	Reclaimed soil	-	-	-	90.2	38.2	213.5	40	40	1.4	0.04	[32]
Datong , China	Reclaimed soil	-	3.82	-	-	44.75	-	-	44.75	0.31	0.205	[33]
Panyi, China	Reclaimed soil	-	6.44	-	-	40.28	-	-	52.93	0.43	0.126	[33]
Xinzhuangzi, China	Reclaimed soil	–	5.86	-	-	43.52	-	-	42.58	0.51	0.177	[33]
Baodian, China	Reclaimed soil	12		-	101.8	30.9	-	-	37.78	1.97	-	[34]
Heidaigou, China	Reclaimed soil	10	8.89	-	56.7	17	66	27.3	12.2	0.06	0.02	[35]
Huabei, China		45	8.47	-	69.3	19.8	-	-	-	-	-	[36]
Jilin Province, China	Top soil	-	-	-	65.4	21.5	69.6	-	20.9	0.15	-	[37]
Dingji, China	Reclaimed soil	8	17.6	-	46.5	30	41.1	-	23.8	0.13	-	[38]
Guizhou, China	Mine-impacted soil	-	-	-	135.8	-	-	-	42.4	-	-	[39]
Raniganj, India	Native soil	8	-	462.3	44.3	12.2	46.7	26.23	8.19	0.955	-	[40]
Surat, India	Agricultural soil	8	-	-	108.3	110.4	37.9	65.5	17.8	1.56	-	[41]
Raniganj, India	Top soil	3	-	86	148.6	47.3	240	124.6	-	-	-	[42]
Sonepur Bazari, India	Opencast mine-impacted soil	32	-	3.96	947	27	98	34	27.3	0.012	-	[43]
Jaintia, India	AMD contaminated soil	18	-	232	53.9	22.9	143	38.4	23	1.53	-	[44]
Makum, India	AMD contaminated soil	11	-	399	63.4	22.7	202	83	13.9	1.32	-	[45]
Ledo, Tinsukia, India	Mine-impacted soil	-	-	-		-	112	87.5	183	2.6	-	[46]
Gangreung, Korea	AMD contaminated soil	-	-	-	87.3	41	35.8	42.6	32.9	1.1	-	[17]
Barapukuria, Bangladesh	AMD contaminated soil	30	17.5	1886	296	-	-	-	433	-	-	[8•]
Barapukuria, Bangladesh	Paddy soils	-	22.4	1048	160	29	107	98.5	188.6	-	-	[18]
Tibagi River watershed, Brazil	Regular soils	-	-	3700		-	-	-	-	4.48	-	[47•]
Oltu, Turkey		19	-	-	35.9	23.4	135.6	59.8	34.2	0.03	0.69	[48]
Ptolemais, Greece		101	12.3	-	-	-	17.5	10.1	-	-	-	[49]
Ptolemais-Amynteon, Greece	Regular soil	-	9.3	-	94.5	45.7	522.5	390	64.2	0.25	-	[50]
Ptolemais-Amynteon, Greece	Reclamed soil	-	6.25	-	56	32.5	205.8	137	61.3	0.25	-	[50]
Douro, Portugal	Waste-impacted soil	3	38.3	139	57	36.5	92.3	21.4	30.8	0.2	-	[51]
Tula, Moscow, Russia		134	17.4	-	164.5	-	-	-	-	-	-	[52]
Palapye, Botswana	Mine soil	27	9.8	-	65	35.4	125.2	47.3	22.8	-	-	[53]
Smolnica, Southern Polland	Reclaimed soil, organic rich	-	-	-	142	18	-	-	39.9	1.65	-	[54]
Emalahleni, South Africa	Mine-impacted soil	693	0.5	-	36	22	419	20	19	-	-	[55]
Okaba, Nigeria	Mine-impacted soil	11	-	-	1.5	0.5	-	4.3	0.5	0.6	-	[56]
Pokrok, Czech Republic	Reclaimed soil	103	4.48	599	25.2	13.7	-	-	18.4	0.27	-	[57]
Minimum			0.5	86	1.5	0.5	17.5	4.3	0.5	0.02	0.012	
Maximum			38.3	3,700	296	110.4	523	390	433	4.48	0.69	
World background soil			11.4	571	67.8	28.2	70.9	17.8	28.4	0.49	0.06*	[58, 59*]
Upper continental crust			2	900	52	14	35	19	17	0.102	0.056	[60]
Reference soil, China			11.2	-	74	23	61	27	27	0.097	0.065	[61]
Reference soil, USA			5.5	380	55	21	41	15	17	-	0.05	[62]
Reference soil, Spain			-	-	192	-	73	43	30	0.3	-	[63]
Reference soil, Brazil			-	-	59.9	35.1	40.3	13.2	17	0.5	-	[64]
Target value, Dutch Ministry of Housing			29	-	140	36	100	35	85	0.8	0.3	[65]
Soil quality for agricultural soil, Canada			12	-	200	63	64	50	70	1.4	6.6	[66]

No. number of samples, *As* arsenic, *Mn* manganese, *Zn* zinc, *Cu* copper, *Cr* chromium, *Ni* nickel, *Pb* lead, *Cd* cadmium, *Hg* mercury

