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Health Risk Assessment of Children Exposed to the Soil Containing Potentially Toxic Elements: A Case Study from Coal Mining Areas

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Abstract: Coal mine activities lead to the release of potentially toxic elements (PTEs) to the surrounding areas. The present study concerns the health risk caused due to the exposure of PTEs (Hg, As, Cd, Cr, and Pb) in the children residing in the areas around coal mines. The PTEs content and bioaccumulation coefficient (BAC) in the plant, viz., *Albizia lebbeck* and *Madhuca longifolia* growing on the nearby soils of the coal mine affected areas were also estimated. The results demonstrated that the hazard quotient (HQ) for Cr (0.211) in the roadside soil (RSS) was higher than other PTEs. The hazard index (HI) was also at the maximum in the RSS (0.553) followed by the core zone soil (0.541). In RSS, Cr contributed the maximum for the HI value (38%) which elucidated that Cr might cause health problem in the long term. The Cr concentration (5.49 mg kg^{-1}) was also higher than other PTEs in the plant leaves of *M. longifolia* and was two-fold higher than *A. lebbeck*. Except Cd, the accumulation of other PTEs in the leaves of both the species were low, which could be due to their low availability in soils. The BAC for Cr in *M longifolia* was comparatively higher than *A. lebbeck* and was found at the maximum for Cd (0.29) in *M longifolia*. The outcomes of the study elucidated that although there is no severe health risk in children, the data indicated that the prolonged exposure to PTEs might lead to serious health issues.

Keywords: toxic elements; coal mines; health risk; hazard index; bioaccumulation coefficient

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1. Introduction

The surface coal mining activity causes drastic and immediate degradation of soil [1]. It is axiomatic that soil quality gets deteriorated due to loss of vegetation cover, excavation, transportation, stockpiling of coal and waste rocks. The continuous deterioration of soil quality in the vicinity of the coal mines areas is of great concern for the environment. The coal mining activities release certain major potentially toxic metal(loid)s (PTEs) such as arsenic (As), cadmium (Cd), chromium (Cr), mercury (Hg), and lead (Pb) which are considered as the major soil polluters for the nearby areas [2,3]. Cortes-Ramirez et al. [4] has reported in his review which includes 28 epidemiological case studies which suggest there is a close relation between coal mining and a broad spectrum of diseases in population living in proximity of coal mining. Such severe health threat incidences might be caused by heavy metals released to the environment from coal mining and coal utilization, residential waste, industrial activities, and agricultural wastes due to expansion of settlement near coal industries [5,6].

These PTEs form an important polluting group, which tends to accumulate in the ecological food chain and affects human health [7,8]. Entry of these PTEs, such as Cd in humans, can cause kidney dysfunction, lung cancer, and hypertension, whereas As could lead to skin cancer, dermal lesions, and peripheral vascular diseases. Exposure to Pb leads to nephropathy, plumbism, and gastrointestinal colic problems whereas Hg causes damage to nervous system, kidney, liver misfunctioning and reduced immune response [9]. Chromium itself could lead lung and nasal cancer, dermatitis, and ulcers. Therefore, human health risks related to soil pollution in coal industries need attention to improve the living condition of nearby residents.

The complexity of ecosystem risk drives the development of various modeling approaches. Previously, potential ecological risk [10], species sensitivity distribution [11], soil to plants transfer of heavy metals [12], and human health risk from exposure to contaminated soil [13,14] are widely applied to simulate risks from metals in soils. Here we have focused on the health risk and soil to plant transfer of PTEs which are relatively less reported for coal mine-influenced land use areas, as compared to severely mining and technogenically impacted studies.

In a study by Chen et al. [15], the health risk assessment of soil PTEs was found below the safe limits, however, prolonged exposure may harm the health of the children population. In a similar study, the human health risk assessment also showed non-carcinogenic values lower than threshold values, and a significant ingestion of PTEs can occur in children [16]. Li et al. [17] also worked on the human exposure to bioaccessible PTEs in soil and reported Cd and Pb showed the highest non-cancer risk, which would result in unacceptable cancer risk for children. Timofeev et al. [18] observed that As, Pb, Co, and Cr caused the most significant impact on human health in all land-use areas in the urban soils of Mongolia. The PTEs contributed more than 97% to the value of health index (HI) which was the medium for children. According to Yang et al. [19], the presence of PTEs like As, Cd, and Pb in industrial and residential soils led to the severe health risk and found children were more affected by PTE pollution than adults. In the northern Telangana region of India, a study on the health risk assessment of PTEs in surface soils showed that the HI values of the studied PTEs were below the recommended limit (HI < 1), indicating no non-carcinogenic risks in children [20].

In the coal mine areas, the plant species are also being recognized as the indicators of PTEs pollution. The plant leaves were used as accumulative bio-monitors of PTEs in the affected areas [1]. Thus, accessing the metal content in plant parts from mining influenced lands could help to biomonitor the level of contamination, its transfer in higher trophic level and can act as bioindicator for the need and urgency of health risk assessment [21].

