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RESEARCH

Impact of solid waste dumping on soil quality and its potential risk on human health and environment

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Abstract The soil, comprising minerals, organic matter, and living organisms, serves as a critical component of our environment. However, anthropogenic activities, such as uncontrolled sewage disposal and industrial waste, have led to pervasive soil pollution, impacting ecosystems and human health. This comprehensive study scrutinizes the intricate dynamics of soil pollution resulting from open waste dumping, specifically examining its impact on the health of local communities and the environment in Haridwar municipality. In this study, four solid waste dumping sites were meticulously surveyed, with soil samples analyzed for 19 parameters through statistical tools like one-way ANOVA, Kruskal–Wallis tests, soil pollution indices, and potential health risk assessment. The Geo-accumulation Index (Igeo) and contamination factor (CF) followed the heavy metals in the order of Zn > Mn > Fe > Cu in all selected sites. Additionally, a potential health risk assessment considered ingestion, inhalation, and dermal exposure pathways, revealing a high non-carcinogenic risk of metals (Mn > Fe > Zn > Cu) for both children and adults. In the ingestion pathway, the hazard quotient indicated a high risk of metals for both children and adults in the range of 1192.73 to 2066.94 for child and 191.98 to 312.16 for adults. Crucially, the HQ revealed potential health risks, emphasizing the urgency of addressing metal contamination. However, the findings indicate that dumping sites directly or indirectly affects the local people of Haridwar municipality. Therefore, this study provides a baseline framework for minimizing the impact of dumping sites on local population and the environment.

Keywords Solid waste dumping sites · Soil contamination · Human health risk · Heavy metals · Soil pollution indices

Introduction

Soil, a dynamic and intricate natural resource comprising mineral particles, organic matter, water, and air (Yang & Zhang, 2015), plays a vital role in the

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Earth's ecosystem by supporting plant growth, facilitating biological activities, and contributing to nutrient cycling. It serves not only as a food producer but also as a protector of water sources, a habitat for animals, and a source of essential nutrients for plants (Saha et al., 2022b). Unfortunately, this indispensable environmental component faces pollution threats from various anthropogenic activities (Yeboah et al., 2019; Kumar et al., 2019; Bharti et al., 2020).

Soil pollution, primarily induced by uncontrolled sewage disposal, industrial waste, and agricultural runoff, introduces a myriad of pollutants, including heavy metals, metalloids, lanthanides, actinides, and transition metals (Ali et al., 2014; Machender et al., 2011; Saha et al., 2017; Kumar et al., 2021; Kormoker et al., 2021; Saha et al., 2022b). The infiltration of heavy metals into the soil, originating from both natural processes and human activities, poses multifaceted risks due to the complex interplay between soil composition and interactions (Alengebawy et al., 2021).

Anthropogenic sources such as mining, electroplating, industrial and domestic waste, wastewater, and agrochemicals contribute significantly to the intricate mosaic of soil pollution (Bharti et al., 2020; Kamboj et al., 2017; Kumar et al., 2021; Saha et al., 2022b). The accumulation of toxic chemicals in flora disrupts the food chain balance, threatening both human and environmental health (Ali et al., 2014; Tomno et al., 2020). Heavy metals in topsoil and dust can enter the human body, posing risks to biological functions (Akinsanya et al., 2019; Alengebawy et al., 2021; Kormoker et al., 2021; Saha et al., 2022b; Tomno et al., 2020).

The intricate interplay of contaminants in the complex soil environment demands focused attention to comprehend and address soil pollution challenges. People in India are migrating from rural to cities as a result of the country's rapid industrialization and population growth, producing hundreds of tonnes of MSW every day (Gupta et al., 2015). MSW has accumulated in every nook and corner as a result of poor collection and inadequate conveyance (Malav et al., 2020). Unscientific solid waste disposal, especially in cities like Haridwar, emerges as a significant cause of contamination, leading to health hazards and the generation of leachate—a potent pollutant consisting of heavy metals, organic matter, and pathogenic bacteria (Saha et al., 2022b; Bisht et al., 2022). Leachate percolation induces organic, bacteriological, and heavy metal pollution in soils, surface water, and groundwater (phreatic zone) (Javahershenas et al., 2022; Zhao et al., 2021). Since 2002, despite the creation of many engineered landfills in India, including Haridwar, a notable number of these functional sites lack proper impact assessments (Swati et al., 2018).

Haridwar, a city in Uttarakhand, faces unique challenges due to the convergence of religious practices, tourism, and industrialization. Solid waste generation surges during festivals, fairs, and in old industrial areas, including automobile and pharmaceutical industries (Kamboj & Kamboj, 2020). Amidst this complex tapestry, the current research seeks to address a critical gap by systematically monitoring and creating a comprehensive database for the quality of soil in and around dumping sites. The pressing need for such an initiative is underscored by the lack of meaningful data on soil pollution in Haridwar, hindering systematic comparisons of current pollution levels with historical data. While extensive studies have been conducted in Haridwar on soil and groundwater contamination by researchers like Bhutiani et al. (2017), Kamboj and Kamboj (2019), Kumar et al. (2019), Bharti et al. (2022), and Bahukhandi et al. (2023), this study focused on solid waste contamination which marks the first comprehensive exploration in this domain. By methodically monitoring the soil quality in and near dumping sites, our research fills a vital gap and attempts to build an extensive database. Since there is a dearth of useful information about soil pollution in Haridwar that prevents systematic comparisons, this study offers a ground-breaking investigation into solid waste contamination and offers crucial insights for environmental knowledge and management.

The research significance lies in not only identifying challenges posed by soil pollution but also in laying the groundwork for safeguarding the health and well-being of the local population and preserving the environment in this spiritually significant city. This work marks a crucial step toward addressing the environmental challenges faced by Haridwar, making it a valuable contribution to the field of soil pollution research.

Material and methods

Study area

Haridwar is one of the most sacred cities is situated in the newly created state of Uttarakhand, with

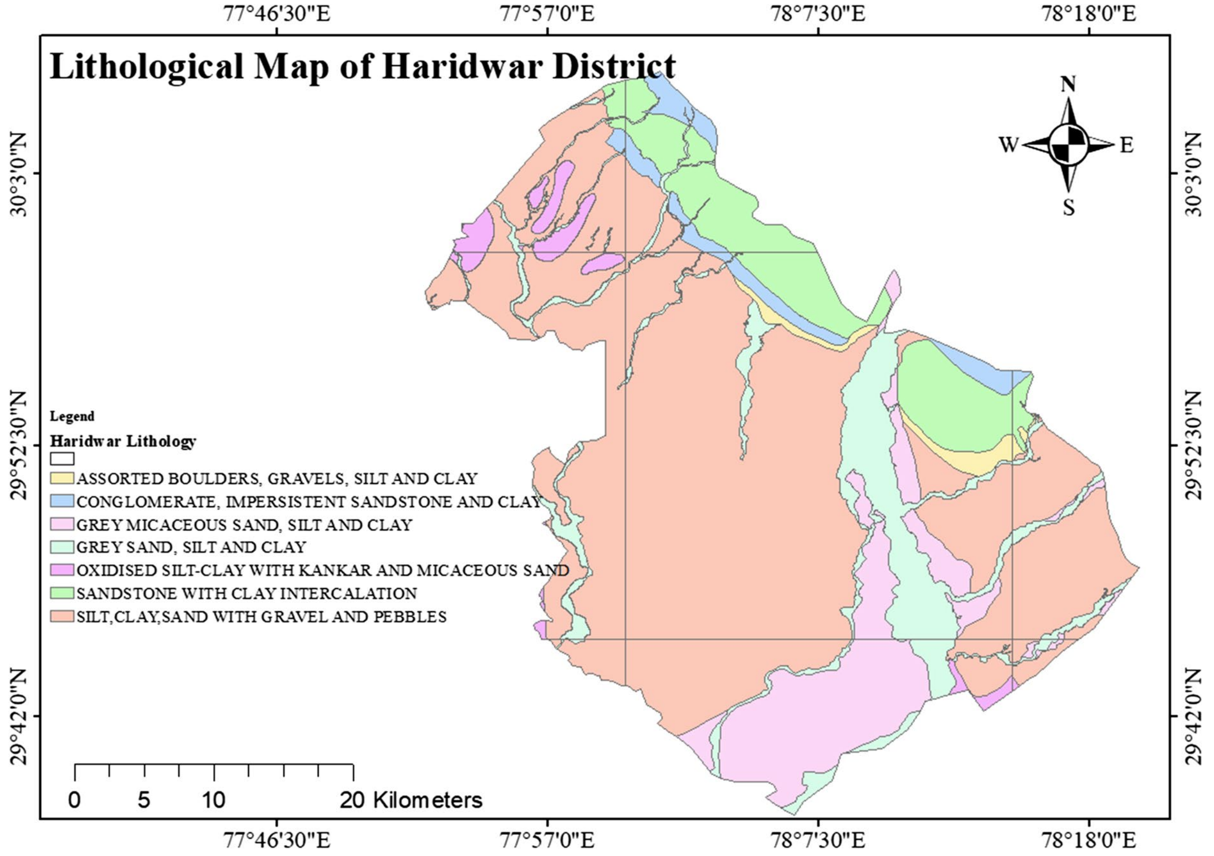


Fig. 1 Lithological Map of Haridwar District

geographical coordinates ranging from 29.9457°N latitudes to 78.1642°E longitudes. The study area experiences a subtropical climate characterized by three distinct seasons: Winter, Summer, and Monsoon. During the study, the highest recorded temperature in summer was 40 ± 2.08 °C, and the lowest in winter was 4.0 ± 1.08 °C. The average annual rainfall was 960 mm, mainly occurring during the monsoon season (Kamboj & Kamboj, 2019; Kamboj et al., 2022). In terms of geological structure, Haridwar is divided into three parts namely the lower Shivalik Himalayan, the upper piedmont area (Bhabhar region), and lower piedmont area (Tarai region) (Bahukhandi et al., 2023; Bisht et al., 2022). The lithological structure comprises assorted boulders, gravels, pebbles, sandstone, sand, silt, and clay, with the predominant part showing a lithological structure of silt, clay, sand with gravels, and pebbles (CGWB, 2016). The lithological map of the Haridwar district is depicted in Fig. 1. The Haridwar district covers an area of 2360 km^2 and has a population of 2.29 lakhs as per the 2011 census. The city attracts millions of tourists monthly, particularly during festivals like Savan and Kumbh.