- indicates data not available

* indicates the Hg value cited from reference [59], while rests are cited from reference [60]

Table 9 Contamination factor (*CF*), Nemerow integrated pollution index (NIPI), integrated pollution index (*IPL*), degree of contamination (C_{deg}), and modified degree of contamination ($_mC_d$) of trace elements in coal-mine soils collected from various cities/countries

Location	Soil type	*CF*									NIPI	PLI	C_{deg}	$_mC_d$	Reference
		As	Mn	Zn	Cu	Cr	Ni	Pb	Cd	Hg					
Antaibao, China	Reclaimed soil	-	-	-	1.10	0.84	-	0.34	0.18	1.67	1.12	0.63	4.14	0.83	[26]
Fushun, China	Reclaimed soil	-	0.25	0.68	0.58	0.60	-	-	0.86	-	0.88	0.67	2.72	0.68	[27]
Heidaigou, China	Reclaimed soil	-	-	0.83	0.64	1.04	1.57	0.44	0.18	0.50	1.07	0.62	5.20	0.74	[28]
Laohutai, China	Reclaimed soil	-	-	0.97	1.22	1.02	-		0.04	-	1.01	0.47	3.25	0.81	[27]
Pindingshan, China	Reclaimed soil	-	-	0.59	1.38	8.38	1.08	2.16	2.65	-	2.35	1.87	16.25	2.71	[29]
Pingshuo, China	Reclaimed soil	-	-			0.58	-	0.82	0.43	0.33	0.82	0.51	2.15	0.54	[30]
Xuzhou, China	Reclaimed soil	-	-	1.93	1.85	1.04	-	1.68	6.53	0.50	2.10	1.65	13.53	2.26	[31]
Huainan, China	Reclaimed soil	-	-	1.33	1.35	3.01	2.25	1.42	2.86	0.67	1.56	1.65	12.89	1.84	[32]
Datong , China	Reclaimed soil	0.34	-	-	1.59	-	-	1.59	0.63	3.42	1.57	1.13	7.56	1.51	[33]
Panyi, China	Reclaimed soil	0.56	-	-	1.43	-	-	1.88	0.88	2.10	1.32	1.23	6.85	1.37	[33]
Xinzhuangzi, China	Reclaimed soil	0.51	-	-	1.54	-	-	1.51	1.04	2.95	1.49	1.30	7.56	1.51	[33]
Baodian, China	Reclaimed soil	-	-	1.50	1.10	-	-	1.34	4.02	-	1.73	1.73	7.96	1.99	[34]
Heidaigou, China	Reclaimed soil	0.78	-	0.84	0.60	0.93	1.53	0.43	0.12	0.33	1.06	0.56	5.57	0.70	[35]
Huabei, China		0.74	-	1.02	0.70	-	-	-	-	-	0.96	0.81	2.47	0.82	[36]
Jilin Province, China	Top soil	-	-	0.96	0.76	0.98	-	0.74	0.31	-	0.93	0.70	3.76	0.75	[37]
Dingji, China	Reclaimed soil	1.54	-	0.69	1.06	0.58	-	0.84	0.27	-	1.09	0.73	4.98	0.83	[38]
Guizhou, China	Mine-impacted soil	-	-	2.00	-	-	-	1.54	-	-	1.37	1.74	3.51	1.75	[39]
Raniganj, India	Native soil	-	0.81	0.65	0.43	0.66	1.47	0.29	1.95	-	1.19	0.74	6.27	0.90	[40]
Surat, India	Agricultural soil	-		1.60	3.91	0.53	3.68	0.63	3.18	-	1.76	1.71	13.54	1.93	[41]
Raniganj, India	Top soil	-	0.15	2.19	1.68	3.39	7.00	-	-	-	2.22	1.67	14.40	2.88	[42]
Sonepur Bazari, India	Opencast mine soil	0.34	1.68	0.69	0.95	1.38	1.91	0.96	0.024	-	1.2	0.68	7.94	1.13	[43]
Jaintia, India	AMD contaminated soil	-	0.41	0.79	0.81	2.02	2.16	0.82	3.12	-	1.51	1.16	10.13	1.45	[44]
Makum, India	AMD contaminated soil	-	0.70	0.94	0.80	2.85	4.66	0.49	2.69	-	1.81	1.37	13.14	1.88	[45]
Ledo, Tinsukia, India	Mine-impacted soil	-	-	-	-	1.58	4.92	6.48	5.3	-	2.35	4.04	18.29	4.57	[46]
Gangreung, Korea	AMD contaminated soil	-	-	1.29	1.45	0.50	2.39	1.17	2.24	-	1.40	1.29	9.05	1.29	[17]
Barapukuria, Bangladesh	AMD contaminated soil	1.54	3.30	4.37	-	-	-	15.35	-	-	3.28	4.29	24.56	6.14	[8•]
Barapukuria, Bangladesh	Paddy soils	1.96	1.84	2.36	1.03	1.51	5.53	6.69	-	-	2.20	2.42	20.92	2.99	[18]
Tibagi River watershed, Brazil	Regular soils	-	6.48	-	-	-	-	-	9.14	-	3.01	7.70	15.62	7.81	[47•]
Oltu, Turkey		-	-	0.53	0.83	1.91	3.36	1.21	0.06	11.50	2.67	0.77	19.41	2.77	[48]
Ptolemais, Greece		1.08	-	-	-	0.25	0.57	-	-	-	0.92	0.53	1.89	0.63	[49]
Ptolemais-Amynteon, Greece	Regular soil	0.82	-	1.39	1.62	7.37	21.91	2.28	0.51	-	3.68	2.30	35.90	5.13	[50]
Ptolemais-Amynteon, Greece	Reclamed soil	0.55	-	0.83	1.15	2.90	7.70	2.17	0.51	-	2.23	1.44	15.81	2.26	[50]
Douro, Portugal	Waste-impacted soil	3.36	0.24	0.84	1.29	1.30	1.20	1.09	0.41	-	1.51	0.93	9.74	1.22	[51]
Tula, Moscow, Russia		1.53	-	2.43	-	-	-	-	-	-	1.48	1.92	3.95	1.98	[52]
Palapye, Botswana	Mine soil	0.86	-	0.96	1.26	1.77	2.66	0.81	-	-	1.42	1.26	8.31	1.38	[53]
Smolnica, Southern Polland	Reclaimed soil, organic		-	2.9	0.64	-	-	1.41	3.37	-	1.6	1.45	7.5	1.88	[54]
Emalahleni, South Africa	Mine soil	0.04	-	0.53	0.78	5.9	1.12	0.67		-	1.93	0.66	9.06	1.5	[55]
Okaba, Nigeria	Mine soil		-	0.02	0.02	-	0.24	0.02	1.22	-	0.87	0.07	1.5	0.25	[56]
Pokrok, Czech Republic	Reclaimed soil	0.39	1.05	0.37	0.49	-	-	0.65	0.55	-	0.9	0.55	3.5	0.58	[57]
Minimum		0.04	0.15	0.02	0.02	0.25	0.24	0.02	0.02	0.33	0.82	0.07	1.52	0.25	
Maximum		3.36	6.48	4.37	3.91	8.38	21.91	15.35	9.14	11.50	3.68	7.70	35.90	7.81	