The present study aimed to assess the health risks posed by PTEs in the children population residing in the proximity of coal mines. To achieve the goal of this research, our previous data of PTEs concentration in the land-use soil of coal mine areas were mined for the calculation of health risk. Along with the health risk estimation, the PTEs concentrations in the two dominant plant species found in the nearby areas of coal mines were also determined. The bio-accumulation coefficient (BAC) of PTEs in the plant leaf was calculated to check the mobility of PTEs from soil to the aerial parts of the plant.

2. Study Area

The present study was focused on the application of the previously published data on the PTE contents of coal mines. [21]. For this, the analyzed data of PTEs concentration in the land-use soils of coal mining areas of Jharia coalfield (JCF, 23°39′– 23°48′ N and longitudes 86°11′–86°27′ E) (roadside, forest, core zone, and agricultural area) were used to calculate the health risk. The JCF has a coal reserve of 19,000 MT of high-grade coking coal, which covers approximately 210 km^2 of area, and produces 37 Mt (2016-17) annually. JCF is prominent for its production of bituminous coal. Bastacolla open cast project (OCP) produces 0.24 MT of coal per year by shovel-dumper combination and covers an area of 240 ha (barren land 49%, agriculture 7%). The coalfield has a long mining history, dense settlement, and underground coal mine fires.

The coal, soil, and tree leaf samples were collected from Bastacolla OCP. The composite sampling method was adopted for collecting environmental samples. The soil and leaf samples were collected from ten trees for each species. The coal and soil samples were air dried for three days, oven dried at 45 °C and sieved through 0.15 mm sieve. The plant samples were cleaned in running tab water, dried at 45 °C, ground and passed through 1 mm sieve. A 0.1 g of sample was acid digested on hot plate using mixture of HNO_3 and $HClO_4$ (5:2; v/v) and concentrations were determined using flame atomic absorption spectrophotometer (FAAS) and cold vapor atomic absorption spectrophotometer (CV-AAS) [21].

Samples of roadside soil (RSS) were collected from both edges of the road. The sampling covered the distance of 500 m from the edge of coal mine road. Reclaimed Mine area (RMS) soil samples were composed of matured trees with ground vegetations. The area was located 1 km away from the active mine site. The core zone area (CZS), where the active mining activities were taken place, was considered as the core zone area, and was found completely barren without any vegetation cover. The agricultural area (AS) was considered as the reference site because of the minimal or no influence of coal mining activities. It was located 2 km away from the active coal mines and was used for cultivating paddy and wheat crops.

3. Mathematical Methodology

3.1. Health Risk Models

A human health risk model was applied in the land-use soils for the risk assessment of PTEs through three exposure routes (ingestion, inhalation, and dermal contact) in the children population. The potential health risk was assessed by calculating the hazard quotient (HQ), which is the ratio of the analyzed dose of PTEs through each exposure route and the corresponding reference exposure dose (RfD) [22]. The assessment of human health risk includes the following basic steps:

(a) Hazard identification: identification of the available toxic element in the soils are the aim of the hazard identification step. In the present work, the five potentially toxic metal(loid)s (As, Cd, Cr, Hg, and Pb) were identified as the cause of possible hazards in the study area.
(b) Exposure assessment: the exposure time of the identified hazard to the human are assessed in this process. It was calculated by calculating the average daily intake (ADI) of the soil particles containing PTEs.
(c) Toxicity assessment: the toxicity level of the PTEs in the contaminated soils were assessed in this step and reference dose were used to calculate the toxicity level.
(d) Risk characterization: the cancerous and non-cancerous risk of PTEs in human were analyzed through risk characterization steps of the human health risk assessment.

The given formulas were used to calculate the ADI (mg kg-day^{-1}) through three different routes (ing = ingestion; derm = dermal and inh = inhalation):

$$\mathrm{ADI_{ing}} = \mathrm{C} \times \frac{\mathrm{Ing\ R} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT}} \times 10^{-6} \quad (1)$$

$$\mathrm{ADI_{derm}} = \mathrm{C} \times \frac{\mathrm{SA} \times \mathrm{SL} \times \mathrm{ABS} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT}} \times 10^{-6} \quad (2)$$

$$\mathrm{ADI_{inh}} = \mathrm{C} \times \frac{\mathrm{Inh\ R} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{PEF} \times \mathrm{BW} \times \mathrm{AT}} \quad (3)$$