Sampling location, sample collection, and preparation

The Haridwar municipality, with 60 wards, employs a door-to-door collection method for solid waste. Collected waste is transferred to larger bin setups and then to the municipality's four dumping sites, i.e., S1 to S4 illustrated in Table 1, Fig. 2. The four sampling sites are selected in S1, S2, and S3 which are collection points and small dumping sites, while S4 is the largest and main dumping site. All dumping sites contain plastic, kitchen waste, industrial and agricultural effluent, textile, paper, and other waste.

Table 1 Geocoordinates of selected sampling location in adjacent area of solid waste dumping sites

Municipal solid waste dumping sites	Sampling code	Geo-coordinates	Area of solid waste dumping sites in acres	Samples depth (cm)
Kadach Mohalla Near Taxplas Factory	S1	29.933273°, 78.113656°	1.1	0–30
Old Industrial Area	S2	29.943518°, 78.142622°	4.73	0–30
Amla Bhaag Near Gurukula Kangri University	S3	29.916871°, 78.128114°	4.32	0–30
Sarai	S4	29.899493°, 78.090855° and 29.895569°, 78.091376°	45.90	0–30

Sample collection and preparation

In the present study, soil samples were collected from the four solid waste dumping sites declared by Haridwar municipality during 2020–2021. Three of the selected sites are collection points where waste is collected from surrounding areas, stored for a few days (10–15), and then taken to the fourth site, i.e., the landfill or main dumping site. The 4th landfill site is the permanent landfill of the Haridwar Municipality area where the waste from all the collection sites is dumped. At each sampling site, the locations were randomly selected by using a global positioning system (GPS) and 10 m × 10 m sampling plots were laid down at five sampling points in each dumpsite. Soil samples were collected over 0–30 cm depth from the surface with the help of an auger and made into composite soil sample. Soil samples were collected from the selected dumping sites at a frequency of ($4 \times 3 = 12$) through a composite method. These collected soil samples were brought to the laboratory in sterilized polythene bags and further stored at a temperature of 4 °C until further analysis. The soil physico-chemical parameters such as pH, soil texture, bulk density (BD), porosity, electrical conductivity (EC), moisture content (MC), organic carbon (OC) and organic matter (OM), Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), Sulphur (S), Boron (B), and four heavy metals namely Iron (Fe), Copper (Cu), Zinc (Zn), and Manganese (Mn) were calculated. The rationale behind this limited selection of heavy metals is based on the outcomes of the atomic absorption spectroscopy (AAS) analysis, where the concentrations of most other metals were below the detection limit. Consequently, these four metals were chosen for their detectability, allowing for a more precise and reliable assessment of soil pollution in the solid waste dumping sites in Haridwar. Physico-chemical and heavy metal analysis of collected soil samples was done by following Trivedy and Goel (1986) and Behera (2006) the methods and protocols.

Analysis of soil samples

The physico-chemical properties of the soil were evaluated to get an idea of the nature and accumulation of heavy metals in the soil as per Trivedy and Goel (1986) (and Behera (2006). The EC of the soil samples was determined using an EC meter (Model No. ESICO-1601), and the pH of the collected samples was also measured using a digital pH meter (Model No. ESICO-1012) in a slurry of distilled water at a ratio of 1:1 (w/v). Soil texture and OC are the most important parameters for evaluating the heavy metal status in the soil, which were determined using the Bouyoucos hydrometer method and the Walkley–Black method, respectively. The N, P, and K were determined using the spectrophotometer method (Model No.: Carry 60 UV–VIS, Agilent technologies) and the Flame photometer (Model No. ESICO-1382) was used respectively.

To analyze the heavy metals in the soil samples, the samples were treated with a triacid mixture (1:1:5) of HNO_3, H_2SO_4, and $HClO_4$. A certain amount of the soil sample (1.0 g) was then added to 15 mL of the triacid mixture, and wet digestion was performed at 80 °C for 30 min. The solution was diluted to 100 mL with deionized water after filtering through Whatman filter paper No. 41. The concentrations of heavy metals were determined using an AAS (Model No. AAS4129, ECIL, India). The detection limit of AAS using air acetylene flame for Fe, Zn, Cu, and Mn is 0.02, 0.005, and 0.01 mg/L, respectively. For reliability and accuracy of data, soil sample

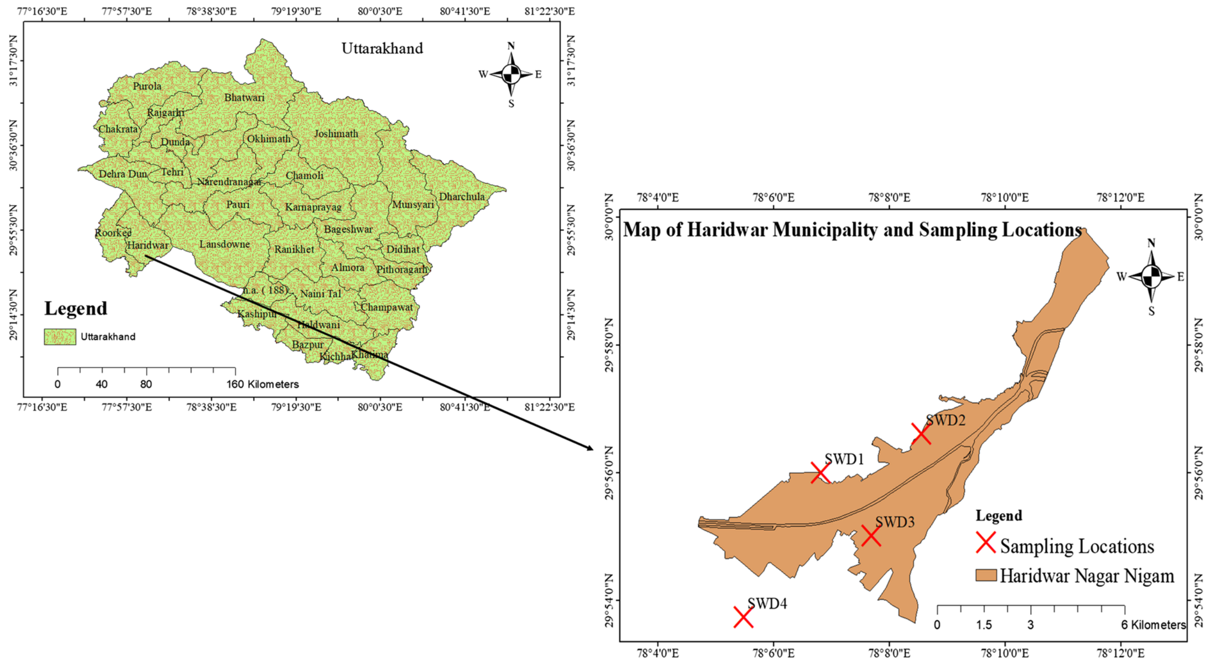


Fig. 2 Sampling location of solid waste dumping sites in Haridwar Municipality

analysis was done in replicates, and instruments were controlled through standard and blank samples.

Soil pollution indices

In the present study, pollution indices, namely the geo-accumulation Index (Igeo), contamination factor (CF), enrichment factor (EF), degree of contamination (CD), pollution load index (PLI), potential ecological risk index (PERI), and ecological risk index factor (ERI), were used to assess heavy metal pollution in the soil. Table 2 shows the calculation formulas, values, and status of the selected indices. The Igeo assessed heavy metal pollution in relation to the world shale concentrations /background/reference concentrations in a specific area. In the present study, the background/reference value of heavy metals namely Fe, Cu, Zn, and Mn is 4.32, 1.34, 0.21, and 0.70 taken from the undisturbed area of the Haridwar region, i.e., the Forest area (Bharti et al., 2020, 2022). The CF indicates the contamination level based on the background/reference value (Bhutiani et al., 2017; Saha et al., 2022a). The EF is applied to assess the soil pollution (naturally and anthropogenically) in relation to the background heavy metal concentration. In the present study, Fe was used as a background metal, due to its relatively high concentration in nature (Sappa et al., 2020). The CD expresses the overall contamination based on the sum of contamination factors at sites, while the PLI provides complete information about heavy metal toxicity (Yang et al., 2011). Additionally, the PERI and ERIF were measured to assess the ecological risk degree based on the Tr and contamination level of heavy metal in soil samples. In the present study, the Tr for Fe, Cu, Zn, and Mn is 1, 5, 1, and 1, respectively (Alengebawy et al., 2021; Saha et al., 2022b).

