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ORIGINAL PAPER

Assessment of heavy metal contamination in street dust: concentrations, bioaccessibility, and human health risks in coal mine and thermal power plant complex

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Abstract Coal mining has also been associated with adverse environmental and health impacts including cancer and respiratory disorders, with the presence of thermal power plants exacerbating the problem of heavy metal pollution. Minimal studies have been conducted on the environmental impacts, health risks, and bioaccessibility of heavy metals in coal mine areas. Consequently, samples of street dust were collected from different locations in the Singrauli mine complex and analysed. Heavy metals (Cu, Ni, Zn, Cr, Co, As, and Mo) were found to be higher than the background concentration, with the maximum concentration was found in areas close to the Thermal Power Plants, like Near Vindyachal TPP, Near Shakti Nagar TPP, and Anpara. The highest geo-accumulation index value was found for Co, Mo, Zn, and As, indicating moderate to strong pollution levels. Health risk assessment (for both adults and children) revealed that Cr and Fe posed significantly higher Hazard Quotient and Hazard Index (HI) values, indicating significant non-carcinogenic threats. Moreover, Carcinogenic Risk (CR) values for Cd, Cr, and Ni indicated a risk of carcinogenicity to the public exposed to road dust. The study also examined the bioaccessibility of the metals, which showed that the gastric phase accumulated a higher percentage of Ni (42.52%), Pb (34.79%), Co (22.22%), As (20%) and Cu (15%) than the intestinal phase. Strong positive correlation was observed between metal concentration (Cu, Pb, Cr, Fe, Zn, and Mn), HI, and CR of adult and child, while bioaccessibility of intestinal phase was positively correlated with gastric phase of metals (Cu, Ni, Co, As, and Mn).

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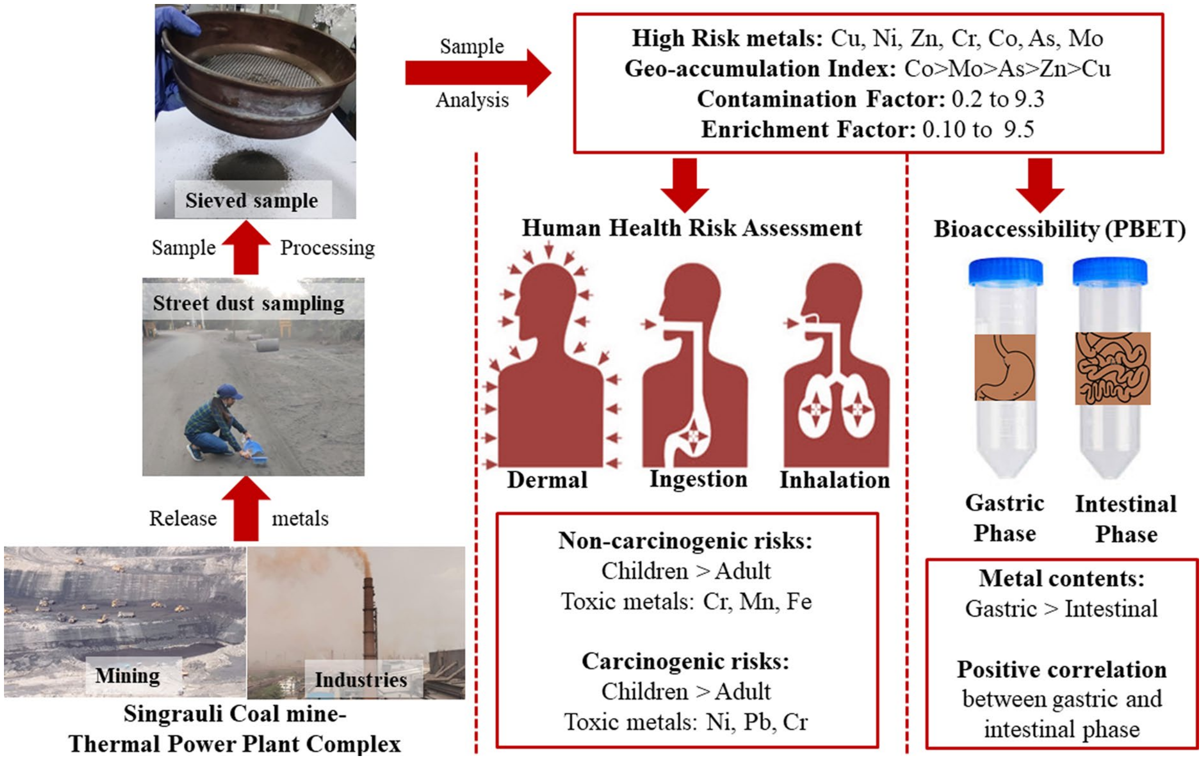
Graphical abstract



Keywords Coal mine area · Heavy metals · Human health risk assessment · Bioaccessibility · Carcinogenic risks · Non-carcinogenic risks

Introduction

Coal has been the primary source of energy for human civilization for centuries, and with the growing population and energy demands, coal mining and thermal power plants (TPP) have increased significantly (Kumar et al., 2023; Kumari et al., 2019; Oberschelp et al., 2019; Ray et al., 2022). According to the International Energy Agency (IEA), coal accounted for around 27% of global energy consumption in 2019, making it the second-largest primary energy source worldwide (IEA, 2021). While these sources of energy have been essential to power our economies and sustain our modern lifestyles, their widespread usage has also had significant environmental impacts (Rathore & Wright, 1993; Tao et al., 2022). Further, coal mining is associated with drilling, blasting, and transportation (from mine to surface), resulting in adverse ecological impacts including dust pollution, deforestation, soil erosion, coal related solid waste, air and water pollution, greenhouse gas emissions, environmental degradation, and health hazards (Bimpong et al., 2022; Ijaz et al., 2020; Romana et al., 2022; Sharma et al., 2021; Song et al., 2023; Yadu et al., 2020).

Coal mining has also been associated with an increase in the incidences of lung cancer, asthma, coal workers pneumoconiosis (CWP), silicosis, asbestosis, and other respiratory diseases including black lung disease, which is caused by inhaling coal dust (Ishtiaq et al., 2018; Kamanzi et al., 2023; Karatela et al., 2022). Further, the burning of coal in TPP releases harmful pollutants into the air and water, leading to respiratory diseases, acid rain, and contamination of water sources (Dontala et al., 2015; Finkelman et al., 2021). The environmental and health impacts are increasingly apparent, particularly in areas where heavy metals are present in significant quantities, where mining and burning of coal could result in the release of heavy metals into the environment (Kumari & Bhattacharya, 2023; Zhai et al., 2009). Moreover, coal mining and TPP generate significant amounts of waste products, including fly ash, bottom ash, sulphur dioxide, hydrogen sulphide, and boiler slag, which contain high concentrations of heavy metals such as arsenic, cadmium, chromium, lead, and mercury, consequently leaching into environment, polluting groundwater, surface water, and soil systems (Gopinathan et al., 2022a; Jang et al., 2015; Kumari & Bhattacharya, 2023; Liu et al., 2017; Saikia et al., 2014; Sawarkar et al., 2023). The problem of heavy metal pollution has been exacerbated by urbanization and intensified industrialization (Antoci et al., 2018; Yadav et al., 2019).

In coal mine complexes, heavy metal exposure could occur via inhalation of airborne pollutants, ingestion of contaminated water and food, and skin contact with contaminated soil (Han et al., 2020; Wuana & Okieimen, 2011). Exposure to heavy metals could occur at various stages of the coal mining and power generation process, including mining, transportation, storage, combustion, and waste disposal (Dhaliwal et al., 2020). Exposure to heavy metals is associated with a range of adverse health effects, including cancer, neurological disorders, developmental abnormalities, and cardiovascular disease (Fu & Xi, 2020; Jaishankar et al., 2014). The toxicity of heavy metals depends on factors, including chemical form, dose, duration of exposure, and route of exposure (Tchounwou et al., 2012). Heavy metals pose carcinogenic and non-carcinogenic risks in humans (Saleh et al., 2019). Several heavy metals found in coal mine areas with TPP are classified as carcinogens such as arsenic, which has been linked to skin, lung, bladder, and liver cancers, when exposed to high levels (Chen et al., 1992). Cadmium has been linked to lung, prostate, and breast cancers, while chromium has been linked to lung cancer (Beveridge et al., 2010; Huff et al., 2007). Exposure to heavy metals could also cause non-cancerous health effects, such as neurological disorders, developmental abnormalities, and cardiovascular disease (Rehman et al., 2018). For example, lead exposure causes developmental delays in children, cognitive impairment, and cardiovascular disease, while mercury exposure causes neurological damage and impairs cognitive function (Kim et al., 2015; Rice et al., 2014).

Bioaccessibility is a crucial factor in determining the health risks associated with exposure (Gu et al., 2016; Hong et al., 2016). It refers to the fraction of a substance that is released from a material and is available for absorption into the body. The extent to which heavy metals are absorbed through ingestion depends on their bioaccessibility in the gastrointestinal system. Since, heavy metals entering the human body may not be fully absorbed, evaluating the total concentration of ingested materials and their bioaccessibility is crucial. Bioaccessibility of heavy metals in coal mine areas could vary depending on several factors, including the chemical form of the metal, the pH of the environment, and the presence of other compounds that could affect metal solubility (Peijnenburg & Jager, 2003; Reeder et al., 2006; Wong, 2003). Two main methods are typically used to assess the availability of metals in humans: in-vitro analysis, which involves chemical testing, and in-vivo techniques, which rely on biological markers and bioaccumulation (Kumari & Bhattacharya, 2023). In-vitro methods are generally preferred over in-vivo methods because they are cost-effective and do not present any ethical issues. In recent years, a variety of in-vitro digestion models have been developed, accepted, and widely used to investigate the bioaccessibility and risks of contaminants in food, soils, dust, and particulate matter (Beriro et al., 2016; Gu & Gao, 2018; Hong et al., 2016; Zhuang et al., 2016). To assess the risk posed to adults and children, the United States Environment Protection Agency (USEPA) has developed a health risk assessment model that evaluates the carcinogenic and non-carcinogenic effects of metal concentrations (Su et al., 2013).