where C is the PTE concentration in soil (mg/kg). The recommended values are: ingestion rate (Ing R)-200 mg day^{-1} [23]; inhalation rate (Inh R)-10 m day^{-3} [23]; exposure frequency (EF)-350 day year^{-1} [24]; exposure duration (ED)-6 year [23]; exposed skin area (SA)-2800 cm^2 [23]; skin adherence factor (SL)-0.2 mg cm^{-1} day^{-2} [23]; dermal absorption factor (ABS) (unitless)-0.001 for all elements except arsenic (0.03) [24]; particle emission factor (PEF)-1.36 × 10^9 m kg^{-3} [23]; average body weight (BW) for children-15 kg [24]; and averaging time (AT) for non-carcinogens = ED × 365 day [24]. The non-carcinogenic risk was calculated as hazard quotient (HQ), which is a unitless quantity. It can be defined as the probability of human population suffering an adverse health effect. It is the ratio of the ADI of PTEs through each exposure routes to the RfD [25] (Supplementary Table S1). The total hazard quotient (THQ) is the addition of individual HQs and represents the magnitude of health risk. If the value of THQ > 1, there is non-carcinogenic risk. The degree of health risk increases with the increase in the value of THQ [26].

$$HQ_{soil} = \frac{ADI}{RfD} \quad (4)$$

HQ or HI < 1; adverse health effects are unlikely even for sensitive population; HQ or HI > 1; potential for chronic effect

3.2. Bioaccumulation Coefficient (BAC) of PTEs in Plant Leaf

Bioaccumulation coefficient (BAC) is the ratio of PTEs concentration in the plant to the PTEs in soil and was calculated by using the formula [27]:

$$\text{BAC (Leaf) Total} = \frac{\text{Total PTEs concentration in tree leaves}}{\text{Total PTEs concentration in soils}} \quad (5)$$

The quality assurance and quality control were tested in batches to minimize the sample contamination. The reagent blank and certified reference material (CRM; MESS-4; National Research Council, Canada) were also processed along with the samples and selected samples were rechecked to find its accuracy by comparing the obtained results with CRM. For calibration, standard reference materials (AccuTrace, Accu Standard Inc., New Haven, CT, USA) were used, and accuracy of the method was assured by replicate analysis of the elements. The calibration coefficients were maintained at ≥0.999.

4. Results and Discussion

The average Hg concentration in the top-soil of roadside area of the Jharia coalfield was >2 mg kg^{-1}. The total Hg content in roadside soil (RSS) was five-fold higher than the agricultural soil (AS). Similarly, As content in RSS was three times higher than the AS, which could be due to the deposition of contaminated coal dust. The assessment study has also reported that the Cd (1.94 mg kg^{-1}) and Cr (48.55 mg kg^{-1}) contents in the topsoil (0–10 cm) of the roadside area were higher than that of AS (reference soil) [21]. The Pb content in the soil of the core zone of mining areas was two-fold higher than AS. The higher concentrations of Hg and other PTEs in soils of mining areas were possibly due to the coal-dust deposition from coal mines and transport activities [1,8].

4.1. Assessment of Children Health Risk of Potentially Toxic Metal(loid)s

The results of non-carcinogenic human health risk assessment of PTEs in all land-use soils (roadside, forest, core zone, and agricultural soils) of the coal mining areas through three exposure routes (ingestion, inhalation, and dermal contact) for children are shown in Tables 1–5. The health risk mathematical equations were applied on the dataset of PTEs concentration in the soil samples of the land-use area of coal mines by the standard methods given by USEPA. The results showed that the ingestion of soil particles was the major exposure route for PTEs to the children. Similar results were also observed by [16,28,29]. Therefore, the inhalation of contaminated soil particles through the mouth and nose was less than the other exposure routes [16]. The result also showed that the total HQ values for non-carcinogenic health risks among children for all studied PTEs were less than one, which elucidated that no health risk was posed to the children. However, it was also suggested that the prolonged exposure of the contaminated soil dust can cause risks among the children particularly residing near the roadside and core zone mine areas, because the values of HQs for all five PTEs in the roadside (0.55) and core zone mine area (0.54) were comparatively higher than the other two land-use areas (reclaimed and agricultural area).

Table 1. Average daily dose (ADD) and hazard quotient (HQ) of Cr in three soil profiles (0–10, 10–20 and 20–30 cm) of different land-use areas of coal mine, Jharia coalfield.