Potential health risk assessment

The health risk assessment model was applied to assess the health effects of heavy metals exposure through inhalation, dermal, and ingestion. Utilizing epidemiological data and findings from animal studies, indicators of heavy metals in the soil have been categorized into non-carcinogenic and carcinogenic entities. In this study, four elements, i.e., Fe, Cu, Zn, and Mn, were used to evaluate the health risk assessment in the context of non-carcinogenic risk to children and adults in the selected

Table 2 Description of soil pollution indices

S. No	Indices name	Formula	Formula abbreviation	Value	Status	References
1.	**Geo-accumulation Index (Igeo)**	$Igeo = \log_2[\frac{C_n}{1.5\times B_n}]$	C_n = Concentration of heavy metals B_n = Background/reference value of Heavy Metals	$Igeo \leq 0$	Uncontaminated	Hakanson, 1980; Deely & Ferguson, 1994; Manju & Ilavarasan, 2016; Bhutaini et al., 2017; Saha et al., 2022a, 2022b
				$0 < Igeo < 1$	Uncontaminated to moderately contaminated	
				$1 < Igeo < 2$	Moderately Contaminated	
				$2 < Igeo < 3$	Moderately to heavily contaminated	
				$3 < Igeo < 4$	Heavily contaminated	
				$4 < Igeo < 5$	Heavily to extremely contaminated	
				$Igeo \geq 5$	Extremely contaminated	
2.	**Contamination Factor (Cf)**	$Cf = \frac{C_n}{B_n}$	C_n = Concentration of heavy metals B_n = Background/reference value of Heavy Metals	$Cf < 1$	Low contamination factor	
				$1 < Cf < 3$	Moderate Contamination factor	
				$3 < Cf < 6$	Considerable contamination factor	
				$Cf \geq 6$	Very high contamination factor	
3.	**Enrichment Factor (EF)**	$EF = \frac{\left(\frac{C_{nx}}{C_{Fe\ x}}\right)}{\left(\frac{C_{n\ b}}{C_{Fe\ b}}\right)}$	Cn x = Concentration of heavy metals in soil sample Cn b = Concentration of heavy metals in background/reference value $C_{Fe\ x}$ = Concentration of Iron in soil sample $C_{Fe\ b}$ = Concentration of Iron in background/reference value; B_n = Background/reference value of Heavy Metals	$EF < 2$	Deficiency to minimal enrichment	
				$2 < EF < 5$	Moderate enrichment	
				$5 < EF < 20$	Significant enrichment	
				$20 < EF < 40$	Very High enrichment	
				$EF \geq 40$	Extremely High enrichment	

Table 2 (continued)

S. No	Indices name	Formula	Formula abbreviation	Value	Status	References
4.	**Degree of Contamination (Cd)**	$Cd = \sum_{i=0}^{n} C_f$	Cf = Contamination factor	Cd < 8	Low contamination	
				8 < Cd < 16	Moderate contamination	
				16 < Cd < 32	Considerable contamination	
				Cd ≥ 32	Very High degree of contamination	
5.	**Pollution Load Index (PLI)**	$PLI = (Cf1 \times Cf2 \times Cf3 \times \ldots \ldots .. \times Cfn)^{1/n}$	Cf = Contamination factor	PLI < 1	No Pollution	
				1 < PLI < 2	Moderate pollution	
				2 < PLI < 3	Heavy Pollution	
				PLI ≥ 3	Extremely Heavy pollution	
6.	**Potential Ecological Risk Index (PERI)**	$E_r = T_r \times C_f$	Er = potential ecological risk index Tr = Toxic response factor of Metals Cf = Contamination factor	Er < 40	Low risk for environment	
				40 < Er < 80	Moderate Risk	
				80 < Er < 160	Considerable risk	
				160 < Er < 320	High Risk	
				ER ≥ 320	Very High Risk for the Environment	
7.	**Ecological Risk Index Factor (ERIF)**	$\mathrm{ERI} = \sum E_r$	Er = potential ecological risk index	ERI < 150	Low Risk	
				150 < ERI < 300	Moderate Risk	
				300 < ERI < 600	Considerable Risk	
				ERI ≥ 600	High Risk	

Background value (Bn) of Fe, Cu, Zn, and Mn is 4.32, 1.34, 0.21, and 0.70 respectively (Bharti et al., 2020, 2022). All values in mg/kg study area. Fe and Mn are indeed natural components of soil and are essential nutrients for plants and humans. While they are not typically considered contaminants, elevated concentrations beyond normal levels can have adverse effects. Cu and Zn, although essential for various biological processes, can become environmental contaminants when present in excess due to anthropogenic activities such as industrial discharges or agricultural runoff. Excessive concentrations of certain metals, even essential micronutrients like iron (Fe) and manganese (Mn), can lead to health issues in humans and adverse effects on plants and other biodiversity. The process of Health risk assessment and data analysis is shown in Fig. 3. The status of the HI showed $HI \leq 1$ (no noncarcinogenic risk) and $HI \geq 1$ (high noncarcinogenic risk) respectively.

Statistical analysis and software

The mean, standard deviation, Kruskal–Wallis (K-W test), kurtosis, and skewness test were applied for all the selected 19 parameters. The K-W test was applied to analyze and test the significant difference among the selected sites (S1 to S4). While the Kurtosis test was applied to analyze whether the data distribution is heavily left tailed or right tailed. The kurtosis results show leptokurtic, platykurtic, and mesokurtic distribution based on positive, negative, and near zero value respectively. However, skewness was applied to assess the asymmetry and symmetry of data distribution. The value from -0.5 to 0.5 shows a symmetrical distribution.

Pearson's correlation coefficient analysis and principal component analysis

The Pearson's correlation coefficient analysis was employed to assess the relationship among the soil parameters at the selected sampling sites. The obtained values lie between -1 (negative) and 1 (positive) correlation. However, the principal component analysis (PCA) tool is used to reduce the bulky data into simple data with the minutest error. It is also used to control the factor loading variables in the observed variables (Bahukhandi et al., 2023; Kamboj et al., 2022). Based on cumulative percentage and eigenvalue, the tool divides the data into factors loading, i.e., PC1, PC2, and PC3. The factors loadings with eigenvalue > 1 are selected. This tool, based of obtained value, separates the variables and demonstrates the higher substantial variables that alter the soil quality. Hence, PCA was applied to assess a complete image of soil quality parameters in the selected sites. This was done using the ORIGIN Pro software (Student version) for the study.

Software used

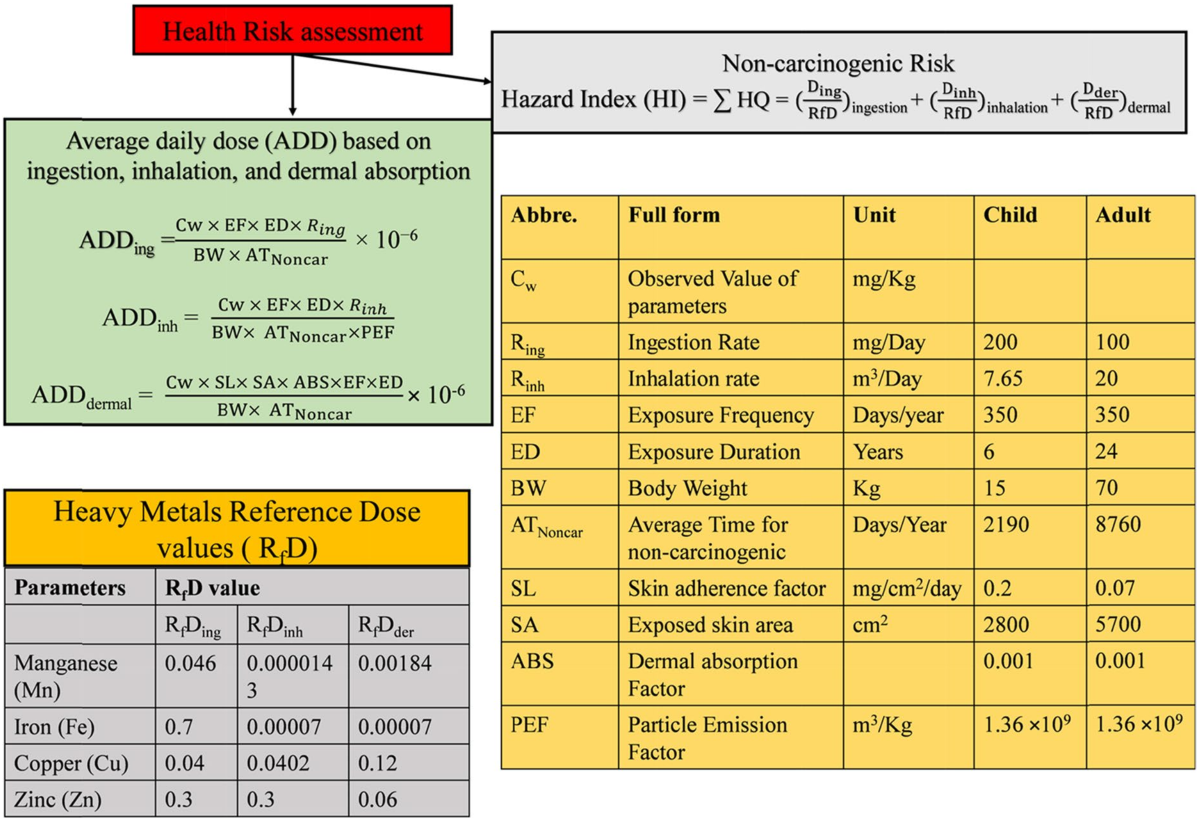
The data analysis was done with the help of Microsoft Excel 2021 (Microsoft Crop.) and Origin Pro (Student version) was used for Pearson's correlation coefficient and PCA.