Mining, being a crucial industry of the nation, thrives in India due to its abundant array of mineral resources. Coal, the predominant mineral resource in India, is being extensively extracted and serves as the primary fuel for power generation in the country, contributing to approximately 50–55% of the total power generated. According to a recent study conducted in Hami, China, the primary source of metal pollution was found to be the dust generated from coal combustion and combustion products. Approximately 54% of the metal pollution in the area was attributed to the coal mining region (Jia et al., 2023). Nevertheless, the extraction of coal has detrimental effects on the environment, including soil erosion, acid mine drainage, degradation of agricultural land, and alterations to the natural topography and drainage patterns. The emissions released by these coal-fired power plants are responsible for the prevalence of environmental issues such as dust, haze, and smog in the region. Every year, these power plants emit six million tons of fly ash, which accumulates in thick piles up to 5 feet in certain areas of Singrauli. These fly ash piles contain hazardous heavy metals such as mercury, cadmium, lead, arsenic, and fine particles. Tuberculosis, bronchitis, and asthma are prevalent in this region, attributed to the inhalation of fine dust particles and fly ash fines (Yadav, 2021). The incomplete combustion in these power plants leads to the emission of black carbon soot, threatening human health and the environment (Bhardwaj et al., 2020). In developing countries, TPPs heavily depend on coal combustion sourced from coal mines, making it a significant anthropogenic contributor of trace elements and various metals (Gopinathan et al., 2022c; Rai, 2009). However, PM_{10} and $PM_{2.5}$ levels in the surrounding air found no evidence of carcinogenic or non-carcinogenic risks to adults and children due to metals like Pb, As, Co, Cr, Ni, Hg, and Cd as per the standards set by USEPA (Yadav, 2021). Furthermore, in other areas of India, such as near Jharia mine in Dhanbad, there were reports of carcinogenic effects of metals such as Cd, Cr, and Ni (Roy et al., 2019). However, in the present study, the focus was placed on analyzing street dust for further examination. This research also involved the determination of in vitro bioaccessibility using street dust composed of small particles that can adhere to hands and fingers, making them easily ingestible. In vitro bioaccessibility studies examine the fine dust that can be inhaled, leading to deposition in different parts of the lung.

Furthermore, it is hypothesized in the study that the concentrations of heavy metals in the Singrauli coal mine area could exceed permissible limits set by regulatory bodies due to extensive coal mining, heavy vehicle movements, the presence of TPPs, and associated industrial activities. It is further hypothesized that these heavy metals pose potential health risks to the local population, both in terms of carcinogenic and non-carcinogenic effects. Considering the lack of comprehensive studies on heavy metal bioaccessibility in Indian coal mine areas, it is also hypothesized that the bioaccessible fractions of heavy metals in the Singrauli mine complex might be substantial. In light of the "Energy Capital of India" designation of Singrauli (Agrawal et al., 2010) and its significance in coal mining and thermal power generation, it is anticipated that the study would highlight the health risks associated with these industries.

While studies have been conducted on the environmental impacts, health risks, and bioaccessibility of heavy metals in coal mine areas globally, studies reporting the concentrations of toxic metals along with the carcinogenic and non-carcinogenic health risks and bio-accessibility of heavy metals in coal mines of India have remained redundant (Reis et al., 2014; Skála et al., 2022; Zádrapová et al., 2019). Moreover, such studies have not been performed with respect to Singrauli coal mine complex. A search on the Web of Science Core Collection database, with keywords "bioaccessibility coal mine" on 30th of April, 2023, revealed minimal global studies, with only Singh and Singh (2022) covering human health risk assessments in a coal mine area in India (Jharia coalfields) and none covering bioaccessible fractions of heavy metals. Consequently, it was felt essential to investigate such a crucial area, and this study was performed with the following objectives: (i) determination of total concentrations of heavy metals and analyses of pollution indices in the Singrauli coal mine area; (ii) assessment of the human health risks emanating from the heavy metals in Singrauli region; and (iii) analysis of the bioaccessible fractions of the heavy metals in the Singrauli mine complex. Additionally, by bringing attention to the health risks associated with coal mining and thermal power plants, this article could raise public awareness and prompt policy-makers to take action to mitigate these risks and encourage environmental sustainability.

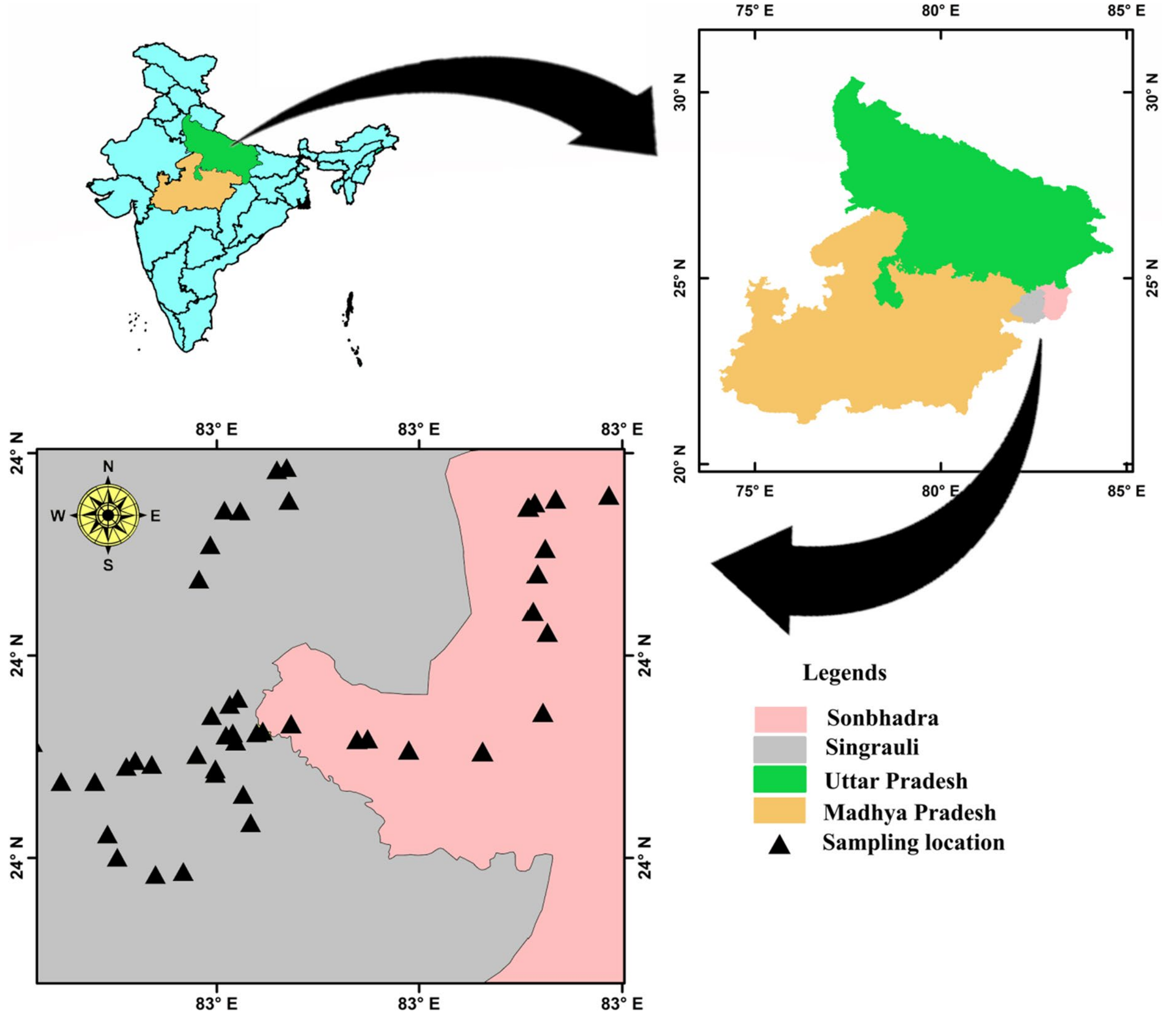


Fig. 1 Sampling location of Singrauli

Material and methods

Study area and sampling

In the Singrauli region, from 11 distinct sampling location a total of 44 samples were collected (n = 4) from each location which is spread over a 2200 km^2 area between 23° 47′–24° 12′ N and 81° 48′–82° 52′ E (Sonebhadra district of Uttar Pradesh and Singrauli district of Madhya Pradesh), consisting of multiple open cast coal mines and coal-based TPPs (capacity of more than 9000 MW) are located in the Singrauli region making it a highly polluted area (Shirin et al., 2021; Yadav & Hopke, 2020). The sampling location includes Jayanta Morwa, Dudhichua, Near Vindyachal TPP, Shakti Nagar, Anpara, Amlori, Bina, NTPC colony, NCL Quarters, Nigahi, and Khadia (Fig. 1). The locations were classified into three main areas: coal mine areas, industrial areas, and residential areas. Since the study area is primarily located near the coal mine complex, the majority of the sampling locations were designated as coal mine areas. Specifically, in the current study, places like Jayant Morwa, Dudhichua, Amlohri, Khadia, and Nigahi are completely situated within the coal mine area. Locations such as Near Vindyachal TPP, Near Shakti Nagar TPP, and Anpara fall within the vicinity of TPPs and hence considered as an industrial area. Additionally, locations such as NTPC colony, NCL quarter, and Bina were in close proximity to residential areas. Street dust (approximately 500 g) was collected during the winter season (January, 2022) from the edge of roads using a brush and a plastic shovel and kept in air-tight polyethylene bags. The samples were labeled and transported to the laboratory, where they were air-dried, sieved (< 250 µm), and stored for further analysis.