Health Risk	Depth (cm)	ADD_{ing}	ADD_{derm}	ADD_{inh}	Total ADD	HQ_{ing}	HQ_{derm}	HQ_{inh}	Total HQ
Roadside soil (RSS)	0–10	6.21×10^{-4}	1.74×10^{-6}	2.28×10^{-8}	6.23×10^{-4}	0.21	-	7.61×10^{-4}	2.11×10^{-1}
	10–20	5.82×10^{-4}	1.63×10^{-6}	2.14×10^{-8}	5.84×10^{-4}	0.19	-	7.13×10^{-4}	1.91×10^{-1}
	20–30	5.24×10^{-4}	1.47×10^{-6}	1.93×10^{-8}	5.25×10^{-4}	0.17	-	6.42×10^{-4}	1.71×10^{-1}
Core zone soil (CZS)	0–10	7.08×10^{-4}	1.98×10^{-6}	2.60×10^{-8}	7.10×10^{-4}	0.24	-	8.67×10^{-4}	2.41×10^{-1}
	10–20	6.33×10^{-4}	1.77×10^{-6}	2.33×10^{-8}	6.35×10^{-4}	0.21	-	7.76×10^{-4}	2.11×10^{-1}
	20–30	5.71×10^{-4}	1.60×10^{-6}	2.10×10^{-8}	5.73×10^{-4}	0.19	-	7.00×10^{-4}	1.91×10^{-1}
Reclaimed mine soil (RMS)	0–10	5.32×10^{-4}	1.49×10^{-6}	1.95×10^{-8}	5.34×10^{-4}	0.18	-	6.51×10^{-4}	1.81×10^{-1}
	10–20	4.81×10^{-4}	1.35×10^{-6}	1.77×10^{-8}	4.82×10^{-4}	0.16	-	5.89×10^{-4}	1.61×10^{-1}
	20–30	4.46×10^{-4}	1.25×10^{-6}	1.64×10^{-8}	4.47×10^{-4}	0.149	-	5.46×10^{-4}	1.50×10^{-1}
Agricultural soil (AS)	0–10	2.80×10^{-4}	7.84×10^{-7}	1.03×10^{-8}	2.81×10^{-4}	0.09	-	3.43×10^{-4}	9.03×10^{-2}
	10–20	2.34×10^{-4}	6.55×10^{-7}	8.61×10^{-9}	2.35×10^{-4}	0.08	-	2.87×10^{-4}	8.03×10^{-2}
	20–30	2.10×10^{-4}	5.87×10^{-7}	7.71×10^{-9}	2.11×10^{-4}	0.07	-	2.57×10^{-4}	7.03×10^{-2}

-: not calculated; Cr reference exposure dose (RfD_{dermal}) not recommended by any sources. So, HQ_{derm} not calculated; ing: ingestion; derm: dermal; inh: inhalation.

Table 2. Average daily dose (ADD) and hazard quotient (HQ) of As in three soil profiles (0–10, 10–20 and 20–30 cm) of different land-use areas of coal mine, Jharia coalfield.

Health Risk	Depth (cm)	ADD_{ing}	ADD_{derm}	ADD_{inh}	Total ADD	HQ_{ing}	HQ_{derm}	HQ_{inh}	Total HQ
Roadside soil (RSS)	0–10	4.18×10^{-5}	3.51×10^{-6}	1.54×10^{-9}	4.53×10^{-5}	0.14	0.012	5.12×10^{-6}	1.52×10^{-1}
	10 20	3.81×10^{-5}	3.20×10^{-6}	1.40×10^{-9}	4.13×10^{-5}	0.13	0.011	4.67×10^{-6}	1.41×10^{-1}
	20–30	3.18×10^{-5}	2.67×10^{-6}	1.17×10^{-9}	3.45×10^{-5}	0.11	0.009	3.90×10^{-6}	1.19×10^{-1}
Core zone soil (CZS)	0–10	3.50×10^{-5}	2.94×10^{-6}	1.29×10^{-9}	3.79×10^{-5}	0.12	0.010	4.29×10^{-6}	1.30×10^{-1}
	10–20	3.36×10^{-5}	2.82×10^{-6}	1.24×10^{-9}	3.64×10^{-5}	0.11	0.009	4.12×10^{-6}	1.19×10^{-1}
	20–30	3.23×10^{-5}	2.72×10^{-6}	1.19×10^{-9}	3.50×10^{-5}	0.11	0.009	3.96×10^{-6}	1.19×10^{-1}
Reclaimed mine soil (RMS)	0–10	2.71×10^{-5}	2.28×10^{-6}	9.97×10^{-9}	2.94×10^{-5}	0.09	0.008	3.32×10^{-6}	9.80×10^{-2}
	10–20	4.08×10^{-5}	3.43×10^{-6}	1.50×10^{-9}	4.42×10^{-5}	0.14	0.011	5.00×10^{-6}	1.51×10^{-1}
	20–30	4.51×10^{-5}	3.79×10^{-6}	1.66×10^{-9}	4.89×10^{-5}	0.15	0.013	5.53×10^{-6}	1.63×10^{-1}
Agricultural soil (AS)	0–10	1.38×10^{-5}	1.16×10^{-6}	5.08×10^{-10}	1.50×10^{-5}	0.05	0.004	1.69×10^{-6}	5.40×10^{-2}
	10–20	9.33×10^{-6}	7.84×10^{-7}	3.43×10^{-10}	1.01×10^{-5}	0.03	0.003	1.14×10^{-6}	3.30×10^{-2}
	20–30	4.99×10^{-6}	4.19×10^{-7}	1.83×10^{-10}	5.41×10^{-6}	0.02	0.001	6.11×10^{-7}	2.10×10^{-2}

ing: ingestion; derm: dermal; inh: inhalation.