Result and discussion

Concentration of heavy metals and physico-chemical parameters

The contamination of heavy metals and changing physico-chemical parameters of soil have become a matter of great concern. Heavy metals are found in the soil due to both natural and manmade reasons. Geological processes such as the breakdown of parent rock, the formation of sedimentary rock, and volcanic eruptions contribute to natural causes of soil formation. Anthropogenic factors, on the other hand, encompass solid waste dumping, wastewater irrigation, agrochemical fertilizers, pesticides, combustion of fossil fuels, sewage sludge, and direct soil contamination (Bharti et al., 2022; Saha et al., 2022b).

The descriptive statistics data for the physico-chemical and heavy metal concentrations at the selected four sites are presented in Table 3 and Fig. 4, respectively. Additionally, inferential statistics data is provided in Tables S1 to S4 (Supplementary Tables). The first step for analysis is an assessment of soil texture because it represents the type of soil. Soil texture revealed that concentration of sand (%), silt (%), and clay (%) was found in the range of 49.79 ± 1.98 (S3) to 53.94 ± 1.37 (S1), 40.44 ± 2.41 (S4) to 44.01 ± 1.86 (S3), and 3.76 ± 1.90 (S1) to 6.57 ± 1.61 (S4) respectively. Based on the texture results, it was found that all dumping sites contain sandy loam soil. The pH range of sandy loam soil usually lies from 6.2 to 7.9 and it is very fertile, deep, and moist in nature. But in the rainy season, the big problem of sandy loam



Non-carcinogenic Risk

$$\text{Hazard Index (HI)} = \sum HQ = \left(\frac{D_{ing}}{RfD}\right)_{ingestion} + \left(\frac{D_{inh}}{RfD}\right)_{inhalation} + \left(\frac{D_{der}}{RfD}\right)_{dermal}$$

Average daily dose (ADD) based on ingestion, inhalation, and dermal absorption

$$ADD_{ing} = \frac{Cw \times EF \times ED \times R_{ing}}{BW \times AT_{Noncar}} \times 10^{-6}$$

$$ADD_{inh} = \frac{Cw \times EF \times ED \times R_{inh}}{BW \times AT_{Noncar} \times PEF}$$

$$ADD_{dermal} = \frac{Cw \times SL \times SA \times ABS \times EF \times ED}{BW \times AT_{Noncar}} \times 10^{-6}$$

Heavy Metals Reference Dose values (R_fD)

Parameters	R_fD value		
	R_fD_{ing}	R_fD_{inh}	R_fD_{der}
Manganese (Mn)	0.046	0.000014 3	0.00184
Iron (Fe)	0.7	0.00007	0.00007
Copper (Cu)	0.04	0.0402	0.12
Zinc (Zn)	0.3	0.3	0.06

Abbre.	Full form	Unit	Child	Adult
C_w	Observed Value of parameters	mg/Kg		
R_{ing}	Ingestion Rate	mg/Day	200	100
R_{inh}	Inhalation rate	m^3/Day	7.65	20
EF	Exposure Frequency	Days/year	350	350
ED	Exposure Duration	Years	6	24
BW	Body Weight	Kg	15	70
AT_{Noncar}	Average Time for non-carcinogenic	Days/Year	2190	8760
SL	Skin adherence factor	mg/cm^2/day	0.2	0.07
SA	Exposed skin area	cm^2	2800	5700
ABS	Dermal absorption Factor		0.001	0.001
PEF	Particle Emission Factor	m^3/Kg	1.36×10^9	1.36×10^9

Fig. 3 Procedure and calculation of potential health risk assessment

soil is nutrient leaching that directly contaminates the soil and groundwater aquifers (Jaskulska et al., 2020; Javeed et al., 2019).

Nowadays, heavy metals contamination is responsible for soil pollution throughout the world. The concentration of Fe (mg/kg) in soil samples at selected sites S1, S2, S3, and S4 was 13.43 ± 1.05, 15.91 ± 1.52, 16.46 ± 0.70, and 18.22 ± 0.90, respectively. The average value of Cu (mg/kg) in sites S1, S2, S3, and S4 was 0.19 ± 0.04, 1.08 ± 0.10, 0.24 ± 0.01, and 0.55 ± 0.03 respectively. The concentration of Zn (mg/kg) in sampling sites S1 (2.93 ± 0.71), S2 (2.55 ± 0.21), S3 (1.49 ± 0.06), and S4 (3.28 ± 0.16) respectively. Furthermore, the concentration of Mn (mg/kg) was found to be 4.89 ± 0.35 in S1, 2.07 ± 0.25 in S2, 2.04 ± 0.09 in S3, and 1.46 ± 0.07 in S4, respectively. The findings on heavy metals unequivocally indicate elevated contamination levels in the dumping sites. This heightened concentration in the soil is noteworthy as it directly impacts groundwater aquifers through the leaching process, as observed in the study by Bisht et al. (2022). In the present study, the heavy metal concentration is found higher than the previous results of research conducted by Bharti et al. (2022). The reason behind the higher concentration of these metals in dumping sites may be the anthropogenic waste that is varied from urbanization, the commercial, industrial, and agricultural sector (Bharti et al., 2022; Ekere et al., 2020; Saha et al., 2022b). The elevated concentration of Zn results from Zn-coated sheets used in dry cells, e-waste, roofing materials, fertilizers, wood preservatives, and the incineration of dry cells and electronic waste (Regmi et al., 2022; Twumasi et al., 2016). These diverse sources contribute to the accumulation of Zn in the soil, highlighting the multifaceted nature of its presence in the environment. The presence of zinc in the studied area can be linked to specific industries and activities. Neel Metal Products Ltd., U.S. Metal Products, and Amco Industries, situated in proximity to sites 1 and 2, are probable contributors due to their engagement in smelting processes. Conversely,

Table 3 Descriptive analysis data of physico-chemical parameters of soil samples in selected sampling location (Mean ± S.D.)

Parameters		Unit	Sampling locations				K-W test	Kurtosis	Skewness
			Kadach Mohalla (S1)	Old Industrial Area (S2)	Aamla Bagh (S3)	Sarai (S4)			
pH			7.48 ± 0.31^{a}	7.56 ± 0.32^{a}	7.76 ± 0.33^{a}	7.39 ± 0.15^{a}	$p > 0.05$	0.95	0.86
MC		(%)	21.83 ± 0.82^{a}	19.31 ± 0.99^{b}	19.48 ± 0.98^{b}	18.01 ± 0.67^{b}	$p < 0.05$	1.96	0.95
BD		**(g/cm3)**	1.27 ± 0.09^{a}	1.14 ± 0.03^{a}	1.27 ± 0.12^{a}	1.28 ± 0.31^{a}	$p > 0.05$	3.93	−1.98
Porosity		(%)	52.23 ± 3.21^{a}	57.06 ± 1.13^{a}	52.20 ± 4.40^{a}	51.89 ± 11.71^{a}	$p > 0.05$	3.92	1.98
EC		**(µS/cm)**	312.49 ± 43.97^{a}	270.78 ± 27.58^{a}	339.59 ± 23.86^{a}	286.74 ± 15.38^{a}	$p > 0.05$	−1.49	0.41
OC		(%)	1.12 ± 0.20^{a}	0.70 ± 0.09^{a}	0.84 ± 0.10^{a}	0.90 ± 0.13^{a}	$p > 0.05$	1.20	0.64
OM		(%)	1.94 ± 0.34^{a}	1.20 ± 0.16^{b}	1.45 ± 0.17^{b}	1.55 ± 0.22^{b}	$p < 0.05$	1.19	0.62
N		**(mg/kg)**	132.45 ± 22.95^{a}	121.51 ± 18.69^{a}	110.37 ± 26.44^{a}	173.15 ± 59.80^{a}	$p > 0.05$	2.05	1.38
P		**(mg/kg)**	5.74 ± 0.37^{a}	5.10 ± 0.67^{a}	5.83 ± 0.25^{a}	6.66 ± 0.76^{a}	$p > 0.05$	1.51	0.44
K		**(mg/kg)**	64.34 ± 1.94^{a}	81.25 ± 9.41^{b}	87.35 ± 6.61^{b}	80.90 ± 6.29^{b}	$p < 0.05$	2.70	−1.44
Ca		(%)	4.61 ± 0.73^{a}	6.53 ± 1.03^{a}	6.08 ± 1.21^{a}	6.68 ± 1.54^{a}	$p > 0.05$	2.40	−1.59
Mg		(%)	2.79 ± 0.62^{a}	3.56 ± 0.63^{a}	2.60 ± 0.41^{a}	2.64 ± 0.54^{a}	$p > 0.05$	3.25	1.80
S		**(mg/kg)**	14.07 ± 1.45^{a}	22.50 ± 4.04^{b}	12.58 ± 2.24^{a}	13.73 ± 3.05^{a}	$p < 0.05$	3.64	1.88
B		**(mg/kg)**	0.51 ± 0.13^{a}	0.90 ± 0.08^{a}	0.78 ± 0.03^{a}	0.71 ± 0.13^{a}	$p < 0.05$	0.99	−0.75
Fe		**(mg/kg)**	13.43 ± 1.05^{a}	15.91 ± 1.52^{b}	16.46 ± 0.70^{b}	18.22 ± 0.90^{b}	$p < 0.05$	1.29	−0.53
Cu		**(mg/kg)**	0.19 ± 0.04^{a}	1.08 ± 0.10^{a}	0.24 ± 0.01^{a}	0.55 ± 0.03^{b}	$p < 0.05$	0.67	1.23
Zn		**(mg/kg)**	2.93 ± 0.71^{a}	2.55 ± 0.21^{a}	1.49 ± 0.06^{b}	3.28 ± 0.16^{a}	$p < 0.05$	1.40	−1.18
Mn		**(mg/kg)**	4.89 ± 0.35^{a}	2.07 ± 0.25^{b}	2.04 ± 0.09^{b}	1.46 ± 0.07^{c}	$p < 0.05$	3.43	1.79
Soil Texture	Sand	(%)	53.94 ± 1.37^{a}	53.61 ± 2.38^{a}	49.79 ± 1.98^{a}	52.99 ± 2.28^{a}	$p > 0.05$	3.11	−1.75
	Silt	(%)	42.09 ± 1.53^{a}	42.34 ± 1.93^{a}	44.01 ± 1.86^{a}	40.44 ± 2.41^{a}	$p > 0.05$	1.35	0.02
	Clay	(%)	3.76 ± 1.90^{a}	4.05 ± 1.69^{a}	6.20 ± 1.63^{a}	6.57 ± 1.61^{a}	$p > 0.05$	-5.47	0.02