Heavy metal analysis and pollution assessment

During heavy metal analysis of street dust samples, an additional step was incorporated where samples were sieved using a 63 µm nylon mesh sieve. The sieving process was performed to ensure that only particles of the desirable size was included during subsequent analysis (Zheng et al., 2020). Dust samples (0.1 g) were digested in microwave digester (Milestone Connect Ethos Easy) using a strong acid mixture of nitric acid (HNO_3), hydrogen peroxide (H_2O_2), hydrofluoric acid (HF), and sulphuric acid (H_2SO_4) in a ratio of (4:1:3:3). Following digestion, sample volume was made upto 50 ml with 1% HNO_3, filtered, and metals (As, Cr, Pb, Zn, Ni, Cu, Mo, V, Se, Mn, Fe, and Co) analyzed by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES; Perkin Elmer Optical 2100 V) (Ishtiaq et al., 2018).

Geoaccumulation Index (I_{geo})—I_{geo} was determined to validate contamination of street dust and calculated using (1) (Al-Haidarey et al. 2010; Hasan et al., 2013; Ibanez et al., 2010; Müller, 1969):

$$I_{geo} = \mathrm{Log}_2\left(C_m/1.5 * B_m\right) \tag{1}$$

Where C_m refers to metal concentration in street dust, B_m refers to the background geochemical value of the metal, constant factor 1.5 is used to minimize possible lithologic or anthropogenic variation in reference background value.

Enrichment Factor (EF)—EF was determined to identify the extent of metal enrichment in street dust and calculated using (2) (Sutherland, 2000):

$$EF = C_m/\mathrm{Fe(street\ dust)}/C_m/\mathrm{Fe(backgroud\ value)} \tag{2}$$

Contamination Factor (CF)—CF was determined to quantify the degree of contamination with respect to the background values and calculated using (3)

$$CF = C_m/B_m \tag{3}$$

Pollution Load Index (PLI)—The comprehensive effect of various metals is evaluated by PLI, which gives equal consideration to the contribution of different species.

$$PLI_{zone} = \sqrt[n]{CF_1 \times CF_2 \times CF_3 \times \cdots \times CF_n} \tag{4}$$

$$PLI_{zone} = \sqrt[m]{PLI_1 \times PLI_2 \times PLI_3 \times \cdots \times PLI_n} \tag{5}$$

where, n denotes no. of species considered, while m refers to the no. of samples collected.

Bioaccessibility of heavy metals

Bioaccessibility of metals was determined using Physiologically Based Extraction Test (PBET), where analysis is done for gastric/stomach as well as intestinal phase. Moreover, the samples underwent an additional step in the PBET analysis, where they were sieved using a nylon mesh sieve with a size of 63 µm. For further analysis, 0.3 g of street dust sample was selected. For gastric phase, gastric solution was prepared by mixing 2.5 g pepsin, 1 g trisodium citrate, g malic acid, and 840 µl lactic acid syrup in double distilled water made up to 2 L (pH 1.5 maintained using HCl). Gastric phase analysis was done by mixing street dust sample with gastric solution (1:100 w/v) and shaken for an hour at 150 rpm at 37 °C. For intestinal phase, intestinal solution was made with gastric phase solution by adding 0.5 g pancreatin per L (pH-7 maintained using sodium hydrogen carbonate). Intestinal phase analysis was done by mixing street dust sample with intestinal solution (1:100 w/v) and shaking for 4 h at 37 °C. Later, the solutions were filtered, and the metal concentrations in the extracts were analysed using ICP-OES (Gu & Gao, 2018).

Human health risk assessment

The human health risk assessment (HHRA) of metals in street dust was performed using the exposure pathways model. Three major metal exposure pathways emanating from street dust has been identified

(Gope et al., 2017; Mestanza-Ramón et al., 2023): ingestion of dust, inhalation of re-suspended dust, and absorption from skin-adhered (dermal) dust. The chronic daily intake (CDI) is calculated by the following equations:

$$\mathrm{CDI} = \mathrm{C_{Soil}} \times \frac{\mathrm{EF \times ED \times IR}}{\mathrm{BW \times AT}} \times 10^{-6} \tag{6}$$

$$\mathrm{CDI_{ingestion}} = \mathrm{C} \times \frac{\mathrm{R_{ing} \times E_{Exp} \times T_{Exp}}}{\mathrm{ABW \times T_{avg}}} \times 10^{-6}(\mathrm{mg/kg/day}) \tag{7}$$

$$\mathrm{CDI_{inhalation}} = \mathrm{C} \times \frac{\mathrm{R_{inh} \times E_{Exp} \times T_{Exp}}}{\mathrm{PEF \times ABW \times T_{avg}}} \tag{8}$$

$$\mathrm{CDI_{dermal}} = \mathrm{C} \times \frac{\mathrm{SAF \times A_{skin} \times DAF \times E_{Exp} \times T_{Exp}}}{\mathrm{ABW \times T_{avg}}} \times 10^{-6} \tag{9}$$

where, ABW denotes average body weight [18 kg for child and 60 kg for adult], A_{skin} signifies skin area [2800 cm^2 for child and 5700 cm^2 for adult], DAF is dermal absorption factor (unit less) [0.001 for both child and adult], E_{exp} is exposure frequency [365 days $year^{-1}$], PEF is the particle emission factor [1.36×109 m^3 kg^{-1}], R_{Ing} denotes Ingestion Rate [100 mg day^{-1} for adult, 200 mg dust day^{-1} for child (1–6 years)], R_{inh} represents inhalation rate [20 m^3 day^{-1} for adult, 10 m^3 day^{-1} for child], SAF denotes skin adherence factor [0.2 mg cm^{-2} h^{-1} for child and 0.07 mg cm^{-2} h^{-1} for adult], T_{exp} denotes Exposure duration [6 years for child and 24 years for adult], T_{avg} denotes the average time [for non-carcinogens, $T_{avg} = T_{exp} \times 365$] (Manual, 1998; Rout et al., 2013; US Environmental Protection Agency, 2011; USEPA, 1984).

The assessment of non–carcinogenic risk is done using the equations:

$$\mathrm{HQ} = \frac{\mathrm{CDI_i}}{\mathrm{R_fD}} \tag{10}$$

$$\mathrm{HI} = \sum \mathrm{HQ_i}(\mathrm{ingestion/inhalation/dermal}) \tag{11}$$

where, R_fD denotes Reference Dose, and CDI_i signifies chronic daily intake via ingestion, inhalation, and dermal pathway (i stands for different pathways). $HI < 1$ suggests no significant risk, while $HI > 1$ indicates non-carcinogenic effects (USEPA, 1984).

Carcinogenic risk (CR) is calculated using the equations:

$$\mathrm{CR_i} = \mathrm{CDI_i} \times \mathrm{SF_0} \tag{12}$$

$$\mathrm{CR} = \sum \mathrm{CR_i} \tag{13}$$

where, SF_0 is the carcinogenic slope factor (dimensionless). A CR value of 10^{-6}–10^{-4} suggests tolerable carcinogenic risk. $CR > 10^{-4}$ denotes unacceptable risk, while $CR < 10^{-6}$ signifies no significant health hazards.

Quality control and quality assurance

High-quality analytical grade reagents were employed in the experiment to ensure stringent quality control. For the analysis, glassware that had been meticulously washed with 10% nitric acid was utilized to prevent any potential contamination. Certified Reference Material (CRM) was utilized to prepare all reagents and standard solutions, with the volume being adjusted using double distilled water. NIST certified soil reference material, GBW07411, was utilized for the metal analysis. The relative percentage differences (RPD) observed in the analysis was within the permissible standard of ±20%. To validate the results, samples were analyzed in triplicate, and the average value for each sample was reported in the results section. The detection limit of all the analyzed metals for the ICP-OES Perkin Elmer DV-2100 were Cr (0.02–20.0 ppm), Cd (0.01–10.0 ppm), Cu (0.04–40.0 ppm), Mn (0.001–10.0 ppm), Fe (0.01–10.0 ppm), Pb (0.01–100.0 ppm), Ni (0.05–50.0 ppm), and Zn (0.02–20.0 ppm).

Statistical analysis

The results were subjected to statistical analysis using correlation coefficients to investigate the relationship between the concentration of total heavy metals and indicators of human health risk. Additionally, correlation studies were conducted between the concentration of total heavy metals and the bioaccessibility phases, such as the gastric and intestinal phases. The correlation analysis was performed using Origin Pro 9.0.