No. number of samples, *As* arsenic, *Mn* manganese, *Zn* zinc, *Cu* copper, *Cr* chromium, *Ni* nickel, *Pb* lead, *Cd* cadmium, *Hg* mercury

- indicates data not available

Portugal, which indicates moderate contamination, while the rest are uncontaminated. Similarly, the *CF* of As was low and varied from 0.04 to 3.36 (Table 9), confirming most soils have low to moderate As contamination. The highest *CF* value was found in Douro, Portugal, similar to the I_{geo} values, indicating considerable contamination.

Cadmium (Cd)

Cadmium is a toxic metal and an environmental hazard. The average Cd concentration in surface soils around the coal mine sites varies from 0.02 to 4.48 mg/kg (Table 8). Most of the soils values, except from Heidaigou and Laohuti (China) and Sonepur Bazari (India), are higher than the UCC and China reference soils. Compared to the world average soil, 14 out of 34 sites exceeded the average values of Cd. The highest average concentration was reported in the surface soil samples from the Tibagi River watershed in Brazil. The target value of Cd for clean soil is 1 mg/kg of soil [65], which is exceeded in soils from Pindingshan, Xuzhou, Huainan, and Boadian in China; Jaintia and Makum in India; and Gangreung in Korea.

The I_{geo} values of Cd in studied soils varies from −5.9 to 2.64 (Table 10), indicating uncontaminated to moderate-strong contamination. The maximum values from the Tibagi River, Brazil and Xuzhoiu, China show moderate-strong contamination, with the rest having moderate to low contaminated categories. The *CF* classified the soils as having low to very high contamination with respect to Cd. The high I_{geo} was consistent with high *CF* values.

Chromium (Cr)

The average Cr concentrations in the surface soils varied between 17.7 and 523 mg/kg, and most soils exceeded the world soil average and UCC values (Table 8). The target value for clean soil and the intervention value for soil remediation as established by VROM are 100 mg/kg and 380 mg/kg [65], respectively. This indicates the average concentrations of soil from Greece exceeded this limit, implying this area needs to be promptly managed for Cr contamination. The remaining cities have sustainable Cr content in soil quality levels.

The obtained I_{geo} values vary from −2.6 to 2.48 (Table 10), which can be categorized as uncontaminated to moderately contaminated. While the *CF* varies from 0.25 to 8.35 (Table 9), soils from Ptomemain in Greece indicate very high contamination.

Nickel (Ni)

The average Ni concentration varies from 4.3 to 390 mg/kg. Most of the soils exceeded the average value of the world background soil and UCC (Table 8). Most of sites, except Okaca (Nigeria) and Ptolemais (Greece), also exceeded the Ni values compared to the US reference soil (15 mg/kg), while a total of 13 sites have higher values than the reference soil of China (27 mg/kg). The target and intervention values for Ni established by the Dutch are 35 and 210 mg/kg, respectively [65]. Soils from Greece have an average value of 390 mg/kg, which is higher than the target value, suggesting that remediation is needed.