The same letters (a–c) indicate no significant difference between the sampling location values at $p < 0.05$

MC moisture content, *BD* bulk density, *EC* electrical conductivity, *OC* organic carbon, *OM* organic matter, *N* nitrogen, *P* phosphorus, *K* potassium, *Ca* calcium, *Mg* magnesium, *S* sulphur, *B* boron, *Fe* iron, *Cu* copper, *Zn* zinc, *Mn* manganese, *S.D.* standard deviation, % percentage, *mg* milligram, *Kg* kilogram

sources like wood preservatives and fertilizers may be linked to agricultural practices and carpentry work near sites 3 and 4. This identification of industry-specific and localized sources enriches our comprehension of zinc contamination origins in the study area.

At the same time, the evaluation of physico-chemical parameter and soil texture was done to get an idea about the accumulation of heavy metals. The pH of the sites ranged from 7.39 ± 0.15 (S4) to 7.76 ± 0.33 (S3). According to WHO, the soil pH which ranges from 6.5 to 6.8 is recommended for agricultural purposes. In the present study, pH shows the neutral to slightly alkaline nature of soils of solid waste dumping sites. It has been reported that the pH of dumpsite soil is found alkaline in nature (Obasi et al., 2012; Getachew & Habtamu, 2015; Ekere et al., 2020).

Other parameters like MC, BD, porosity, EC, OC, N, P, K, Ca, Mg, S, and B were also analyzed. The MC (%) was found in range the of 18.01 ± 0.67 (S4) to 21.83 ± 0.82 (S1), BD (g/cm^3) was in the range of 1.14 ± 0.03 (S2) to 1.28 ± 0.31 (S4), whereas porosity (%) was found in the range of 51.89 ± 11.71 to 57.06 ± 1.13 respectively. Higher MC in soil may be a result of biodegradable waste that contains high moisture (Regmi et al., 2022). The concentration of EC (µS/cm), OC (%), and OM (%) was found in the range of 270.78 ± 27.58 (S2) to 339.59 ± 23.86 (S3), 0.70 ± 0.09 (S2) to 1.12 ± 0.20 (S1), and 1.20 ± 0.16 (S2) to 1.94 ± 0.34 (S1) respectively. In dumping sites, assorted waste from industry, agricultural, and urbanization sector increase the salt and ionic concentration that

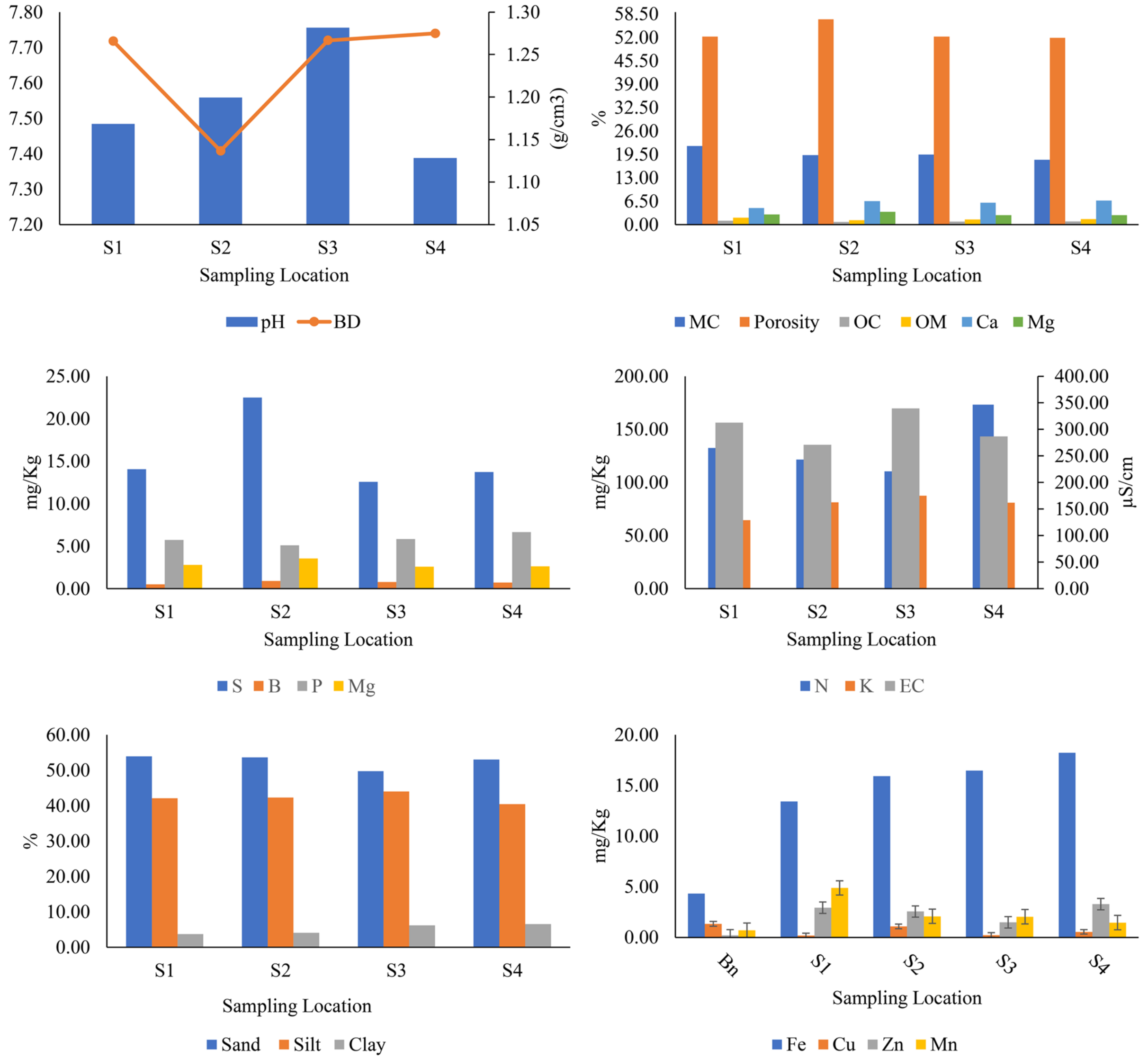


Fig. 4 Variation in physico-chemical and heavy metal characteristics of soil in selected sampling location

increase the EC in dumping sites soil. In addition, a higher value of EC directly or indirectly increases the salt concentration of groundwater aquifers through leachate (Bisht et al., 2022; Pillai et al., 2014). However, the nutrient parameters namely N (mg/kg), P (mg/kg), K (mg/kg), Ca (%), Mg (%), S (mg/kg), and B (mg/kg) were in range the of 110.37 ± 26.44 (S3) to 173.15 ± 59.80 (S4), 5.10 ± 0.67 (S2) to 6.66 ± 0.76 (S4), 64.34 ± 1.94 (S1) to 87.35 ± 6.61 (S3), 4.61 ± 0.73 (S1) to 6.68 ± 1.54 (S4), 2.60 ± 0.41 (S3) to 3.56 ± 0.63 (S2), 12.58 ± 2.24 (S3) to 22.50 ± 4.04 (S2), and 0.51 ± 0.13 (S1) to 0.90 ± 0.08 (S2) respectively. The higher concentration of N, P, K, and Ca in soil samples of dumping sites may be due to the disposal of the mixed waste composition of the industrial, vehicular, commercial, rural, and agricultural sectors. In this study, the N and P was found in the higher amount at S4 that indicates the N related waste was dumped in this site for a longest time and P content was found higher amount due to the leachate transformation and higher household organic waste disposal (Vaverková et al., 2018; Sheijany et al., 2020; Shah et al., 2020; Regmi et al., 2022).