Table 1 Total metal concentrations in different sampling locations in Singrauli

Sampling Location		Cu	Ni	Pb	Zn	Cr	Co	As	Fe	V	Mo	Mn
Jayant Morwa (PLI-1.35)	Total Metal Conc. (mg/kg)	76.55±44.65	59.85±9.98	6.83±1.01	188.15±46.90	125.07±11.80	19.35±3.47	14.86±2.80	33,961.5±10,839.1	71.48±13.76	13.45±16.20	591.53±217.77
	I_{geo}	0.18	− 0.77	− 2.14	0.40	− 0.11	1.31	0.90	− 1.06	− 1.07	2.16	− 1.11
	CF	1.70	0.88	0.34	1.98	1.39	3.72	2.80	0.72	0.71	6.73	0.70
	EF	2.36	1.22	0.47	2.75	1.93	5.17	3.89	1.00	0.99	9.35	0.97
Dudhichua (PLI-1.34)	Total Metal Conc. (mg/kg)	54.5±11.07	60.4±15.36	8.13±1.81	263.7±100.80	142.3±18.45	24.2±1.99	13.95±1.40	41,204±7332.74	92.5±7.87	3.9±2.71	737.3±196.97
	I_{geo}	− 0.31	− 0.76	− 1.88	0.89	0.08	1.63	0.90	− 0.78	− 0.70	0.38	− 0.79
	CF	1.21	0.89	0.41	2.78	1.58	4.65	2.79	0.87	0.93	1.95	0.87
	EF	1.39	1.02	0.47	3.18	1.81	5.33	3.20	1.00	1.06	2.23	0.99
NTPC colony (PLI-1.23)	Total Metal Conc. (mg/kg)	43.5±3.24	45.83±7.9	10.17±2.32	256.5±16.8	129.5±27.81	18.83±4.11	15.96±1.7	42,723.33±4985.6	69.5±21.98	2.67±1.25	823.83±120.32
	I_{geo}	− 0.63	− 1.15	− 1.56	0.85	− 0.06	1.27	1.09	− 0.73	− 1.11	− 0.17	− 0.63
	CF	0.97	0.67	0.51	2.70	1.44	3.62	3.19	0.91	0.70	1.33	0.97
	EF	1.07	0.74	0.56	2.98	1.59	4.00	3.53	1.00	0.77	1.47	1.07
Near Vindyachal TPP (PLI-2.34)	Total Metal Conc. (mg/kg)	274.83±94.7	99±16.31	19.83±3.70	427.83±161.6	240.17±45.7	40.5±9.19	17.5±2.8	55,811.67±4919.8	130±29	10.83±1.18	954.5±99.00
	I_{geo}	2.03	− 0.04	− 0.60	1.59	0.83	2.38	1.22	− 0.34	− 0.21	1.85	− 0.42
	CF	6.11	1.46	0.99	4.50	2.67	7.79	3.50	1.18	1.30	5.42	1.12
	EF	5.17	1.23	0.84	3.81	2.26	6.59	2.96	1.00	1.10	4.58	0.95
Khadia (PLI-1.15)	Total Metal Conc. (mg/kg)	62.75±7.75	40.75±1.25	4.50±10	214.25±11.25	116.75±0.25	20.25±0.25	8.5±1.50	46,687.5±6162.50	74.5±60	4.25±3.75	759.75±70.25
	I_{geo}	− 0.11	− 1.32	− 2.74	0.59	− 0.21	1.38	0.18	− 0.60	− 1.01	0.50	− 0.75
	CF	1.39	0.60	0.23	2.26	1.30	3.89	1.70	0.99	0.75	2.13	0.89
	EF	1.41	0.61	0.23	2.28	1.31	3.94	1.72	1.00	0.75	2.15	0.90
Amlohri (PLI-1.53)	Total Metal Conc. (mg/kg)	66.83±30.66	55.17±18.9	10.83±17.9	225.83±55.63	139.67±40.10	23.5±4.02	9.00±1.78	41,525±6515.40	84.5±13.77	13.17±11.9	797.67±125.84
	I_{geo}	− 0.01	− 0.89	− 1.47	0.66	0.05	1.59	1.17	− 0.77	− 0.83	2.13	− 0.68
	CF	1.49	0.81	0.54	2.38	1.55	4.52	3.37	0.88	0.85	6.58	0.94
	EF	1.69	0.92	0.62	2.70	1.76	5.14	3.83	1.00	0.96	7.48	1.07
Nigahi (PLI-1.38)	Total Metal Conc. (mg/kg)	112.17±47.20	42.5±3.61	11.67±1.26	235.33±32.39	131.17±10.60	25.67±1.04	14±1.32	51,533.33±4318.90	96.17±5.84	1.83±1.04	924.67±83.16
	I_{geo}	0.73	− 1.26	− 1.36	0.72	− 0.04	1.72	0.90	− 0.46	− 0.64	− 0.71	− 0.46

Table 1 (continued)

Sampling Location		Cu	Ni	Pb	Zn	Cr	Co	As	Fe	V	Mo	Mn
	CF	2.49	0.63	0.58	2.48	1.46	4.94	2.80	1.09	0.96	0.92	1.09
	EF	2.28	0.57	0.53	2.27	1.33	4.52	2.56	1.00	0.88	0.84	1.00
Near Shakti Nagar TPP (PLI-2.58)	Total Metal Conc. (mg/kg)	181.80 ± 68.39	169.60 ± 50.79	16.4 ± 2.91	342.4 ± 79.43	406.60 ± 161.40	48.40 ± 8.91	18.03 ± 5.30	65,061.00 ± 13,866.61	134.00 ± 10.85	16.10 ± 6.43	1118.40 ± 240.59
	I_{geo}	1.43	0.73	− 0.87	1.26	1.59	2.63	1.27	− 0.12	− 0.16	2.42	− 0.19
	CF	4.04	2.49	0.82	3.60	4.52	9.31	3.61	1.38	1.34	8.05	1.32
	EF	2.93	1.81	0.59	2.61	3.28	6.75	2.62	1.00	0.97	5.84	0.95
Anpara (2.26)	Total Metal Conc. (mg/kg)	139.25 ± 15.30	125.25 ± 72.80	6.63 ± 2.13	393.25 ± 135.10	273.00 ± 123.94	42.63 ± 12.60	16.45 ± 1.60	73,950.00 ± 13,279.92	137.00 ± 22.88	16.63 ± 10.70	1331.88 ± 241.50
	I_{geo}	1.04	0.30	− 2.18	1.46	1.02	2.45	1.13	0.06	− 0.13	2.47	0.06
	CF	3.09	1.84	0.33	4.14	3.03	8.20	3.29	1.57	1.37	8.31	1.57
	EF	1.98	1.18	0.21	2.64	1.94	5.23	2.10	1.00	0.87	5.31	1.00
NCL Quarters (PLI-1.46)	Total Metal Conc. (mg/kg)	79.00 ± 5.72	80.83 ± 14.23	2.67 ± 1.31	219.83 ± 13.76	203.5 ± 41.82	31.00 ± 1.22	12.27 ± 2.50	57,250.00 ± 2345.56	113.17 ± 3.40	5.33 ± 1.70	957.17 ± 102.97
	I_{geo}	0.23	− 0.34	− 3.49	0.63	0.59	1.99	0.86	− 0.31	− 0.41	0.83	− 0.41
	CF	1.76	1.19	0.13	2.31	2.26	5.96	2.73	1.21	1.13	2.67	1.13
	EF	1.45	0.98	0.11	1.91	1.86	4.92	2.25	1.00	0.93	2.20	0.93
Bina (PLI-1.21)	Total Metal Conc. (mg/kg)	30.50 ± 8.00	70.50 ± 33.00	4.00 ± 2.50	185.25 ± 40.25	133.00 ± 22.5	42.50 ± 20.50	11.25 ± 1.20	32,302.50 ± 10,797.50	100.75 ± 21.70	5.00 ± 1.50	558.50 ± 258.00
	I_{geo}	− 1.15	− 0.53	− 2.91	0.38	− 0.02	2.45	0.74	− 1.13	− 0.57	0.74	− 1.19
	CF	0.68	1.04	0.20	1.95	1.48	8.17	2.50	0.68	1.01	2.50	0.66
	EF	0.99	1.51	0.29	2.85	2.16	11.94	3.65	1.00	1.47	3.65	0.96
PLI_{ZONE}: 1.56												

Result and discussion

Heavy metals concentrations

The concentration of metals was measured at 11 sampling locations in Singrauli, and the results are presented in Table 1.The mean concentration of heavy metals, including Cu, Ni, Zn, Cr, Co, As, and Mo, was found to exceed the background levels, with the exception of Pb, V, Fe, and Mn. Specifically, Zn and Cr were approximately three times higher than the background levels, indicating a significant impact of human activities on the area under study (Men et al., 2018). The highest concentrations of metals were observed at locations near the TPPs of near Vindyachal TPP, near Shakti Nagar TPP, and Anpara, suggesting that the proximity of these plants may be responsible for the elevated levels of heavy metals.

The locations of Vindyachal TPP, Shakti Nagar TPP, and Anpara exhibited the highest concentration of Cu, with values of 274.83 ± 94.7, 181.80 ± 68.39, and 139.25 ± 15.30 mg/kg, respectively. These values were approximately three times higher compared to the residential areas. Similarly, for Ni, a similar trend was observed, with values ranging from 40.75 ± 1.25 to 169.60 ± 50.79 mg/kg at Khadia and Shakti Nagar, respectively. The significant concentrations of Ni in these locations can be attributed to the combustion of fossil fuels and the refining of metals like Cu (Lee et al., 2005). In the Singrauli region, the Pb concentrations ranged from 2.67 ± 1.31 mg/kg at NCL Quarters to 19.83 ± 3.70 mg/kg at Vindyachal TPP. However, compared to other locations such as Jharia mining town in Dhanbad, India (70.5 mg/kg), and Delhi, India (293 mg/kg), the Pb concentration was significantly lower in the present study area (Banerjee, 2003; Rout et al., 2015). The range of Zn concentrations varied from 185.25 ± 40.25 mg/kg in Bina, a residential housing colony, to 427.83 ± 161.6 mg/kg in Vindyachal TPP. However, all the sampling locations recorded Zn levels that were more than thrice the acceptable limits set by WHO in 1996. This could be attributed to traffic emissions, tyre wear and tear, and the presence of Zn in local coal, although the latter is insignificant due to the low concentrations in coal (Rout et al., 2015). Therefore, the major contributors of the Zn in the present study were traffic density, poor road quality, and the burning of tyres.