Table 3. Average daily dose (ADD) and hazard quotient (HQ) of Hg in three soil profiles (0–10, 10–20 and 20–30 cm) of different land-use areas of coal mine, Jharia coalfield.

Sites	Depth (cm)	ADD_{ing}	ADD_{derm}	ADD_{inh}	Total ADD	HQ_{ing}	HQ_{derm}	HQ_{inh}	Total HQ
Roadside soil (RSS)	0–10	2.97×10^{-5}	8.31×10^{-8}	1.09×10^{-9}	2.98×10^{-5}	0.10	2.77×10^{-4}	1.27×10^{-5}	1.00×10^{-1}
	10 20	2.17×10^{-5}	6.09×10^{-8}	7.99×10^{-10}	2.18×10^{-5}	0.07	2.03×10^{-4}	9.29×10^{-6}	7.02×10^{-2}
	20–30	1.18×10^{-5}	3.29×10^{-8}	4.32×10^{-10}	1.18×10^{-5}	0.04	1.10×10^{-4}	5.03×10^{-6}	4.01×10^{-2}
Core zone soil (CZS)	0–10	1.52×10^{-5}	4.26×10^{-8}	5.59×10^{-10}	1.52×10^{-5}	0.05	1.42×10^{-4}	6.50×10^{-6}	5.01×10^{-2}
	10–20	1.28×10^{-5}	3.58×10^{-8}	4.70×10^{-10}	1.28×10^{-5}	0.04	1.19×10^{-4}	5.47×10^{-6}	4.01×10^{-2}
	20–30	9.21×10^{-6}	2.58×10^{-8}	3.38×10^{-10}	9.24×10^{-6}	0.03	8.59×10^{-5}	3.94×10^{-6}	3.01×10^{-2}
Reclaimed mine soil (RMS)	0–10	9.08×10^{-6}	2.54×10^{-8}	3.34×10^{-10}	9.11×10^{-6}	0.030	8.47×10^{-5}	3.88×10^{-6}	3.01×10^{-2}
	10–20	9.59×10^{-6}	2.68×10^{-8}	3.53×10^{-10}	9.62×10^{-6}	0.032	8.95×10^{-5}	4.10×10^{-6}	3.21×10^{-2}
	20–30	7.03×10^{-6}	1.97×10^{-8}	2.59×10^{-10}	7.05×10^{-6}	0.023	6.56×10^{-5}	3.01×10^{-6}	2.31×10^{-2}
Agricultural soil (AS)	0–10	5.50×10^{-6}	1.54×10^{-8}	2.02×10^{-10}	5.52×10^{-6}	0.018	5.13×10^{-5}	2.35×10^{-6}	1.81×10^{-2}
	10–20	5.63×10^{-6}	1.58×10^{-8}	2.07×10^{-10}	5.65×10^{-6}	0.019	5.25×10^{-5}	2.40×10^{-6}	1.91×10^{-2}
	20–30	6.01×10^{-6}	1.68×10^{-8}	2.21×10^{-10}	6.03×10^{-6}	0.020	5.61×10^{-5}	2.57×10^{-6}	2.01×10^{-2}

ing: ingestion; derm: dermal; inh: inhalation.

The THQ value in the agricultural soil was found to be the least (0.22), which could be due to the agricultural practices like cropping and watering. Similarly, the THQ was less in the reclaimed mine area (0.42), which could be due to the presence of large numbers of plants and trees. It has also been found that the contribution of Cr was high (38%) among all five PTEs in the RSS, which demonstrated that the Cr could cause the most severe health risk among the children on the prolonged exposure of soil dust in the roadside area (Table 1). In a similar study on coal mines of the Witbank area of Mpumalanga province, South Africa, it was observed that exposure to non-carcinogenic Cr (THQ) to the children population was 8.51 times higher than for adult population [6]. In the previous study, the severity of PTEs' non-carcinogenic risk (THQ) for children and adult has been arranged as Cr, As, Pb, Cd (highest to lowest) [6]. The As was the second highest contributor after Cr, which can cause health risks among the children in the roadside area (Table 2).

Table 4. Average daily dose (ADD) and hazard quotient (HQ) of Cd in three soil profiles (0–10, 10–20 and 20–30 cm) of different land-use areas of coal mine, Jharia coalfield.