Table 4 Results of soil indices measured at designated sites

S. No	Indices	Parameters	Indices value				Indices status			
			Sampling sites				Sampling sites			
			S1	S2	S3	S4	S1	S2	S3	S4
1	Geo-accumulation Index (Igeo)	Fe	1.05	1.30	1.34	1.49	Moderately contaminated	Moderately contaminated	Moderately contaminated	Moderately contaminated
		Cu	-3.41	-0.89	-3.09	-1.87	Uncontaminated	Uncontaminated	Uncontaminated	Uncontaminated
		Zn	3.24	3.04	2.26	3.40	Heavily contaminated	Heavily contaminated	Moderately to heavily contaminated	Heavily contaminated
		Mn	2.23	0.99	0.97	0.48	Moderately to heavily contaminated	Uncontaminated to moderately contaminated	Uncontaminated to moderately contaminated	Uncontaminated to moderately contaminated
2	Contamination Factor (Cf)	Fe	3.11	3.68	3.81	4.22	Considerable contamination factor	Considerable contamination factor	Considerable contamination factor	Considerable contamination factor
		Cu	0.14	0.81	0.18	0.41	Low contamination factor	Low contamination factor	Low contamination factor	Low contamination factor
		Zn	14.12	12.31	7.18	15.81	Very high contamination factor	Very high contamination factor	Very high contamination factor	Very high contamination factor
		Mn	7.03	2.98	2.93	2.10	Very high contamination factor	Moderate contamination factor	Moderate contamination factor	Moderate contamination factor
3	Enrichment Factor (EF)	Fe	1.00	1.00	1.00	1.00	Deficiency to minimal enrichment	Deficiency to minimal enrichment	Deficiency to minimal enrichment	Deficiency to minimal enrichment
		Cu	0.05	0.22	0.05	0.10	deficiency to minimal enrichment	deficiency to minimal enrichment	deficiency to minimal enrichment	deficiency to minimal enrichment
		Zn	4.54	3.34	1.88	3.75	Moderate enrichment	Moderate enrichment	Deficiency to minimal enrichment	Moderate enrichment
		Mn	2.26	0.81	0.77	0.50	Moderate enrichment	Deficiency to minimal enrichment	Deficiency to minimal enrichment	Deficiency to minimal enrichment
4	Degree of Contamination (Cd)		24.40	19.78	14.09	22.53	Considerable contamination	Considerable contamination	Moderate contamination	Considerable contamination
5	Pollution Load Index (PLI)		2.57	3.23	1.94	2.75	High pollution level	High pollution level	Moderate pollution	High pollution Level

Table 4 (continued)

S. No	Indices	Parameters	Indices value				Indices status			
			Sampling sites				Sampling sites			
			S1	S2	S3	S4	S1	S2	S3	S4
6	Potential Ecological Risk Index (PERI)	Fe	3.11	3.68	3.81	4.22	Low risk for environment	Low risk for environment	Low risk for environment	Low risk for environment
		Cu	0.70	4.04	0.88	2.05	Low risk for environment	Low risk for environment	Low risk for environment	Low risk for environment
		Zn	14.12	12.31	7.18	15.81	Low risk for environment	Low risk for environment	Low risk for environment	Low risk for environment
		Mn	7.03	2.98	2.93	2.10	Low risk for environment	Low risk for environment	Low risk for environment	Low risk for environment
7	Ecological Risk Index (ERI)		24.96	23.01	14.80	24.16	Low risk	Low risk	Low risk	Low risk

Fe Iron, *Cu* Copper, *Zn* Zinc, *Mn* Manganese

Soil pollution indices results

In the present study, based on the heavy metal concentration, soil pollution indices such as the Geo-accumulation index (Igeo), Contamination factor (Cf), Enrichment factor (EF), Degree of contamination (CD), Pollution level index (PLI), Potential ecological risk index (PERI), and Ecological risk index (ERI) were assessed, and results are depicted in Table 4 and Fig. 5. The Igeo for Fe in selected sites ranges from 1.05 (S1) to 1.49 (S4) and shows moderate contamination. In case of Cu, Igeo values ranging from − 3.41 (S1) to − 0.89 (S2) show uncontaminated condition. While Igeo value of Zn ranges from 2.26 (S3) to 3.40 (S4) showing heavily contamination. Although, Igeo value of Mn was observed in the ranges of 0.48 (S4) to 2.23 (S1) respectively. The determination of contamination factor revealed the contribution status of metal contamination in soil. Fe shows higher contamination in S4 (4.22) and lower in S1 (3.11), Cu shows a higher value in S2 (0.81) and lower in S1 (0.14), Zn was found higher in S4 (15.81) and lower in S3 (7.18), and Mn was found lower in S4 (2.10) and higher in S1 (7.03). The overall Igeo and CF followed the heavy metals in order of Zn > Mn > Fe > Cu in all selected dumping sites. The obtained results clearly indicate Zn is the main contamination element in dumping sites. Additionally, EF reflects the sources of metal contamination in the soil based on the background value. In the present study, the Fe was selected for background value. Metals such as Cu, Zn, and Mn show the range from 0.05 to 0.22, 1.88 to 4.54, and 0.50 to 2.26 respectively. The obtained EF value for Zn and Mn indicates very high contamination factor while Cu shows low contamination factors in all dumping sites. However, the CD and PLI showed the combined metal contamination level in the soil. The CD was calculated in the range of 14.09 (S3) to 24.40 (S1) and demonstrated considerable contamination. PLI was recorded higher in S4 (2.75) and lower in S3 (1.94) which indicate the high pollution level in S1, S2, S4 and moderate pollution level in S3.

PERI was calculated for selected heavy metals. Fe was found in the range of 3.11 (S1) to 4.22 (S4), Cu in the range of 0.70 (S1) to 4.04 (S2), Zn in the range of 7.18 (S3) to 15.81 (S4), and Mn in the range of 2.10 (S4) to 7.03 (S1) respectively. The major contribution for PERI is in order of Cu < Fe < Mn < Zn

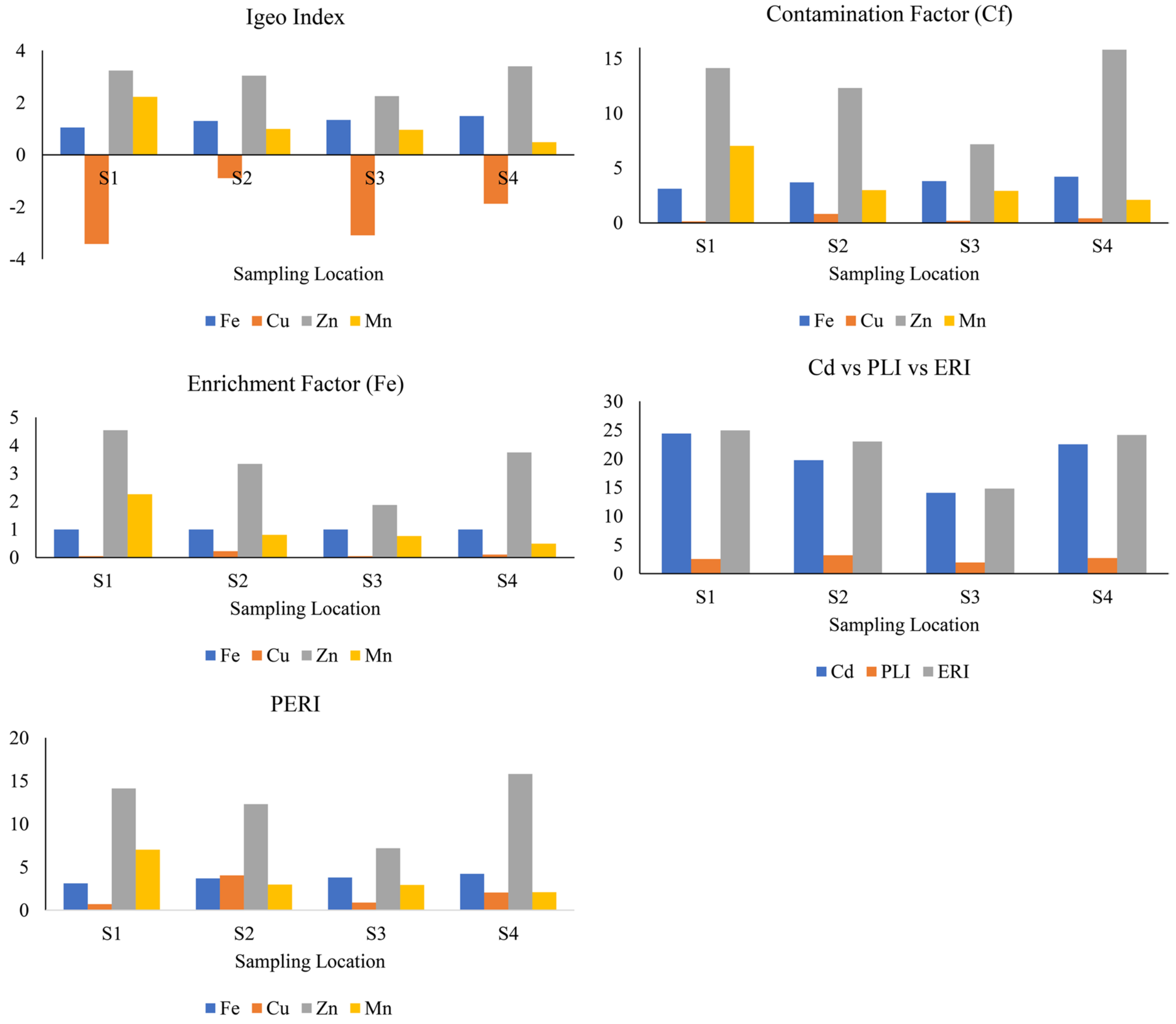


Fig. 5 Variation in soil pollution indices in selected sampling location

respectively. Furthermore, the ERI shows a higher value in S1 (24.96) and lower in S3 (14.80) respectively indicating low risk for the nearby environment. According to soil pollution indices, the heavy metals contribution pattern is Zn > Mn > Fe > Cu in all dumping sites. The majority of Zn and Mn metals may be due to the Zn-coated waste material, burning of e-waste, and dry cells dumped in the solid waste dumping sites. Many researchers noted that due to the high concentration of heavy metals in dumping sites directly or indirectly affects the nearby water bodies, groundwater aquifers, and local peoples (Bisht et al., 2022; Manju & Ilavarasan, 2016; Regmi et al., 2022; Saha et al., 2022a, 2022b; Shah et al., 2020; Sheijany et al., 2020).