The Cr concentrations varied from 116.75 ± 0.25 mg/kg at Khadia to 406.60 ± 161.40 mg/kg at Vindyachal TPP. Additionally, the Cr concentrations in all the locations exceeded the permissible limit set by WHO. The observed values were also higher compared to other coal mine areas investigated in India, such as the Jharia coal field study, where a value of 70.0 mg/kg was found Rout et al (2015). Furthermore, in the Singrauli region near the Lanco thermal power plant, a higher Cr value of 211.1 mg/kg was observed, which was higher than the previously reported values (Romana et al., 2022). Also, higher chromium (Cr) values were observed in the opencast mines of Rajasthan, India (Chakraborty et al., 2023). Historically, coal combustion has served as a prominent source of chromium (Cr) emissions, with the emission profile influenced by the type of coal being burned. Complicating matters further, the emission profile of Cr aligns to a considerable extent with that of soil re-suspension, owing to the similarities between the alumino-silicate structures found in soil particles and coal ash (Charlesworth et al., 2011). The concentrations of Co ranged from 18.83 ± 4.11 mg/kg at NTPC colony to 48.40 ± 8.91 mg/kg at Shakti Nagar. Comparatively, the Co concentrations in Indian coal mines were lower than those in China, where reported values were 81.81 mg/kg at Yulin and 291 mg/kg at Fushun, with coal mining activity being a major source of pollution. In the current study, the As concentrations ranged from 8.5 ± 1.50 mg/kg at Khadiya to 18.03 ± 5.30 mg/kg at Shakti Nagar. However, a previous study conducted in Singrauli reported lower concentrations of As, ranging between 1.0 and 4 mg/kg (Agrawal et al., 2010; Romana et al., 2022). The higher value of As could be attributed to the coal burning process, where As is volatilized into the atmosphere, which subsequently settles on dust particles through condensation. However, the result of the present study showa a lower value of metals in coal mining and industrial area as compared to the recent study done at Baiyin, NW China. Contrary to the recent study conducted in Baiyin, NW China, the findings of the present study indicate lower metal values in both coal mining and industrial areas (Zhang et al., 2023).

The obtained results from the coal mine area, industrial area, and residential area highlight the presence of elevated concentrations of various heavy metals, indicating potential environmental pollution and associated health risks. The highest concentrations of metals were observed in locations around the TPPs of Vindyachal, Shakti Nagar, and Anpara, suggesting a possible correlation between proximity to these plants and increased heavy metal levels. Moreover, emissions released by TPPs could contain heavy metals, which could result in atmospheric deposition of the heavy metals. Further, factors like wind direction, wind speed, topography, and local weather conditions could affect the movement of heavy metal-loaded particles, potentially leading to higher concentrations in nearby areas. Additionally, industrial processes associated with the TPPs, such as coal handling, combustion, and waste disposal, could contribute to the release of heavy metals into the environment.

The close proximity of the coal mine area (Jayant Morwa, Dudhichua, Amlohri, Khadia, and Nigahi) to the TPPs resulted in similar results with respect to heavy metal concentrations. The mining activities in the coal mine area could disturb the soil, releasing heavy metal-loaded particulate matter, which could be carried by wind and deposited in nearby areas and contaminate them with heavy metals. Further, processes, such as loading, unloading, and storage of coal from coal mines to TPPs, could generate dust containing heavy metals, leading to metal pollution in surrounding areas. Additionally, the combustion of coal and fires in coal mine areas release heavy metals into the atmosphere, uplifting the concentrations of heavy metals. Rainfall could leach heavy metals from coal mining areas into nearby areas. Environmental conditions, like prevailing wind patterns, local topography, and meteorological factors, influence the transport and dispersion of heavy metal-loaded dust particles.

Additionally, residential areas (NTPC Colony, NCL Quarter, and Bina were not exempted from heavy metal contamination even though they exhibited the lowest concentrations. Although residential areas might be located away from the coal mine areas and TPPs, heavy metals can still disperse over long distances through transport mechanisms like atmospheric dispersion or water runoff, contributing to heavy metal contamination in residential areas. Moreover, human activities like construction, road traffic, or natural disturbances like wind could re-suspend the metal-loaded dust, causing re-contamination of residential areas with heavy metals. Residents in these areas could be exposed to heavy metals during gardening or outdoor play or during consumption of contaminated water or locally grown food products. The assessments reaffirmed that all areas, including the coal mine area, industrial area, and residential area, were affected by contamination due to their close proximity to coal mine. There is need for comprehensive monitoring, mitigation, and awareness programs to address heavy metal contamination in these areas especially residential areas.

Prior studies have suggested that emissions from coal-fired power plants increased Cd concentrations and heavy traffic, frequent vehicular brake usage, and tyre wear and tear led to higher levels of Fe, Mn, and Cr in Dhanbad, India (Mondal & Singh, 2021), while poor management of coal transport, coal combustion, industrial emission, and weathering augmented Cd and Hg concentrations in Huainan, China (Tang et al., 2017).

In comparison to other studies conducted in coal mine regions across India, street dust of Singrauli was found to have higher concentrations of metals such as Mn, Cr, As, Cu, and Zn. This could possibly arise from various anthropogenic activities in the area, such as heavy traffic, hauling vehicles, smelting, industrial waste, acid mine drainage, and combustion of fuel (Sharma et al., 2021). Another possible reason could be the disposal of fly ash from the TPPs in the area (Gopinathan et al., 2022b; Zierold & Odoh, 2020). A study conducted in Dhanbad, India, where a large mine complex is located, reported lower values of metals such as Mn (34.58 mg/kg), Cr (39.4 mg/kg), As (2.81 mg/kg), Cu (2.1 mg/kg), and Zn (5.6 mg/kg) in comparison to the present study (Mondal & Singh, 2021). However, samples from Jharia site in Dhanbad showed higher concentrations of metals such as Cd, Pb, and Ni. Additionally, metals such as As, Cu, and Zn were found in greater concentrations when compared to other studies involving countries such as China (Huainan, Tangshan, Lianyua, Eastern China, Suzhou, Yangcaogou, Huaibei, Jilin province), South Africa (Mpumalanga), Bangladesh (Barapukuria), Slovakia (Bratislava), Canada (Quinsam), Russia (Chelyabinsk), and Poland (Cao et al., 2020; Halim et al., 2015; Hiller et al., 2017; Jiang et al., 2014; Krupnova et al., 2020; Liang et al., 2017; Lin et al., 2017; Loska et al., 2004; Moriarty et al., 2014; Pandey et al., 2014; Shi et al., 2013; Sun et al., 2019a, 2019b; Tang et al., 2018). It is important to note that all these metals are dispersed in the atmosphere due to poor management of coal transport near the mining area (Kumari & Bhattacharya, 2023).

Assessment of pollution indices

The degree of heavy metal contamination in the street dust of Singrauli was analyzed using the I_{geo}, CF, EF, and PLI methods. The background concentration of metals (in mg/kg) were: Cu(45), Ni (68), Pb(20), Zn(95), Cr(90), Co(5.20), As(5.0), Fe(47,200), V(100), Mo(2.0), and Mn(850) (Hasan et al., 2013; Müller, 1969; Romana et al., 2022; Roy & Bhattacharya, 2022). The I_{geo} values for heavy metals ranged from − 2.90 to 2.63. The highest I_{geo} values were observed for Co, Mo, Zn, and As in all the sampling locations, indicating moderate to strong pollution levels. The mean concentration of I_{geo} value for each metal was: Cu (0.31), Ni (− 0.54), Pb (− 1.93), Zn (0.86), Cr (0.34), Co (1.89), As (0.94), Fe (− 0.57), V (− 0.62), Mo (1.14), and Mn (− 0.59). The maximum I_{geo} values were observed at the Near Shakti nagar TPP and Near Vindyachal TPP locations. Based on the I_{geo} values, it could be concluded that the street dust in the Singrauli region is moderately polluted.

The CF values in Singrauli ranged from 0.20 in Pb at Bina to 9.31 in Co at Near Shakti nagar TPP. Similarly, the mean CF value for each metal was: Cu (1.53), Ni (0.56), Pb (0.25), Zn (0.83), Cr (0.95), Co (1.99), As (0.52), Fe (0.26), V (0.24), Mo (2.68), and Mn (0.25). The highest CF values were found in metals such as Co, As, Zn, Mo, and Cr at all locations. However, Near Vindyachal TPP and Near Shakti nagar TPP had the highest CF values, in consonance with I_{geo} values. Metals such as Cu, Co, and Mo had CF values greater than 6, indicating that they were highly polluted. The EF was assessed to determine whether the levels of potentially toxic elements (PTEs) in the soil were due to anthropogenic activities, presented in Table 1. The EF values for all eleven locations are, ranging from 0.10 for Pb at NCL quarter to 9.35 for Mo at Jayant Morwa. The mean EF value for each metal was: Cu (1.13), Ni (0.35), Pb (0.21), Zn (0.48), Cr (0.52), Co (2.12), As (0.71), V (0.19), Mo (2.56), and Mn (0.05I). The EF trend was found to be similar to that of I_{geo} and CF. It is worth noting that the CF and EF values obtained indicate that the heavy metal pollution in the street dust of Singrauli were mainly caused by anthropogenic activities, particularly coal mining and combustion-related activities.

The PLI of all locations ranged from 1.2 in Bina to 2.58 in Near Shakti nagar TPP, with a PLI_{Zone} value of 1.56. Since, a PLI score greater than 1 indicates pollution, while a score less than 1 indicates a non-polluted site, Singrauli was considered a polluted site (all locations had a PLI value greater than 1) (Mondal & Singh, 2021). Although the PLI scores were lower than in previous studies such as Mondal and Singh (2021) in Dhanbad, India (8.22), Bhuiyan et al., (2010) in Barapukuria coal basin, Bangladesh (4.02), and Gope et al., (2017) in Asansol, India (4.78), Singrauli is still heavily polluted with PTEs in street dust. The presence of coal-based industries and power plants in the region releases a significant amount of heavy metals into the environment through their effluent discharge, fly ash, and coal dust, while large-scale mining activities, vehicular emissions, use of agro-chemicals for farming, or natural geological and hydrological features of the region (Singrauli situated at foothills of Vindhya mountain range) might also add to the pollution load. These findings underscore the need for continued monitoring and mitigation efforts to protect public health and the environment in Singrauli region. In previous studies, metal pollution sources ranged from traffic to industry, tires to fertilizers, and natural to anthropogenic emissions (Li et al., 2017; Padoan et al., 2017).