Sites	Depth (cm)	ADD_{ing}	ADD_{derm}	ADD_{inh}	Total ADD	HQ_{ing}	HQ_{derm}	HQ_{inh}	Total HQ
Roadside soil (RSS)	0–10	2.48×10^{-5}	1.74×10^{-6}	9.12×10^{-10}	2.65×10^{-5}	0.05	1.39×10^{-4}	1.60×10^{-5}	5.02×10^{-2}
	10 20	1.61×10^{-5}	1.63×10^{-6}	5.92×10^{-10}	1.77×10^{-5}	0.03	9.02×10^{-5}	1.04×10^{-5}	3.01×10^{-2}
	20–30	1.50×10^{-5}	1.47×10^{-6}	5.50×10^{-10}	1.65×10^{-5}	0.03	8.38×10^{-5}	9.65×10^{-6}	3.01×10^{-2}
Core zone soil (CZS)	0–10	3.18×10^{-5}	1.98×10^{-6}	1.17×10^{-9}	3.38×10^{-5}	0.06	1.78×10^{-4}	2.05×10^{-5}	6.02×10^{-2}
	10–20	3.03×10^{-5}	1.77×10^{-6}	1.11×10^{-9}	3.21×10^{-5}	0.06	1.70×10^{-4}	1.95×10^{-5}	6.02×10^{-2}
	20–30	2.44×10^{-5}	1.60×10^{-6}	8.98×10^{-10}	2.60×10^{-5}	0.05	1.37×10^{-4}	1.58×10^{-5}	5.02×10^{-2}
Reclaimed mine soil (RMS)	0–10	3.34×10^{-5}	1.49×10^{-6}	1.23×10^{-9}	3.49×10^{-5}	0.07	1.87×10^{-4}	2.15×10^{-5}	7.02×10^{-2}
	10–20	3.77×10^{-5}	1.35×10^{-6}	1.39×10^{-9}	3.91×10^{-5}	0.08	2.11×10^{-4}	2.43×10^{-5}	8.02×10^{-2}
	20–30	4.86×10^{-5}	1.25×10^{-6}	1.79×10^{-9}	4.99×10^{-5}	0.10	2.72×10^{-4}	3.13×10^{-5}	1.00×10^{-1}
Agricultural soil (AS)	0–10	1.27×10^{-5}	7.84×10^{-7}	4.65×10^{-10}	1.35×10^{-5}	0.03	7.09×10^{-5}	8.16×10^{-6}	3.01×10^{-2}
	10–20	1.14×10^{-5}	6.55×10^{-7}	4.18×10^{-10}	1.21×10^{-5}	0.02	6.37×10^{-5}	7.34×10^{-6}	2.01×10^{-2}
	20–30	8.69×10^{-6}	5.87×10^{-7}	3.20×10^{-10}	9.28×10^{-6}	0.02	4.87×10^{-5}	5.61×10^{-6}	2.01×10^{-2}

ing: ingestion; derm: dermal; inh: inhalation.

Table 5. Average daily dose (ADD) and hazard quotient (HQ) of Pb in three soil profiles (0–10, 10–20 and 20–30 cm) of different land-use areas of coal mine, Jharia coalfield.

Health Risk	Depth (cm)	ADD_{ing}	ADD_{derm}	ADD_{inh}	Total ADD	HQ_{ing}	HQ_{derm}	HQ_{inh}	Total HQ
Roadside soil (RSS)	0–10	1.44×10^{-4}	4.05×10^{-7}	5.31×10^{-9}	1.44×10^{-4}	0.04	-	-	0.04
	10 20	1.40×10^{-4}	3.93×10^{-7}	5.16×10^{-9}	1.40×10^{-4}	0.04	-	-	0.04
	20–30	1.28×10^{-4}	3.58×10^{-7}	4.71×10^{-9}	1.28×10^{-4}	0.04	-	-	0.04
Core zone soil (CZS)	0–10	2.01×10^{-4}	5.62×10^{-7}	7.38×10^{-9}	2.02×10^{-4}	0.06	-	-	0.06
	10–20	1.83×10^{-4}	5.13×10^{-7}	6.74×10^{-9}	1.84×10^{-4}	0.05	-	-	0.05
	20–30	1.79×10^{-4}	5.01×10^{-7}	6.58×10^{-9}	1.80×10^{-4}	0.05	-	-	0.05
Reclaimed mine soil (RMS)	0–10	1.58×10^{-4}	4.41×10^{-7}	5.80×10^{-9}	1.58×10^{-4}	0.04	-	-	0.04
	10–20	1.75×10^{-4}	4.89×10^{-7}	6.42×10^{-9}	1.75×10^{-4}	0.05	-	-	0.05
	20–30	1.89×10^{-4}	5.28×10^{-7}	6.94×10^{-9}	1.90×10^{-4}	0.05	-	-	0.05
Agricultural soil (AS)	0–10	1.25×10^{-4}	3.49×10^{-7}	4.59×10^{-9}	1.25×10^{-4}	0.03	-	-	0.03
	10–20	1.12×10^{-4}	3.14×10^{-7}	4.12×10^{-9}	1.12×10^{-4}	0.03	-	-	0.03
	20–30	1.20×10^{-4}	3.35×10^{-7}	4.40×10^{-9}	1.20×10^{-4}	0.03	-	-	0.03

-: not calculated; reference exposure dose (RfD_{dermal} and RfD_{inh}) values of Pb are not recommended by USEPA or other sources. So, HQ_{derm} and HQ_{inh} are not calculated; ing: ingestion; derm: dermal; inh: inhalation.