In studied soils, I_{geo} values range from −2.63 to 3.87 (Table 10). The regular soil from Ptolemais, Greece shows strong contamination, while reclaimed soil from this coal field, along with soil from Raniganj coalfield, showed moderate to strong contamination, while the rest are characterized as being uncontaminated to moderately contaminated. The *CF* factor varies from 0.24 to 21.9 (Table 9); the highest value for soil from Ptolemais-Amynteon (Greece) shows very high contamination, and this soil also had the highest I_{geo} values.

Zinc (Zn)

The average Zn concentrations ranged from 1.5 to 296 mg/kg, and the highest concentration was reported in the soils of Barapukuria coal mine, Bangladesh (Table 8). Most of the sites exceed the level of world background soils and UCC. However, all studies were below the intervention limit (720 mg/kg), which was proposed by VROM [65]. VROM proposed a Zn concentration of 140 mg/kg as the limit of sustainable soil quality, but the average concentrations of Raniganj, Barapukuria, and Tula coal mine regions are higher than the Dutch limit, indicating Zn contamination in these areas.

The I_{geo} values of Zn vary from −6.07 to 1.55 (Table 10), indicating low to moderate contamination. The soils from Barapukuria only show moderate contamination, while the remaining soils are classified as uncontaminated. This is consistent with the *CF* value (Table 9).

Copper (Cu)

The average Cu concentrations in surface soils from various sites ranged from 0.5 to 110 mg/kg (Table 8). Except for the soils from Raniganj, Okaba, and Pokrok, the soils studied exceeded the average concentration of UCC. Compared to the world background soils, eight cities out of the total are higher than the limit; however, soils from Surat, Ranigang, and Gengreung have greater values than the target value of 36 mg/kg established by VROM [65].

The I_{geo} values of Cu vary from −6.4 to 1.38 (Table 10), soil from Surat, India shows moderate contamination, while other soils fall under uncontaminated categories. Similarly, higher *CF* values in soil from Surat indicate moderate contamination.

Lead (Pb)

Lead is a major environmental contaminant in mining-impacted soils. The average Pb concentration varies from 0.5 to 433 mg/kg, and most soils exceeded the respective UCC value, except for four soils (Table 8). Of the total cases reviewed, around 50 % of soils exceeded the world background soil levels and reference

Table 10 Geo-accumulation (I_{geo}) values in soils collected from various sites around coal mines worldwide

Locations	Soil Type	As	Mn	Zn	Cu	Cr	Ni	Pb	Cd	Hg	Reference
Antaibao, China	Reclaimed soil	-	-	-	-0.44	-0.84	-	-2.13	-3.00	0.15	[26]
Fushun, China	Reclaimed soil	-	-	-1.13	-1.38	-1.31	-	-	-0.78	-	[27]
Heidaigou, China	Reclaimed soil	-	-	-0.85	-1.23	-0.53	0.06	-1.79	-3.00	-1.58	[28]
Laohutai, China	Reclaimed soil	-	-	-0.63	-0.30	-0.55	-	-	-5.17	-	[27]
Pindingshan, China	Reclaimed soil	-	-	-1.34	-0.12	2.48	-0.48	0.52	0.85	-	[29]
Pingshuo, China	Reclaimed soil	-	-	-	-	-1.38	-	-0.89	-1.78	-2.17	[30]
Xuzhou, China	Reclaimed soil	-	-	0.37	0.31	-0.53	-	0.15	2.15	-1.58	[31]
Huainan, China	Reclaimed soil	-	-	-0.17	-0.15	1.01	0.58	-0.09	0.96	-1.17	[32]
Datong , China	Reclaimed soil	-2.16	-	-	0.08	-	-	0.07	-1.22	1.19	[33]
Panyi, China	Reclaimed soil	-1.41	-	-	-0.07	-	-	0.31	-0.74	0.49	[33]
Xinzhuangzi, China	Reclaimed soil	-1.55	-	-	0.04	-	-	0.00	-0.50	0.98	[33]
Baodian, China	Reclaimed soil	-	-	0.01	-0.45	-	-	-0.17	1.45	-	[34]
Heidaigou, China	Reclaimed soil	-0.94	-	-0.84	-1.32	-0.69	0.03	-1.80	-3.58	-2.17	[35]
Huabei, China		-1.01	-	-0.55	-1.10	-	-	-	-	-	[36]
Jilin Province, China	Top soil	-	-	-0.63	-0.98	-0.61	-	-1.03	-2.26	-	[37]
Dingji, China	Reclaimed soil	0.04	-	-1.12	-0.50	-1.37	-	-0.84	-2.47	-	[38]
Guizhou Province, China	Mine soil	-	-	0.42	-	-	-	-0.06	-	-	[39]
Raniganj, India	Native soil	-	-0.89	-1.19	-1.79	-1.19	-0.03	-2.38	0.41	-	[40]
Surat, India	Agricultural Soil	-	-	0.10	1.38	-1.49	1.29	-1.26	1.12	-	[41]
Raniganj, India	Top soil	-	-3.32	0.55	0.16	1.17	2.22	-	-	-	[42]
Sonepur Bazari, India	Opencast mine soil	-	0.14	-1.11	-0.64	-0.11	0.34	-0.64	-5.9	-	[43]
Jaintia, India	AMD contaminated soil	-	-1.88	-0.91	-0.89	0.43	0.52	-0.89	1.09	-	[44]
Makum, India	AMD contaminated soil	-	-1.10	-0.68	-0.90	0.93	1.64	-1.62	0.87	-	[45]
Ledo, Tinsukia, India	Mine soil	-	0.11	-	-	0.07	1.71	2.1	1.85	-	[46]
Gangreung, Korea	AMD contaminated soil	-	-	-0.21	-0.05	-1.57	0.67	-0.37	0.61	-	[17]
Barapukuria, Bangladesh	AMD contaminated soil	0.03	1.14	1.55	-	-	-	3.35	-	-	[8•]
Barapukuria, Bangladesh	Paddy soils	0.39	0.29	0.66	-0.54	0.01	1.88	2.15	-	-	[18]
Tibagi River watershed, Brazil	Regular soils	-	2.11	-	-	-	-	-	2.64	-	[47•]
Oltu, Turkey		-	-	-1.50	-0.85	0.35	1.16	-0.32	-4.58	2.94	[48]
Ptolemais, Greece		-0.48	-			-2.60	-1.40			-	[49]
Ptolemais-Amynteon, Greece	Regular soil	-0.88	-	-0.10	0.11	2.30	3.87	0.59	-1.53	-	[50]
Ptolemais-Amynteon, Greece	Reclamed soil	-1.45	-	-0.85	-0.38	0.95	2.36	0.53	-1.53	-	[50]
Douro, Portugal	Waste impacted soil	1.16	-2.62	-0.83	-0.21	-0.20	-0.32	-0.47	-1.85	-	[51]
Tula, Moscow, Russia		0.03	-	0.70	-	-	-	-	-	-	[52]
Palapye, Botswana	Mine soil	-0.80	-	-0.64	-0.26	0.24	0.83	-0.90	-	-	[53]
Smolnica, Southern Polland	Reclaimed soil	-	-	0.48	-1.23			-0.09	1.19	-	[54]
Emlahleni, South Arfica	Mine soil	-5.9	-	-1.49	-0.9	1.97	-0.41	-1.16	-	-	[55]
Okaba, Nigeria	Mine soil	-	-	-6.07	-6.4	-	-2.63	-6.4	-0.26	-	[56]
Pokrok, Czech Republic	Reclaimed soil	-1.93	-0.5	-2.00	-1.6	-	-	-1.2	-1.41	-	[57]
Minimum		-5.9	-3.32	-6.07	-6.4	-2.60	-2.63	-6.4	-5.9	-2.17	
Maximum		1.16	2.11	1.55	1.38	2.48	3.87	3.35	2.64	2.94	