Human health risk assessment

Singrauli is ranked as the 22nd most polluted city in the world, and in order to safeguard the local population, it is crucial to evaluate the health risks posed by the trace elements present in the street dust. A comprehensive health risk assessment was conducted to determine the frequency, occurrence, and significance of pollutants, as well as their connections with contaminant, route, and receptor. The potential risks to human health from urban playground dirt have been analyzed through ingestion, inhalation, and skin contact routes of exposure, and the methodology used for health risk assessment was based on the guidelines and exposure factors handbook developed by the US Environmental Protection Agency (USEPA, 1989, 2001; USEPA, 2001).

Table S1 presents the non-carcinogenic risks for both children and adults arising from heavy elements in street dusts assessed in all sampling locations of Singrauli. It could be observed that children in the city are more vulnerable to non-carcinogenic health risks from road dust compared to adults, with three primary exposure pathways of cutaneous absorption, inhalation, and dust ingestion. For metals such as Cu, Ni, Pb, and Zn, inhalation route showed the highest HQ value, while for Cr and Mn, ingestion was the major route of exposure with the maximum value of HQ. Dermal contact was the primary exposure for children and adults with respect to Fe. The findings of this study are consistent with those of Gope et al. (2017) when calculating non-carcinogenic risks in West Bengal and with Mondal and Singh (2021) in Dhanbad, India.

All the trace elements examined in this study had HI values of < 1 (except for Cr and Fe), indicating no significant non-carcinogenic risks for both adults and children. However, Near Vindyachal TPP, Near Shakti nagar TPP, Nigahi, Anpara, and NCL quarter locations had HI scores greater than 1 for Fe and Cr in children. Sampling sites of Bina and Jayant Morwa also had positive values for Mn. Similar findings were reported by Qiu et al. (2018) in the coal mine area of Northern Anhui Province, China. It is evident from the results that the dominant health risks emanate via ingestion when compared to inhalation and dermal contact, which corroborated with a previous report by Zhang et al. (2021) when analyzing heavy metals in the soil of the coal mine area in Xinjiang, China.

Adults were found to have a significantly higher chance of ingesting heavy metals than children, primarily due to their faster food consumption rate. On the other hand, children were more likely to inhale heavy metals due to their developing respiratory systems, which are more susceptible to getting harmed.

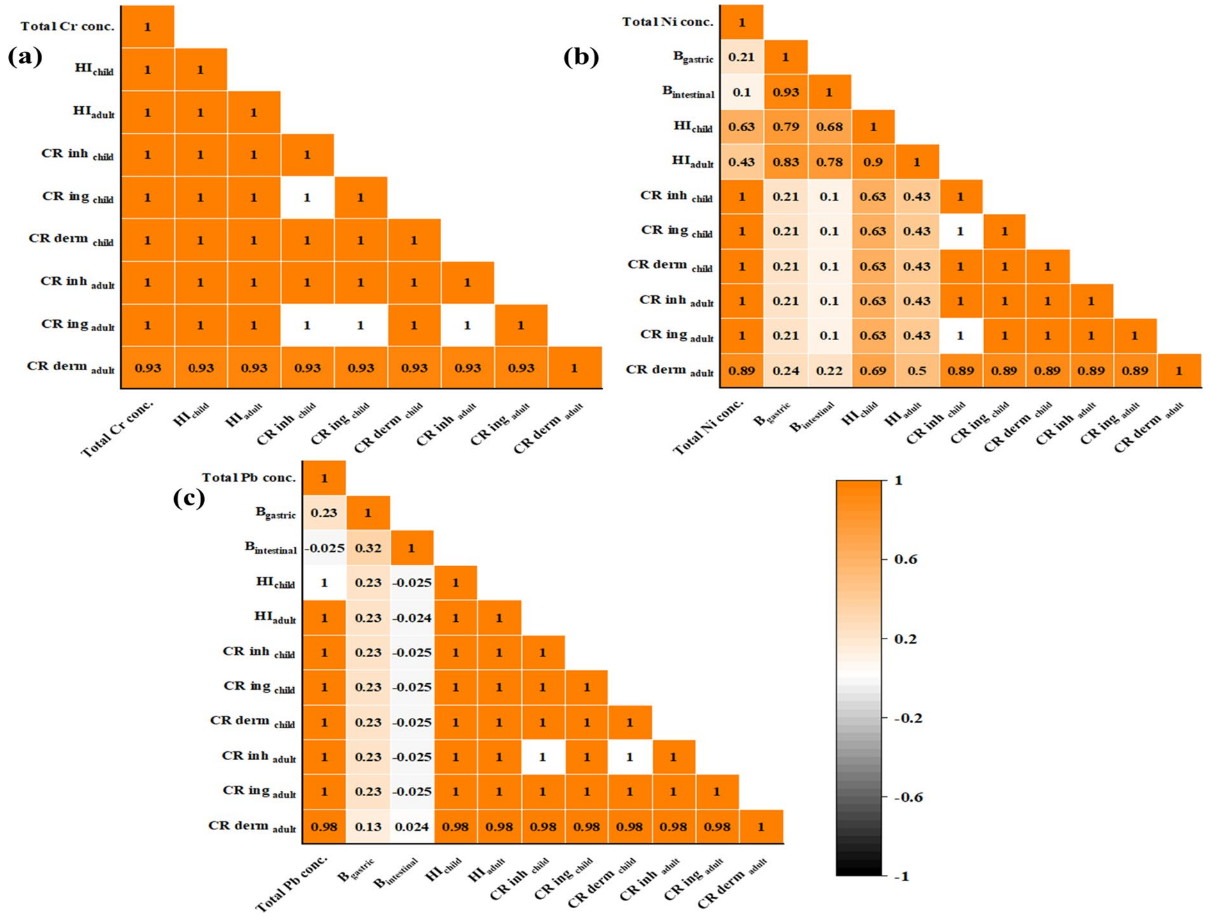


Fig. 2 Correlation plot for total metals, bioaccessible fractions, HI, and CR for **a** Cr, **b** Ni, and **c** Pb

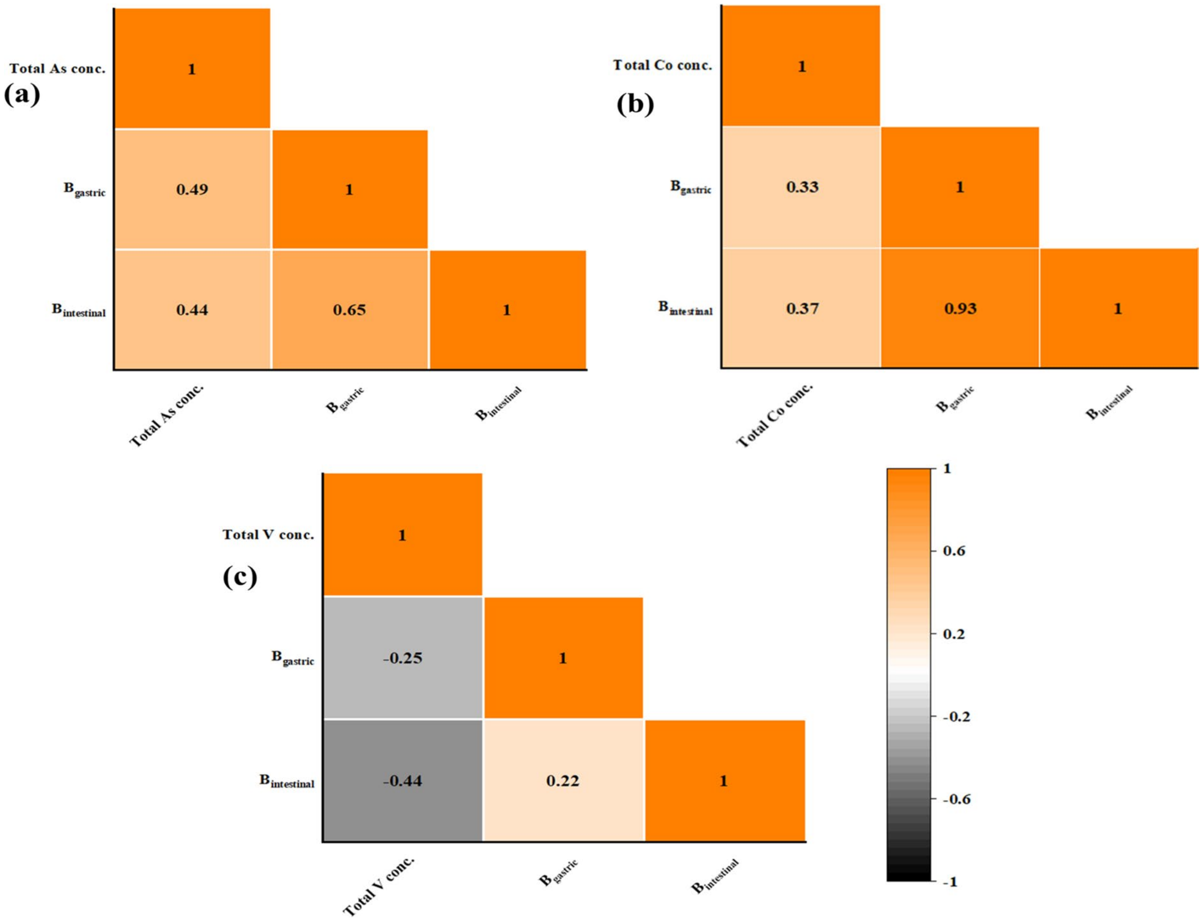


Fig. 3 Correlation plot for total metals and bioaccessible fractions for **a** As, **b** Co, and **c** V

The difference between adults and children with respect to chances of skin absorption was minimal, indicating the negligible potential risks posed by dermal absorption (Maghakyan et al., 2017; Zhang et al., 2021). Metals like Cr, Mn, and Fe pose higher non-carcinogenic risks for both children and adults, while other metals do not pose the same threat of non-carcinogenic effect. A prior study indicated that total and bioaccessible metals strongly correlated with their pH, and organic matter content and posed significant non-carcinogenic risks in children only, but no carcinogenic risks for adults and children (Hu et al., 2011). In another study performed in Dukki coal mine in Pakistan, ingestion was observed as the main pathway of metal exposure in children, chiefly arising from frequent hand-to-mouth movement compared to adults (Ahmad et al., 2020) (Figs. 2, 3, and 4).