The THQ (As) in the roadside area was higher than the other areas, and it was at the maximum (1.52×10^{-1}) in the case of topsoil. The possible reason for higher THQ levels could be due to the higher exposure of soil dust containing the PTE As [30].

In the top-soil (0–10 cm) of the agricultural area, Hg was the highest contributor, which can cause severe health risks after prolonged exposure (Table 3). The Hg also displayed higher HQ value for ingestion pathway in roadside soils (0.1) than the other land-use soils, but the inhalation of Hg can also pose a greater risk [29]. The possible reason for the higher HQ of Hg in roadside soils could be the nearest location of the soil from the coal mine areas. The observed data regarding health risks showed that the prolonged consumption of vegetables and fruits grown on the most contaminated areas (roadside area) can cause severe health impacts on the children residing in the affected areas [31].

In case of Cd, the THQ value was also higher in RSS than the soils of the core zone and reclaimed mine area, which elucidated that the direct exposure of Cd in the long term might cause severe health risks to the exposed population (Table 4). In a similar type of health risk study on the soils contaminated with solid wastes, it was found that the exposed population was more vulnerable to the health risks associated with Cd [32].

Moreover, it was found that the THQ (Pb) in the core zone soil was the maximum (0.06) (Table 5), which could be due to the presence and exposure of Pb among the mine workers. It may be hazardous if there is continuous and prolonged exposure of Pb to the mine workers [33].

In a similar case study in the soils of Huainan in China, the HI of the PTEs was greater than one (HI > 1.5), which suggested that children's health was at a higher risk [34]. Different studies around the world also reported that the chances of high availability of PTEs could increase HI values and lead to health issues in long term (Table 6). In a global meta-analysis study of the health risk assessment of PTEs and their distribution in the soils of the neighboring areas of coal industries, the data of PTEs (As, Cd, Cr, Hg, and Pb) concentration in soil from the published literature (2008–2018) were collected. The results of the global meta-analysis study revealed that the concentration of most of the PTEs was higher in the regions of South Europe, Southeast Asia, and North Africa than the other regions. It has also been reported that the non-carcinogenic risks were caused due to the exposure of soil containing PTEs through the oral ingestion mainly, which was followed by dermal and inhalation pathways. In the global meta-analysis, it was observed that the children were highly vulnerable to the non-carcinogenic risk, while adult population suffer both carcinogenic and non-carcinogenic risks [14].

In a similar kind of study on human health risk assessment of PTEs in coal mine soils, it was found that the non-carcinogenic risk posed by the extractable fractions of PTEs to adults and children fall below the threshold level of 1, while the carcinogenic risk posed by the extractable fraction of Cr was higher than the acceptable level (1×10^{-6}) [35]. Another similar study has been conducted on the soils of coal mining areas of Bangladesh which concluded that the non-carcinogenic risk of PTEs for children was higher than that for the adults. The results demonstrated that the children population are more sensitive to PTEs when exposed to the soil [36].

Table 6. Global potentially toxic metal(loid)s concentration (mg kg^{-1}) in soil and associated health risk values in children.

Region, Country	As	Cd	Cr	Hg	Pb	Hazard Index (HI)	References
Henan Province, China	11.53	0.44	38.87	0.06	17.15	HI < 1 (0.74)	[15]
Yukang City, China	9.037	-	-	0.01	16.28	HI = 0.91 (C); HI = 1.17 (A)	[37]
South Africa	19.44	0.44	653	-	30.75	HI > 1(4.69)	[6]
Huainan, China	16.02	0.84	39.23	0.01	27.27	HI > 1 (1.5)	[35]
Kermanshah province, Iran	-	-	79.21	-	-	HI < 1 (2.18×10^{-7})	[16]
Zhejiang province, China	15.51	0.72	47.73	0.75	68.64	HI < 1	[32]
Ghana	-	0.8	107.01	0.03	71.75	HI < 1 (5.2×10^{-4})	[38]
Darkhan, Mongolia	8.07	0.34	46.6	-	55.3	HI > 1 (1.32)	[18]
Dhanbad, India	3.27	1.94	48.55	2.32	11.30	HI < 1 (0.54)	Present study

C: children; A: adult; values in bracket are HI value reported by authors.

4.2. Potentially Toxic Elements in Plants Growing in the Vicinity of Coalfield

The PTEs concentration in the plant leaves of *A. lebbeck* and *M. longifolia* are presented in Figure 1a. The results showed that the Cr concentration in *M. longifolia* was 5.49 mg kg^{-1} which was 1.84 times higher than the other studied plant species *A. lebbeck*. The concentration of Hg in the leaves of *A. lebbeck* and *M. longifolia* were 0.019 and 0.043 mg kg^{-1}, respectively. Yang et al. [39] reported the peak concentrations of Hg in the leafy vegetables as 0.034 mg kg^{-1}. The Hg accumulation in *M. longifolia* was comparatively higher than that of *A. lebbeck* which could be due to the higher uptake capacity of Hg by the respective plant species. The higher accumulation of PTEs in specific plant species also depends upon the solubility and binding of the dust particles deposited on the surface of leaf, as well as the bioavailability pf the PTEs in the soil [1]. Similarly, the Cd concentration in the leaves of *M. longifolia* was also higher than the *A. lebbeck*. In a previous research study by [40], the Cd and Pb content in the horse chestnut leaves was reported as 4.9 and 20.3 mg kg^{-1}, respectively, and the reported concentrations were above the toxic level in plants.