No. number of samples, *As* arsenic, *Mn* manganese, *Zn* zinc, *Cu* copper, *Cr* chromium, *Ni* nickel, *Pb* lead, *Cd* cadmium, *Hg* mercury

- indicates data not available

value of Chinese soils. The highest concentration was observed from Barapukuria coal mine in Bangladesh, which was the only site to exceed the target limit of 85 mg/kg established for soil remediation [65].

The I_{geo} value of Pb (−6.4 to 3.35) shows no contamination to strong contamination (Table 10). The *CF* varies from 0.02 to 15.35, indicating no contamination to very high contamination (Table 9). The *CF* value for soils from Barapukuria,

Bangladesh were >6, and have the highest I_{geo} value, indicating high contamination.

Mercury (Hg)

Mercury is a persistent, toxic, and bio-accumulative heavy metal. The concentration of Hg in soil in the vicinity of coal mines varies from 0.02 to 0.96 mg/kg (Table 8), the soils from Datong, Panyi, and Xinzhungzi in China and the Tibagi River wastershed in Brazil exceed the world average soil concentrations. These soils are considered to be enriched with Hg according to Gustin and Lindberg [69] since their concentrations exceeded ≥0.1 mg/kg. The highest average concentration was recorded from the Tibagi River wastershed, and exceeds the optimum levels for Hg (0.3 mg/kg) for clean soil according to the Dutch Guidelines [65]

The I_{geo} value varies from –2.17 to 2.9 (Table 10), which fall under class 0 and class 3, showing uncontaminated to moderately contaminated. Similarly, the *CF* varies from 0.33 to 11.5, which indicates low to very high contamination. The highest *CF* and I_{geo} values were found in Oltu, Turkey, indicating high contamination.

Overall Metal Contamination in the Studied Soils

The comprehensive state of contamination of the studied soils around various coal mines was evaluated based on four parameters: C_{deg}, mC_d, *PLI*, and *NIPI* (Table 9). Around 60 % of the sites in the studies reviewed show *PLI* values >1, indicating soil pollution. The C_{deg} values of the studied soils vary from 1.52 to 35.9, while the *mCd* values varied from 0.25 to 7.8. Based on these indices, soil from Pindingshan, Xuzhou, and Boadian coal mines in China; Surat coal mine in India; Bhuiyan coal mine in Bangladesh; Ledo coal mines in India; and the Tibagi River watershed in Brazil have a high degree of pollution based on the concentrations of Cd, Pb, Cu, Cr, and Zn. Soils from Huainan, China; Jaintia and Makum, India; and Gangreung, Korea are categorized as having a moderate degree of contamination, and the rest are classified as having a low degree of contamination. This observation is consistents with *NIPI* values.