Carcinogenic risks arising from routes of inhalation, ingestion and dermal contact for trace metals including Cr, Ni, and Pb in the street dust of Singrauli were calculated for both children and adults (Table 2). These elements were believed to cause cancer primarily through inhalation and ingestion exposure. Moreover, it was observed that their absorption through dermal contact did not have a carcinogenic effect. The range of probable carcinogenic effects of metals Cr and Ni in both children, and adults was approximately between 10^{-4} and 10^{-6}. Similar findings were reported by Mondal and Singh (2021) in the coal mine area of Jharkhand, Dhanbad. Additionally, it was demonstrated that Pb exposure through inhalation could have a carcinogenic effect on children, but it does not affect adults. In a prior study, urban park dust was assessed for health risks, and it was observed that ingestion route mainly posed non-carcinogenic risks,

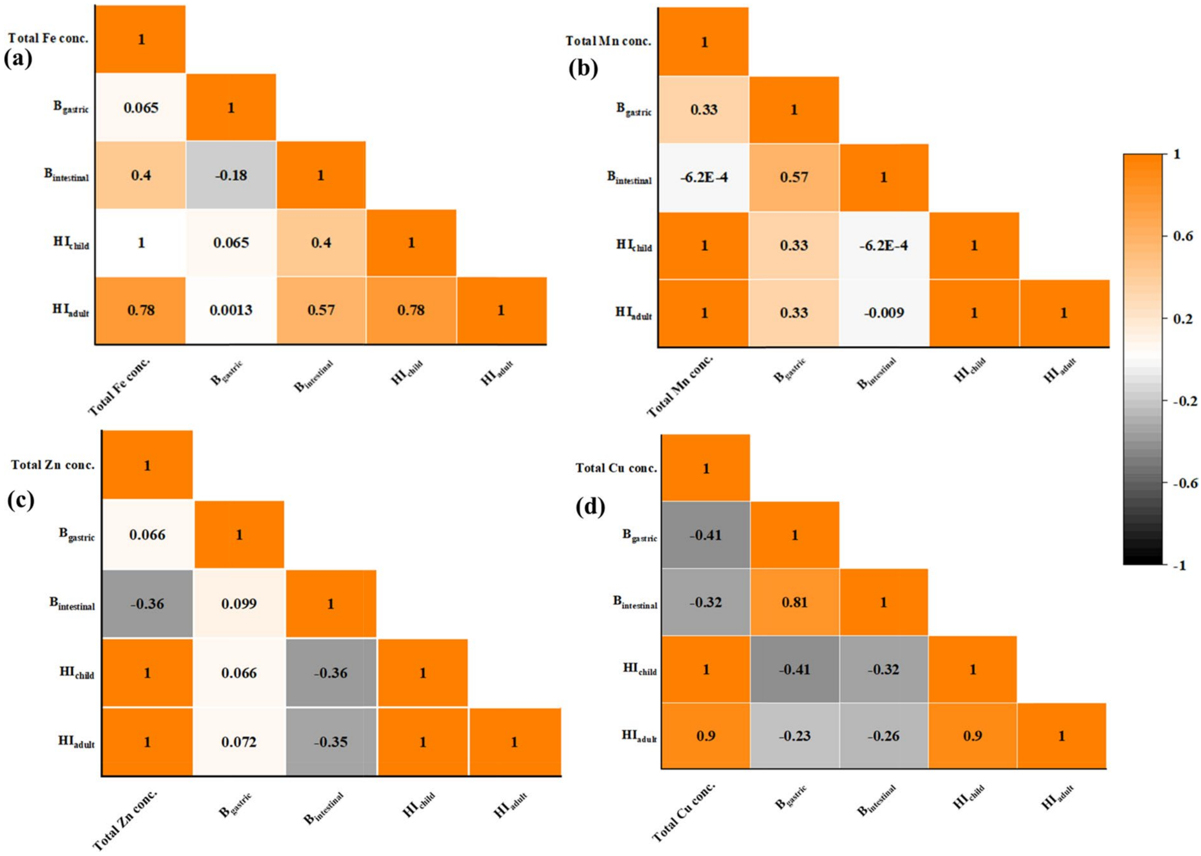


Fig. 4 Correlation plot for total metals, bioaccessible fractions, and HI for **a** Fe, **b** Mn, **c** Zn, and **d** Cu

while Pb, and As posed greater carcinogenic risks in children (Gu et al., 2016). It is noteworthy that there exists a strong correlation between the HI of both adults and children and certain metals, namely Cu, Pb, Cr, Fe, Zn, and Mn (Figs. 2 and 4). Additionally, when considering the carcinogenic risk posed by exposure to these metals, it is observed that Cr, Pb, and Ni show a strong correlation with the total metal concentration and the exposure route (with r^2 values of 1 for ingestion and inhalation, and 0.98 for dermal exposure).

Bioaccessibility of heavy metals

To evaluate the potential impact on human health, PBET was employed to assess the bioaccessibility of heavy metals in soils. Table 3, summarizes the bioaccessibility of Cd, Cr, Cu, Ni, Pb, As, Co, V, Mn, Fe, and Zn in the gastric and intestinal phases of street dust samples, revealing significant differences between the phases. The results demonstrate the varying trends in the metal bioaccessibility, together with different phase. The type of sample used varied according to the region where it was collected, resulting in a distinct pattern of metal content at each site. The bioaccessibility of metal is dependent on its mode of binding to reactive soil surfaces: sorption, complexation, and redox processes (Roy et al., 2023). Furthermore, the bioaccessibility of metals is influenced by a variety of factors, such as climate, environment, traffic volume, coal mine area, commercial area, construction activity, and haul road. Physicochemical parameters such as pH, electrical conductivity, and organic matter also have an impact on heavy metal bioaccessibility (Xing et al., 2019).

It must be noted that Cr was present in higher concentrations in street dust, but it was not bioaccessible because it primarily existed as a residue that is difficult for human gastrointestinal fluid to break down (Han et al. 2020; Li et al., 2013). Similarly, Han et al.

Table 2 Carcinogenic risks in child and adult through routes of inhalation, ingestion, and dermal exposure

Sampling Location	Metal	Child			Adult		
		CDI_{inh}	CDI_{ing}	CDI_{dermal}	CDI_{inh}	CDI_{ing}	CDI_{dermal}
Jayant Morwa	Ni	5.59E−04	2.05E−05	1.56E−06	8.38E−05	1.23E−05	3.34E−07
	Pb	3.19E−06	1.17E−07	8.92E−09	4.78E−07	7.03E−08	1.91E−09
	Cr	5.70E−04	2.09E−05	1.60E−06	8.55E−05	1.26E−05	3.41E−07
Dudhichua	Ni	5.64E−04	2.07E−05	1.58E−06	8.46E−05	1.24E−05	3.37E−07
	Pb	3.79E−06	1.40E−07	1.06E−08	5.69E−07	8.37E−08	2.27E−09
	Cr	6.48E−04	2.38E−05	1.82E−06	9.72E−05	1.43E−05	3.88E−07
NTPC Colony	Ni	4.28E−04	1.57E−05	1.20E−06	6.42E−05	9.44E−06	2.56E−07
	Pb	4.74E−06	1.74E−07	1.33E−08	7.12E−07	1.05E−07	2.84E−09
	Cr	5.90E−04	2.17E−05	1.65E−06	8.85E−05	1.30E−05	3.53E−07
Near Vindyachal TPP	Ni	9.24E−04	3.40E−05	2.59E−06	1.39E−04	2.04E−05	5.53E−07
	Pb	9.26E−06	3.40E−07	2.59E−08	1.39E−06	2.04E−07	5.54E−09
	Cr	1.09E−03	4.02E−05	3.06E−06	1.64E−04	2.41E−05	6.55E−07
Khadia	Ni	3.80E−04	1.40E−05	1.06E−06	5.71E−05	8.39E−06	2.28E−07
	Pb	2.10E−06	7.72E−08	5.88E−09	3.15E−07	4.63E−08	1.26E−09
	Cr	5.32E−04	1.96E−05	1.49E−06	7.98E−05	1.17E−05	3.18E−07
Amlohri	Ni	5.15E−04	1.89E−05	1.44E−06	7.72E−05	1.14E−05	3.08E−07
	Pb	5.06E−06	1.86E−07	1.42E−08	7.58E−07	1.12E−07	3.03E−09
	Cr	6.36E−04	2.34E−05	1.78E−06	9.54E−05	1.40E−05	3.81E−07
Nigahi	Ni	3.97E−04	1.46E−05	1.11E−06	5.95E−05	8.75E−06	2.37E−07
	Pb	5.44E−06	2.00E−07	1.52E−08	8.17E−07	1.20E−07	3.26E−09
	Cr	5.98E−04	2.20E−05	1.67E−06	8.96E−05	1.32E−05	3.58E−07
Near Shakti Nagar TPP	Ni	1.58E−03	5.82E−05	4.43E−06	2.37E−04	3.49E−05	9.47E−07
	Pb	7.65E−06	2.81E−07	2.14E−08	1.15E−06	1.69E−07	4.58E−09
	Cr	1.85E−03	6.81E−05	5.19E−06	2.78E−04	4.09E−05	1.11E−06
Anpara	Ni	1.17E−03	4.30E−05	3.27E−06	1.75E−04	2.58E−05	7.00E−07
	Pb	3.09E−06	1.14E−07	8.66E−09	4.64E−07	6.82E−08	1.85E−09
	Cr	1.24E−03	4.57E−05	3.48E−06	1.87E−04	2.74E−05	7.44E−07
NCL quarters	Ni	7.54E−04	2.77E−05	2.11E−06	1.13E−04	1.66E−05	4.52E−07
	Pb	1.24E−06	4.58E−08	3.48E−09	1.87E−07	2.75E−08	7.45E−10
	Cr	9.27E−04	3.41E−05	2.60E−06	1.39E−04	2.04E−05	5.55E−07
Bina	Ni	6.58E−04	2.42E−05	1.84E−06	9.87E−05	1.45E−05	4.50E−11
	Pb	1.87E−06	6.86E−08	5.23E−09	2.80E−07	4.12E−08	1.28E−13
	Cr	6.06E−04	2.23E−05	1.70E−06	9.09E−05	1.34E−05	4.14E−11