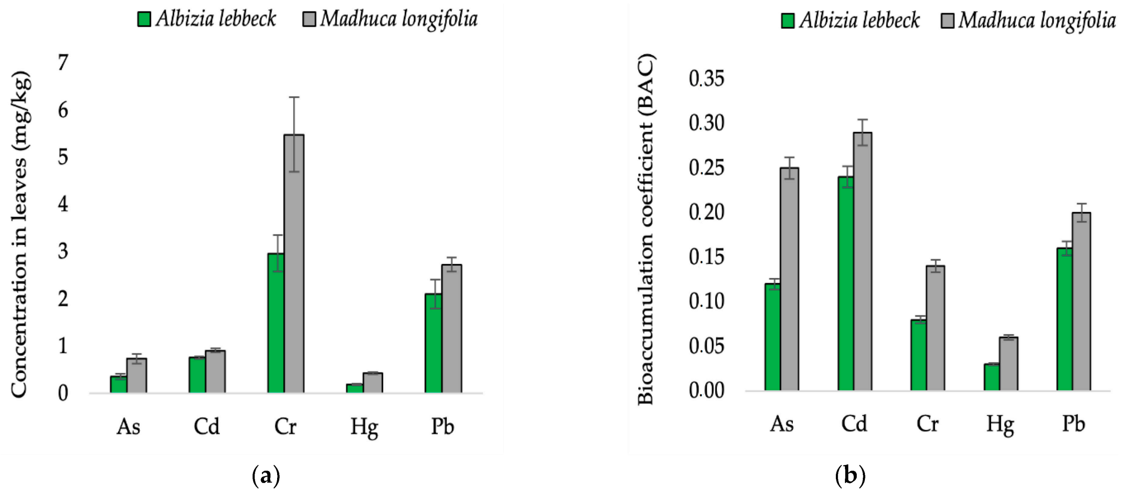

Figure 1. (**a**) Concentration of potentially toxic elements in plant leaf (*n* = 10 per species) grown on the reclaimed soil of Jharia Coalfield, and (**b**) bio-accumulation coefficient (BAC) of potentially toxic elements for plant leaf.

4.3. Bioaccumulation Coefficient (BAC) of Potentially Toxic Elements in Plant

The BAC value for Cr in *M. longifolia* was comparatively higher than *A. lebbeck*, which could be due to the high accumulation capacity of Cr in the concerned plant species (Figure 1b). The Cd accumulation was at the maximum (0.29 mg kg^{-1}) in *M. longifolia*, and the possible reason for the maximum Cd accumulation could be due to the exposure of a high volume of RMS to the roots of the *M longifolia*. In a similar way, the *M. longifolia* also showed the highest accumulation of As, Cr, and Pb. The Pb concentrations in the leaves of *M longifolia* and *A. lebbeck*, were 2.73 and 2.11 mg kg^{-1}, respectively. In a similar work reported by [41], Pb concentration of 0.12 mg kg^{-1} was reported in the leaves of *Azadirachta indica*. The BAC values of all the PTEs were less than 1, indicating that the accumulated PTEs in the plant leaves were less than the soil and its transfer is limited. Nevertheless, the presence of significant concentration of PTEs in leaves showed these plants as bioindicators of metal pollution of this region by coal mining activities.

5. Conclusions

The findings of the study demonstrated that the THQ values of PTEs in all land-use soils (roadside, core zone, reclaimed and agricultural soils) were lower than the critical level (THQ < 1). However, the roadside soils showed the highest THQ values among all land-use soils. Moreover, THQ of Hg was also higher in the roadside soil than the other land-use soil. Among all PTEs, the Cr contribution was the maximum in the RSS. The Cr content in plants was also higher than all other PTEs. The results concluded that the Cr was the most sensitive PTE, which poses higher risk values to children. The bio-accumulation coefficient of Cd was higher than the other PTEs, which signified that the Cd mobility from the soil to plant leaf was at the maximum. The findings of the present study concluded that there were no health risks caused among the children residing in the nearby areas of coal mining, however there is a probability of severe health risks upon the long-term exposure of PTEs via contaminated soil dust.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/met12111795/s1, Table S1: Reference doses (RfD) in (mg kg^{-1} day^{-1}) for the different toxic metals References [24,42,43] are cited in the supplementary materials.

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