Potential Ecological Risk Analysis

The ecological risk of individual elements (E_i) varied significantly among elements (Table 11): As, 0.43–33.5; Zn, 0.02–4.3; Cu, 0.08–19.5; Cr, 0.09–16.7; Pb, 0.73–76.7; Cd, 0.73–274; and Hg, 13–460. In terms of the average values of E_i, these metals were arranged in the following descending order: Hg > Cd > As > Pb > Cu > Cr > Mn. Hg and Cd pose a high risk for soil bodies, their maximum values reaching 469 and 274, respectively. Five sites have a strong potential ecological risk for Hg, and ten sites have a strong potential ecological risk from Cd, whereas other trace elements only show a slight ecological risk to the environment (Table 11). This assessment indicates Hg and Cd are the key elements to be further studied and considered as important in the assessment of metals in coal mine soils. With regard to Cd, the Xuzhou and Baodian coal fields of China, Ledo coal mines in India, Tibagi River watershed in Brazil, and Smolnica coal mines in southern Poland show a high degree of ecological risk. With regard to Hg, a high degree of pollution was observed at Datong and Xinzhuangzi in China, and Oltu in Turkey.

The potential ecological risk (*RI*) represents the sensitivity of various biological communities to toxic substances and illustrates the potential ecological risk caused by overall metal contamination. Based on the *RI* values (Table 11), soil from Xuzhou (China), Tibagi River (Brazil), Smolnica coal mines in southern Poland, and Oltu (Turkey) shows a very high risk of contamination.

Management of Soil Contamination

Management of soil contamination is a global concern for environmental and agricultural sustainability. This can be classified into immediate and long-term actions as follows:

Immediate Action

Immediate action may involve formulating soil quality guidelines and standards, conducting monitoring programs, and enforcing environmental regulations. Government regulators and coal-mining companies must take the first steps to monitor metal pollution nearby the mining areas. The most effective step in managing soil pollution is to control contaminants from their sources, especially waste discharge and overburden, and enforcement of strong environmental regulations and laws [70, 71].

Long-term Action

Long-term measures may include concluding an Environmental Impact Assessment (EIA) on existing and proposed coal-mining projects, and utilizing appropriate technology for remediation of toxic metals. There are several physical, chemical, and biological remedial technologies that have been developed to manage soil pollution [72, 73] (Fig. 3).

Physical Methods

Physical technologies mainly include soil replacement/mixing, capping, and thermal desorption. Soil replacement means using clean soil to replace the contaminated soils with the aim of diluting the metals [73, 74]. Soil capping is a reliable technology that does not involve removal of contaminated soils. Although these traditional methods can

Table 11 Ecological risk (E_i) and potential ecological risk factor (RI) of trace elements in soils worldwide

Location	Soil type	As	Zn	Cu	Cr	Pb	Cd	Hg	RI	Reference
Antaibao, China	Reclaimed soil	-	-	5.52	1.68	1.72	5.51	66.67	81.10	[26]
Fushun, China	Reclaimed soil	-	0.68	2.88	1.21	-	25.71	-	30.48	[27]
Heidaigou, China	Reclaimed soil	-	0.83	3.20	2.08	2.19	5.51	20.00	33.81	[28]
Laohutai, China	Reclaimed soil	-	0.97	6.09	2.04	-	1.22	-	10.32	[27]
Pindingshan, China	Reclaimed soil	-	0.59	6.91	16.76	10.82	79.59	-	114.67	[29]
Pingshuo, China	Reclaimed soil	-	-	-	1.15	4.08	12.86	13.33	31.42	[30]
Xuzhou, China	Reclaimed soil	-	1.93	9.27	2.07	8.40	195.92	20.00	237.60	[31]
Huainan, China	Reclaimed soil	-	1.33	6.77	6.02	7.09	85.71	26.67	133.60	[32]
Datong , China	Reclaimed soil	3.35	-	7.93	-	7.93	18.98	136.67	174.87	[33]
Panyi, China	Reclaimed soil	5.65	-	7.14	-	9.38	26.33	84.00	132.50	[33]
Xinzhuangzi, China	Reclaimed soil	5.14	-	7.72	-	7.55	31.22	118.00	169.63	[33]
Baodian, China	Reclaimed soil	-	1.50	5.48	-	6.70	120.61	-	134.29	[34]
Heidaigou, China	Reclaimed soil	7.80	0.84	3.01	1.86	2.16	3.67	13.33	32.68	[35]
Huabei, China		7.43	1.02	3.51	-	-	-	-	11.96	[36]
Jilin Province, China	Top soil	-	0.96	3.81	1.96	3.71	9.18	-	19.63	[37]
Dingji, China	Reclaimed soil	15.44	0.69	5.32	1.16	4.22	7.96	-	34.78	[38]
Guizhou, China	Mine soil	-	2.0	-	-	7.5	-	-	9.5	[39]
Raniganj, India	Native soil	-	0.65	2.16	1.32	1.45	58.47	-	64.06	[40]
Surat, India	Agricultural Soil	-	1.60	19.57	1.07	3.16	95.51	-	120.91	[41]
Raniganj, India	Top soil	-	2.19	8.39	6.77	-	-	-	17.35	[42]
Sonepur Bazari, India	Opencast mine	3.4	0.69	4.7	2.7	4.8	0.73	-	17.2	[43]
Jaintia, India	AMD contaminated soil	-	0.79	4.06	4.03	4.08	93.67	-	106.64	[44]
Makum, India	AMD contaminated soil	-	0.94	4.02	5.70	2.46	80.82	-	93.94	[45]
Ledo, Tinsukia, India	Mine soil	-	-	-	3.1	32.4	159.18	-	194.7	[46]
Gangreung, Korea	AMD contaminated soil	-	1.29	7.27	1.01	5.83	67.35	-	82.75	[17]
Barapukuria, Bangladesh	AMD contaminated soil	15.35	4.37			76.77	-	-	96.49	[8•]
Barapukuria, Bangladesh	Paddy soils	19.65	2.36	5.14	3.02	33.44	-	-	63.61	[18]
Tibagi River watershed, Brazil	Regular soils	-	-	-	-	-	274.29	-	274.29	[47•]
Oltu, Turkey		-	0.53	4.15	3.83	6.06	1.84	460.00	476.40	[48]
Ptolemais, Greece		10.79	-	-	0.49	-	-	-	11.28	[49]
Ptolemais-Amynteon, Greece	Regular soil	8.16	1.39	8.10	14.74	11.38	15.31	-	59.08	[50]
Ptolemais-Amynteon, Greece	Reclamed soil	5.48	0.83	5.76	5.81	10.87	15.31	-	44.05	[50]
Douro, Portugal	Waste-impacted soil	33.60	0.84	6.47	2.60	5.46	12.24	-	61.22	[51]
Tula, Moscow, Russia		15.26	2.43	-	-	-	-	-	17.69	[52]
Palapye, Botswana	Mine soil	8.60	0.96	6.28	3.53	4.04	-	-	23.41	[53]
Smolnica, Southern Polland	Reclaimed soil	-	2.09	3.19	-	7.0	101	-	113.3	[54]
Emlahleni, South Africa	Mine soil	0.43	0.53	3.9	11.8	3.36	-	-	20	[55]
Okaba, Nigeria	Mine soil	-	0.02	0.08	-	0.08	36.7	-	36.9	[56]
Pokrok, Czech Republic	Reclaimed soil	3.9	0.37	2.4	-	3.26	16.5	-	26.5	[57]
Minimum		0.43	0.02	0.08	0.49	0.08	0.73	13.33	10.32	
Maximum		33.60	4.37	19.57	16.76	76.77	274.29	460.00	476.4	