(2020) found a similar trend for Cr in urban park soil samples in Jiaozuo, China, indicating that the amount of metal present in the dust did not have a significant impact on the amount of bioaccessible metal. However, in most of the samples the gastric phase was found to have more bioaccessible metal than the intestinal phase, also reported by several other researcher groups (Han et al. 2020; Sun et al., 2019a, 2019b; Wang et al., 2021; Zádrapová et al., 2019; Zheng et al., 2020; Zhuang et al., 2016). The lower pH in the gastric stage may have increased the enzyme activity, resulting in a greater bioaccessibility of heavy metals. Trace metals were more likely to be released in an acidic environment, leading to greater bioaccessibility in the stomach phase. However, once they reached the intestinal phase, trace metals were easily precipitated and absorbed, allowing them to be fixed and passivated once again (Zheng et al., 2013). Nonetheless, in certain locations such as Jayant (6.53%), Anpara (5.01%), Nigahi (17.70%), Bina (0.78%), and

Table 3 Bioaccessibility of metals in gastric and intestinal phase

Sampling location	As	Co	Cu	Fe	Mn	Ni	Pb	V	Zn
Jayant Morwa									
Bioaccessibility$_{\text{gastric}}$	2.69	6.72	6.40	0.62	7.20	2.67	11.72	2.80	17.22
Bioaccessibility$_{\text{intestinal}}$	0.00	0.52	6.53	0.05	0.42	1.50	13.18	0.70	0.64
Dudhichua									
Bioaccessibility$_{\text{gastric}}$	2.15	4.94	6.37	0.12	2.12	2.45	33.33	1.21	12.09
Bioaccessibility$_{\text{intestinal}}$	0.57	1.98	5.74	0.09	0.12	0.98	20.00	1.34	2.66
NTPC colony									
Bioaccessibility$_{\text{gastric}}$	20.00	9.88	2.84	0.62	7.26	3.13	6.05	2.31	12.25
Bioaccessibility$_{\text{intestinal}}$	0.57	2.47	1.82	0.03	0.26	0.61	4.54	0.38	0.02
Near Vindyachal TPP									
Bioaccessibility$_{\text{gastric}}$	1.14	22.22	2.62	0.43	3.62	42.53	34.79	1.46	21.64
Bioaccessibility$_{\text{intestinal}}$	0.00	6.91	2.40	0.05	0.48	4.24	0.50	0.69	0.94
Khadia									
Bioaccessibility$_{\text{astric}}$	10.59	2.69	2.04	0.42	12.32	0.53	3.66	1.27	18.31
Bioaccessibility$_{\text{intestinal}}$	0.35	0.62	5.01	0.11	0.47	0.12	1.83	0.75	1.78
Amlohri									
Bioaccessibility$_{\text{gastric}}$	1.78	1.41	13.77	0.63	11.01	0.14	7.50	1.59	25.75
Bioaccessibility$_{\text{intestinal}}$	0.00	0.71	17.70	0.03	2.17	0.28	0.00	1.39	3.02
Nigahi									
Bioaccessibility$_{\text{gastric}}$	5.56	1.70	5.24	0.20	5.67	0.73	29.54	0.95	17.71
Bioaccessibility$_{\text{intestinal}}$	0.00	0.00	7.78	0.01	0.50	0.00	0.00	0.36	1.95
Near Shakti Nagar TPP									
Bioaccessibility$_{\text{gastric}}$	2.14	5.06	9.63	0.63	9.67	1.65	21.43	2.29	24.90
Bioaccessibility$_{\text{intestinal}}$	0.00	1.17	5.35	0.01	1.41	1.41	6.00	0.83	1.36
Anpara									
Bioaccessibility$_{\text{gastric}}$	4.99	3.05	4.02	0.48	3.70	2.32	12.08	2.29	9.18
Bioaccessibility$_{\text{intestinal}}$	0.00	0.94	6.10	0.04	0.52	0.40	3.02	2.29	1.55
NCL quarters									
Bioaccessibility$_{\text{gastric}}$	2.87	4.96	14.68	0.61	9.71	0.17	0.00	0.83	15.47
Bioaccessibility$_{\text{intestinal}}$	0.00	0.00	15.60	0.02	0.60	0.33	0.00	0.54	3.68
Bina									
Bioaccessibility$_{\text{gastric}}$	0.82	3.23	7.59	0.12	2.02	4.95	15.00	1.15	11.83
Bioaccessibility$_{\text{intestinal}}$	0.00	0.00	1.01	0.02	0.31	1.24	0.00	0.88	1.91

Khadia (15.59%), the intestinal phase was found to have a higher concentration of Cu. Furthermore, it was observed that the Ni concentration was higher in the intestinal phase than the gastric phase in the sampling locations of the coal mine area, that is, Nigahi (0.28%) and Khadia (0.33%). The results corroborated with a previous study where metal bioaccessibility was higher in intestinal phase (53.2% Zn, 32.4% Ni, 64.4% Cu, 52.8% Cd, 37.2% Pb, and 36.1% As) compared to gastric phase (37.6% Zn, 26.8% Ni, 30.2% Cu, 41.7% Cd, 32.9% Pb, and 18.6% As) (Okorie et al., 2012).

The results indicate that the Singrauli region has a greater amount of Co, Cu, Ni, Pb, and Zn in bioaccessible form. Near Shakti nagar TPP, Near Vindyachal TPP, Jayant, and Khadia were sampling locations where a higher percentage of bioaccessible metal was found for all metals. The statement indicates that the metals in the vicinity of a TPP and coal mine complex are more bioaccessible when compared to the metals found in residential areas. The elevated metal concentrations in TPP and coal mine area, emanating from coal mining activities, increase the likelihood of their bioaccessibility. Moreover, fine particulate matter loaded with heavy metals could be released into the atmosphere which is more bioaccessible in industrial and coal mine areas, while activities like gardening, plantation, and afforestation could act as natural filters in residential areas, thereby decreasing metal bioaccessibility in residential areas. In industrial and coal mining areas, both the gastric and intestinal phases could be significant, but the role of gastric phase could be slightly more because of the abundantly generated fine particulate matter, which when settled, could be ingested by hand-to-mouth contact. It must also be noted that, inhalation pathway has more detrimental effects compared to ingestion pathway for areas in and around TPP and coal mining complex.

Additionally, Ni (42.52%), Pb (34.79%), Co (22.22%), As (20%), and Cu (15%) were found to have higher concentrations in the gastric phase. A prior study showed that bioaccessibility of As, Pb, Cu, Zn, and Co was higher in mining and smelting areas (40%, 73%, 60%, 49%, and 38%, respectively) in Zambia than mining areas alone (12%, 41%, 57%, 45%, and 34%) denoting that the probable sources of metals were mine wastes, tailings, smelter stacks, and chalcanthite (Ettler et al., 2012). The correlation plots indicate that the bioaccessibility of the intestinal phase was positively correlated with the gastric phase of metals like Cu ($r^2 = 0.805$), Ni ($r^2 = 0.92$), Co ($r^2 = 0.93$), As ($r^2 = 0.65$), and Mn ($r^2 = 0.57$) (Figs. 2, 3, and 4). Compared to previous studies, the present study demonstrated lower concentrations of bioaccessible metals. This could arise from changes in industrial practices or regulations resulting in decreased metal contamination or meteorological factors (like wind patterns, precipitation, or temperature), which influence the transport, deposition, and bioaccessibility of metals. Since there have been minimal studies conducted on the assessment of bioaccessibility in coal mine areas globally and in India, it is difficult to compare the findings of the present study with previous reports.

Conclusion

The study measured heavy metal concentrations at different sampling locations in Singrauli, India. The highest concentrations of metals were observed near the TPPs. Compared to other coal mine regions across India, Singrauli had higher concentrations of metals such as Mn, Cr, As, Cu, and Zn in street dust, which exceeded the permissible limit. The street dust in Singrauli was considered moderately polluted based on the I_{geo} and PLI values. The high CF, and EF values suggest that anthropogenic activities, particularly coal mining and combustion-related activities, were the main causes of heavy metal pollution. Human health risk assessment studies revealed that children in the city were more vulnerable to non-carcinogenic health risks from road dust compared to adults, where children were more likely to inhale heavy metals while adults had a significantly higher chance of ingesting. Further, no significant non-carcinogenic risks for both adults and children were observed in the study. The results also suggest that the Singrauli region has a greater amount of Co, Cu, Ni, Pb, and Zn in bioaccessible form, especially in areas near TPPs.

Based on the findings of the study, the anticipated hypotheses have been substantiated. The concentrations of heavy metals in the Singrauli coal mine area were observed to surpass the permissible limits established by regulatory bodies. This excessive contamination can be attributed to extensive coal mining, heavy vehicle movements, the presence of TPPs, and related industrial activities. Furthermore, the study conclusively indicated that heavy metals pose significant health risks to the local population, encompassing both carcinogenic and non-carcinogenic effects. Additionally, this study also revealed noteworthy bioaccessible fractions of heavy metals within the Singrauli mine complex, emphasizing the importance of further research on the bioaccessibility of heavy metals in Indian coal mine areas. These findings underscore the urgency of addressing the health hazards associated with the mining and power generation industries in Singrauli, lending support to the need for comprehensive remediation measures and continued scientific inquiry.

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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