Results of Pearson's correlation and principal component analysis

Pearson correlation coefficient revealed the relationship between the parameters by giving values between -1 (negative) to 1 (positive). In the present study, Pearson correlation coefficients were applied in combining data of selected parameters that obtained from all selected sites at significant level ($p < 0.05$)

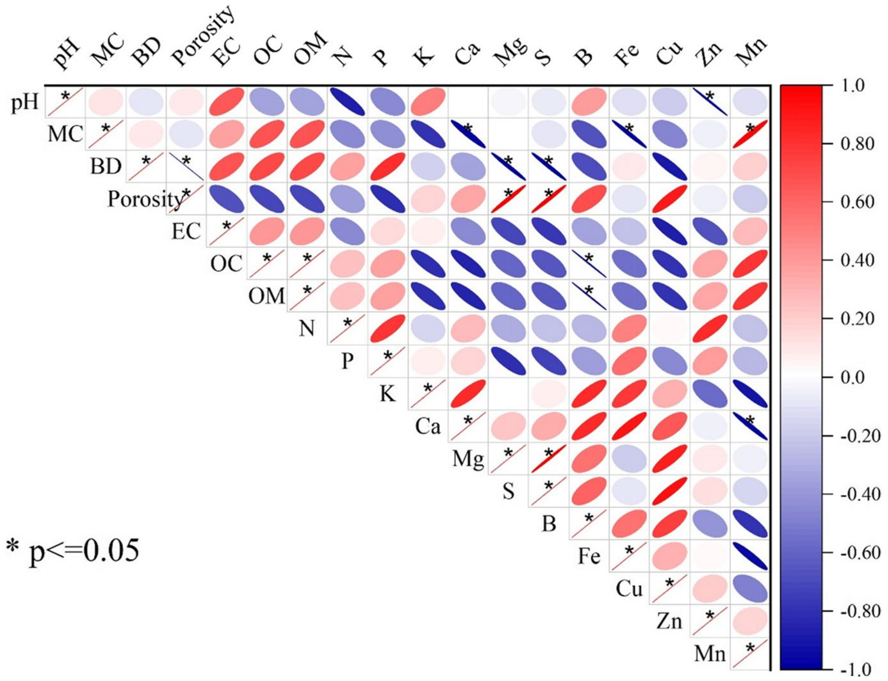


Fig. 6 Pearson correlation coefficient between the parameters in selected sampling location

illustrated in Fig. 6. In Fig. 6, blue colour represents the negative correlation and red colour shows the positive relationship.

The pH shows a strong positive correlation with EC, K, and B, but exhibits a significant negative correlation with N. This relationship is because pH and EC are often correlated, influenced by ion concentration, and as pH changes, it impacts the availability of nutrients like K and B, leading to observed correlations. The complex relationship between soil pH and elements like K and B influences their availability to plants. In acidic soils, K is more available, while B is more accessible in acidic to slightly acidic soils. Maintaining optimal pH is crucial for ensuring proper nutrient uptake, although other factors also play a role in nutrient availability. Porosity demonstrates a negative correlation with EC, OC, OM, P, and a positive correlation with B and Cu, respectively. OC and OM exhibit negative correlations with K, Ca, Mg, S, Fe, Cu, and porosity, while showing positive correlations with N, P, Zn, and Mn, respectively. Heavy metals, such as Cu, show positive correlations with Fe, porosity, Ca, Mg, S, B, and negative correlations with BD, MC, OC, and OM, respectively. Conversely, Zn exhibits positive correlations with OC, OM, N, P, and negative correlations with EC and K, respectively.

In this study, PCA was employed to evaluate the factor-loaded parameters in the selected landfill sites, as outlined in Table 5 and Fig. 7. Three PCA components, namely PC1, PC2, and PC3, were extracted based on eigenvalues exceeding 1, variance percentage, and cumulative percentages. The PCA graph depicted the varying concentration levels of parameters in respective sampling locations using vector lines and positive and negative values. PC1 contributes the 49.917% to the variance in data variability with eigenvalue of 8.985. Whereas PC2 and PC3 contribute cumulative data variability of 77.939% and 100% with eigenvalue of 5.044 and 3.970 respectively. PC1 shows higher factor loading for parameters, i.e., K, Ca, Mg, S, B, Fe, Cu, porosity and pH at S2 site. In PC1, heavy metals namely Zn and Mn show negative loading factor with pH indicates higher concentration level of these metals in low pH. The lower pH increases the mobility of these metals in soil (Getachew & Habtamu, 2015; Ekere et al., 2020). However, PC2 shows higher factor loading for parameters such as BD, EC, N, P, K, Ca, B, and Fe at sampling sites S3 and S4. The positive factor loading of these parameters indicates a common source of contamination. Specifically, the higher levels of N, P, and K in the soil are attributed to fertilizers and organic materials, particularly in

Table 5 Result of PCA showing the factor loading parameters in selected sampling locations

Parameters	PC1	PC2	PC3
pH	**0.222**	−0.223	−1.436
MC	−0.808	−1.099	−0.153
BD	−1.053	**0.796**	−0.209
Porosity	**1.053**	−0.797	**0.208**
EC	−0.762	**0.168**	−1.178
OC	−1.256	−0.148	**0.297**
OM	−1.257	−0.144	**0.295**
N	−0.207	**0.874**	**1.140**
P	−0.552	**1.236**	**0.364**
K	**0.863**	**0.780**	−0.740
Ca	**1.051**	**0.822**	**0.073**
Mg	**0.934**	−0.909	**0.383**
S	**1.006**	−0.780	**0.446**
B	**1.241**	**0.165**	−0.364
Fe	**0.628**	**1.240**	**0.079**
Cu	**1.166**	−0.262	**0.569**
Zn	−0.224	0.106	**1.450**
Mn	−0.931	−0.974	**0.153**
Sampling location			
S1	−1.190	−0.848	**0.337**
S2	**1.257**	−0.773	**0.268**
S3	−0.052	**0.382**	−1.450
S4	−0.015	**1.240**	**0.844**
Eigenvalue	**8.985**	**5.044**	**3.970**
Percentage of variance (%)	**49.917**	**28.022**	**22.061**
Cumulative (%)	**49.917**	**77.939**	**100.000**

MC moisture content, *BD* bulk density; *EC* electrical conductivity, *OC* organic carbon, *OM* organic matter, *N* Nitrogen, *P* phosphorus, *K* Potassium, *Ca* Calcium, *Mg* Magnesium, *S* Sulphur, *B* Boron, *Fe* Iron, *Cu* Copper, *Zn* Zinc, *Mn* Manganese

sites S3 and S4, which are surrounded by agricultural and rural areas. The dumping of assorted waste from these areas further contributes to contamination at these sites. Many other studies also reported the higher concentration of N, P, K in dumping sites due to the mixed type of waste of urbanization, rural area, and the agricultural sector (Bharti et al., 2022; Regmi et al., 2022; Saha et al., 2022b). In addition, PC3 shows moderate factor loading of parameters such as N > Zn > Cu > S > Mg > P > OC > OM > porosity in sampling sites S1, S2, and S4 respectively. The higher presence of these parameters in dumping sites may be attributed to the dumping of waste from industry, vehicular waste, agricultural and organic waste. If the values of these parameters are higher, it may cause various problems for people and nearby environmental components (Regmi et al., 2022; Saha et al., 2022b).

Potential health risk assessment

Potential health risk assessment (PHRA) was calculated to evaluate the non-carcinogenic risk to local people especially on children and adults due to the excessive concentration of Heavy metals. In this study, three contact pathways, i.e., the ingestion, inhalation, and dermal, were calculated and the obtained results were illustrated in Tables 6, 7, 8, and 9 and Fig. 6. In the ingestion pathway, the hazard quotient indicated a high risk of metals in the order of Mn > Fe > Zn > Cu for both children and adults. In the case of children THQ of Fe, Zn, Cu, and Mn through the ingestion pathway ranges from 1051.05 (S3) to 1866.76 (S1) while in the case of adult THQ ranges from 112.61 (S3) to 200.01 (S1) respectively. However, the results of inhalation pathways show higher HQ for Fe and Mn while HQ for Zn and Cu are very low in case of children and adults. The THQ ranges from 135.90 (S4) to 200.19 (S1) and 76.14 (S4) to 112.15 (S1) for child and adult respectively. In addition, HQ of Fe was obtained, i.e., 0.001 while HQ for Zn, Cu, and Mn showing zero value in all selected dumping locations.