No. number of samples, *As* arsenic, *Mn* manganese, *Zn* zinc, *Cu* copper, *Cr* chromium, *Ni* nickel, *Pb* lead, *Cd* cadmium, *Hg* mercury

- indicates data not available

effectively isolate the contaminated soil or reduce the contamination levels, they are high cost technologies, move contamination to another area, and are not suitable for large areas [75, 76]. Another physical technology is thermal desorption, which is based on the phenomenon of the pollutant's volatility upon heating the contaminated soil. Although this technique can be applied for volatile elements such as Hg and As, application is limited

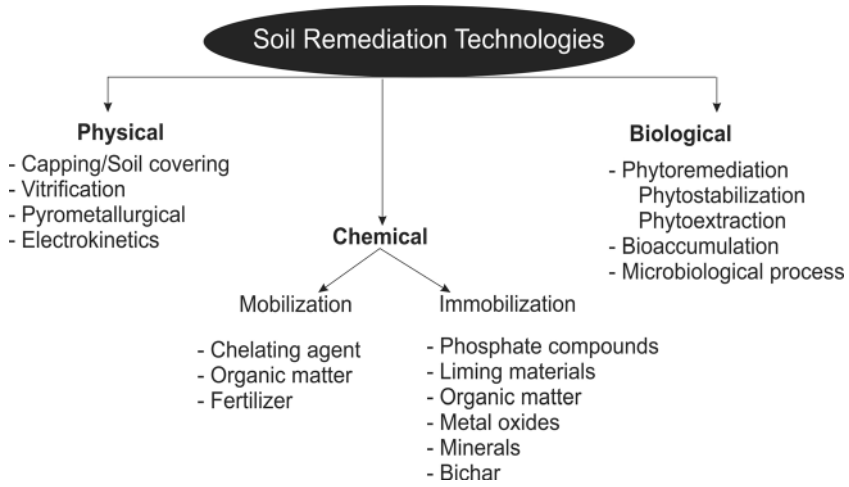

Fig. 3 Various physical, chemical, and biological methods for remediation of heavy metals in soils

because of the need for expensive heating devices and a long-term desorption time in the remediation process [73].

Another technology is electrokinetics, which is a new remediation technique based on the phenomenon of contaminant migration in the form of charged species in an electric field [77]. The current is applied by inserting electrodes in the contaminated soils. Then under the influence of an electromagnetic field, contaminants migrate through the soil within the cathode or anode area, where they can be removed by a variety of processes, including electroplating at the electrodes or chemical precipitation/co-precipitation at the electrodes [78]. However, this technique is strongly dependent on soil conductivity because energy consumption is directly related to the conductivity of soil between the electrodes. Also, this remediation technique may not feasible due to its high cost [79].

Chemical Methods

This technique is based on two fundamental processes to remediate soils, chemical leaching and chemical fixation (immobilization) [80]. Chemical leaching is washing of the contaminated soil by using reagents such as acids, salts, chelating agents, surfactants, etc. The soil washing cost is largely dependent on the extent to which contaminated sites are processed. Use of strong acid washing leads to decreases in soil productivity and adverse changes in the chemical and physical structure of soils due to mineral dissolution [81]. For chelation, EDTA can work in a wide pH range and could extract a significant fraction of metals from contaminated soils [82]. But EDTA is very stable in the soil and can make soil unfit for further use because residual EDTA can slowly leach nutrients from the soil and can disturb the physical and chemical properties of soil. Also, EDTA is expensive and its biological degradability is different. As an alternative, current research has focused on biodegradable and organic chelates such as saponin and tea saponin, which effectively removed toxic metals from soils and greatly reduced the environmental risk [83, 84]. Furthermore, it has been found that some low molecular weight organic acids such as citric and tartaric acid could solubilize metals from contaminated soil through complexation reactions [85, 86]. This is inexpensive, biodegradable, and less destructive to soil structure compared to EDTA. However, this technology is not a permanent solution because it needs long-term monitoring [86]. Chemical treatments can be performed both ex situ and in situ. However, in situ chemical agents must be carefully chosen so they do not cause further contamination. The major problem associated with chemical treatment is the nonspecific nature of the chemical reagents. The chemical added to treat one metal can also target reactive metals and can make them more toxic or mobile. Moreover, the remediation of polluted soil containing trace elements is technically difficult because of high costs and other effects. In addition, these approaches have been mostly studied at a laboratory level, though some are being studied in the field, but they are still small scale.

Biological Methods

Recently, use of phytoremediation as a potentially promising, low-cost, and in-situ new technology to remove pollutants from contaminated soils has gained increasing attention as an alternative to conventional physical and chemical methods [87, 88]. Phytostabilization and phytoextraction are the main two types of phytoremediation methods to treat metal-contaminated soils [89]. The key of these methods is the selection of appropriate plant species that are tolerant to trace elements. Although this method is being field-tested at a variety of sites in the USA and Europe, full-scale application of these techniques is limited and few performance data are available. Phytoremediation methods will likely be limited to use in shallow soils with low levels of metal contamination. Although phytoremediation is currently receiving more advantages over other physico-chemical

methods, there are still some issues associated with this technique. For example, this method may not be applicable in areas of elevated contamination, as plants could be affected by metal toxicity. In addition, to date this technique has only been tested in laboratories, and more research is required in the field.

Overall, metal contamination in soils varies considerably depending on site-specific factors, especially those that affect the mobility of metals. Thus, the selection of suitable techniques depends on the soil type, extent and nature of the metal contamination, cost and availability of materials, and relevant regulations.

Conclusions

This paper reviews the total concentration of trace elements (As, Cd, Cu, Cr, Hg, Mn, Ni, Pb, and Zn) in soils near coal mines in various countries. The average concentration of these elements varies widely, but most of these values are higher than their respective values in world background soils. The I_{geo} and CF values indicate that the contamination levels of Ni and Pb are higher than other elements. The highest I_{geo} values for Ni are observed in Ptolemain-Amynteaon, Greece, while the highest values for Pb were recorded at Barapukuria, Bangladesh. The highest I_{geo} values of As, Hg, Cd, and Cr were found at the Tula mines in Russia, Oltu in Turkey, Barapukuria in Bangladesh, and Pindingshan in China, respectively. This is consistent with the CF index. This clearly shows that individual metal pollution in soils around the coal mines is site-specific. The ecological risk index (E_i) indicates an obvious risk from Cd, especially in the Tabagi River watershed (Brazil) and Ledo coal mines (India), and Hg, especially in the Oltu coal-mining area (Turkey), and therefore are chosen as the key elements to predict pollution trends. The integrated indices, such as C_{deg}, mC_d, IPL, *and* $NIPI$, reveal that the soils from Barapukuria (Bangladesh), Ptolemais-Amynteon (Greece), and the Tibagi River (Brazil) have a higher degree of contamination than other sites.

To control metal contamination in soil, monitoring and legislative measures must be taken as immediate steps. For the long term, scientific research and remedial technology should be implemented. Chemical immobilization, soil leaching, and phytoremediation are frequently used for remediation purposes; among them phytoremediation is the best available technology for remediation of soils. However, these technologies have mainly been demonstrated at an experimental level and more work should be focused at field level.

Compliance with Ethical Standards

Human and Animal Rights and Informed Consent No Human or Animal Studies Performed by the Authors:

This article does not contain any studies including human or animal subjects.

Human Studies Done by Authors (but no Animal Studies) This article does not contain any studies with animal subjects performed by any of the authors. With regard to the authors' research cited in this paper, all procedures were followed in accordance with the ethical standards of the responsible committee on human experimentation and with the Helsinki Declaration of 1975, as revised in 2000 and 2008.

Animal Studies Done by Authors (but no Human Studies) This article does not contain any studies with human subjects performed by any of the authors.

With regard to the authors' research cited in this paper, all institutional and national guidelines for the care and use of laboratory animals were followed.

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