The assessment of the combined potential health risk assessment of metals through ingestion, inhalation, and dermal pathways was conducted; the HI was found in the range of 1192.73 (S3) to 2066.94 (S1) for child and 191.98 (S3) to 312.16 (S1) for adults (Fig. 8). The HI analysis indicated high non-carcinogenic risk to local peoples. Fe toxicity causes symptoms such as nausea, vomiting, abdominal pain, and in severe cases, organ damage. Cu poisoning is characterized by symptoms such as nausea, vomiting, diarrhea, and, in extreme cases, liver and kidney damage. High levels of Zn can lead to Zn toxicity, causing symptoms such as nausea, vomiting, loss of appetite, and impaired immune function, whereas Mn poisoning can lead to neurotoxic effects such as tremors, muscle spasms, and, in chronic cases, neurological disorders (Bisht et al., 2022; Saha et al., 2022b; Wahab et al., 2020). Many researcher states that Fe does not exhibit direct chemical toxicity, but it has been noted that Fe influence the geochemistry

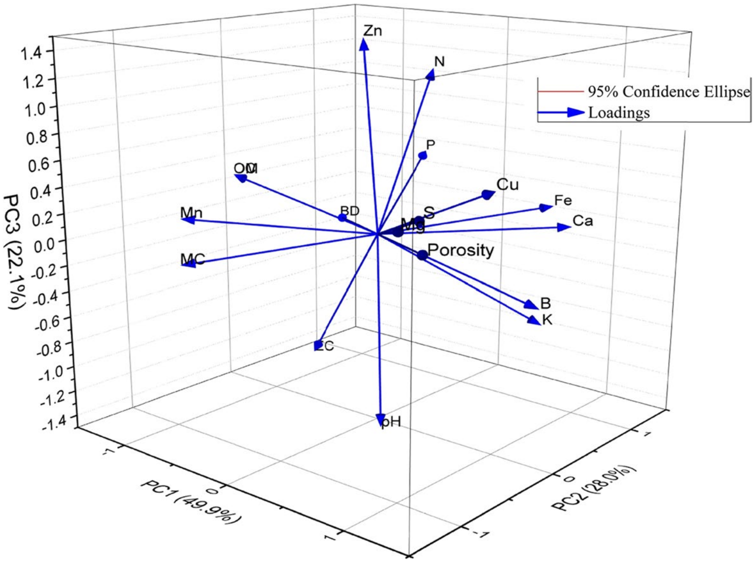


Fig. 7 PCA plot showing the factor loading parameters in selected study location

of other potentially toxic metals (Saha et al., 2022b; Wahab et al., 2020; Weissmannová et al., 2019).

Current challenges, policies related to open dumping sites in respect to Haridwar municipality of lower shiwalik Himalayan region

Solid waste management involves the collection, segregation, transportation, disposal, and recycling of waste in any area. Haridwar is a city with a mixed type of waste, including plant residues, flowers, food waste, especially in upper portion of Haridwar where we have majority of temples and ashram. The city comprises residential, commercial, and industrial area where both biodegradable and non-biodegradable is generated. The main challenge in Haridwar is segregation and disposal of the waste. As per the government norms for the disposal of waste, we need a proper well-maintained landfill site. It should be away from water bodies, wildlife habitat area, and agricultural fields. A major part of Haridwar is covered with Rajaji National Park, Ganga River, residential and industrial areas. To address the problem and adhere to the criteria, the municipality has established a landfill site outside the Nagar Nigam boundary.

However, due to the scarcity of an isolated land, landfill is established in barren land adjacent to agricultural fields and residential area of village. The dumping of waste releases harmful chemicals and pollutants into the soil, leading to several negative effects. It can contain a variety of toxic substances, such as heavy metals, chemicals, and other hazardous materials. When these constituents leach into the soil, they can contaminate the surrounding area, water bodies making it difficult or even impossible to grow crops or other plants which is even proven in the study of Bisht et al., 2022. In addition to environmental concerns, waste dumping can also pose health hazards for adjacent communities. Toxic chemicals and pollutants can mix in the air, potentially causing respiratory problems and other health issues. The common problem of open dumping of solid waste can cause soil degradation, groundwater contamination, health hazard, effect on wildlife habitat, and many more.

In 1992, the Indian government made an amendment (74th Constitutional Amendment) that granted the authority and accountability for the management of solid waste to urban local bodies such as Municipal Corporations, Municipal Councils, and Nagar Panchayats. Since then, the solid waste management in India is governed by various policies and laws. For instance, the Swachh Bharat Abhiyan has led to an increase in waste segregation at source, and the Solid Waste Management Rules have helped in reducing landfill sites and promoting waste minimization.

The implementation of these policies and laws has also led to an increase in public awareness and improved involvement of communities in waste management activities, which has contributed to

Table 6 Potential health risk hazard quotient based on ingestion pathway

Sampling location	Child					Adults				
	HQ for Fe	HQ for Cu	HQ for Zn	HQ for Mn	THQ	HQ for Fe	HQ for Cu	HQ for Zn	HQ for Mn	THQ
S1	255.81	63.33	130.22	1417.39	**1866.76**	27.41	6.79	13.95	151.86	**200.01**
S2	303.05	360.00	113.33	600.00	**1376.38**	32.47	38.57	12.14	64.29	**147.47**
S3	313.52	80.00	66.22	591.30	**1051.05**	33.59	8.57	7.10	63.35	**112.61**
S4	347.05	183.33	145.78	423.19	**1099.35**	37.18	19.64	15.62	45.34	**117.79**
Min	255.81	63.33	66.22	423.19	**1051.05**	27.41	6.79	7.10	45.34	**112.61**
Max	347.05	360.00	145.78	1417.39	**1866.76**	37.18	38.57	15.62	151.86	**200.01**
Mean ± S.D	304.86 ± 37.70	171.67 ± 136.31	113.89 ± 34.43	757.97 ± 447.08	**1348.38 ± 374.13**	32.66 ± 4.04	18.39 ± 14.61	12.20 ± 3.69	81.21 ± 47.90	**144.47 ± 40.09**

Fe Iron, *Cu* Copper, *Zn* Zinc, *Mn* Manganese, *HQ* hazard quotient, *THQ* total hazard quotient, *Min* minimum, *Max* maximum, *S.D.* standard deviation

Table 7 Potential health risk hazard quotient based on inhalation pathway

Sampling location	Child					Adults				
	HQ for Fe	HQ for Cu	HQ for Zn	HQ for Mn	THQ	HQ for Fe	HQ for Cu	HQ for Zn	HQ for Mn	THQ
S1	71.95	0.00	0.00	128.23	**200.19**	40.31	0.00	0.00	71.84	**112.15**
S2	85.23	0.01	0.00	54.28	**139.53**	47.75	0.01	0.00	30.41	**78.17**
S3	88.18	0.00	0.00	53.50	**141.68**	49.40	0.00	0.00	29.97	**79.37**
S4	97.61	0.01	0.00	38.29	**135.90**	54.68	0.00	0.00	21.45	**76.14**
Min	71.95	0.00	0.00	38.29	**135.90**	40.31	0.00	0.00	21.45	**76.14**
Max	97.61	0.01	0.00	128.23	**200.19**	54.68	0.01	0.00	71.84	**112.15**
Mean ± S.D	85.74 ± 10.60	0.00 ± 0.00	0.00 ± 0.00	68.58 ± 40.45	**154.32 ± 30.67**	48.03 ± 5.94	0.00 ± 0.00	0.00 ± 0.00	38.42 ± 22.66	**86.46 ± 17.18**

Fe Iron, *Cu* Copper, *Zn* Zinc, *Mn* Manganese, *HQ* hazard quotient, *THQ* total hazard quotient, *Min* minimum, *Max* maximum, *S.D.* standard deviation

Table 8 Potential health risk hazard quotient based on dermal pathway

Sampling location	Child					Adults				
	HQ for Fe	HQ for Cu	HQ for Zn	HQ for Mn	THQ	HQ for Fe	HQ for Cu	HQ for Zn	HQ for Mn	THQ
S1	0.001	0.000	0.000	0.000	**0.001**	0.000	0.000	0.000	0.000	**0.000**
S2	0.001	0.000	0.000	0.000	**0.001**	0.000	0.000	0.000	0.000	**0.000**
S3	0.001	0.000	0.000	0.000	**0.001**	0.000	0.000	0.000	0.000	**0.000**
S4	0.001	0.000	0.000	0.000	**0.001**	0.000	0.000	0.000	0.000	**0.000**
Min	0.001	0.000	0.000	0.000	**0.001**	0.000	0.000	0.000	0.000	**0.000**
Max	0.001	0.000	0.000	0.000	**0.001**	0.000	0.000	0.000	0.000	**0.000**
Mean ± S.D	0.001 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	**0.001 ± 0.000**	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	**0.000 ± 0.000**

Fe Iron, *Cu* Copper, *Zn* Zinc, *Mn* Manganese, *HQ* hazard quotient, *THQ* total hazard quotient, *Min* minimum, *Max* maximum, *S.D.* standard deviation

Table 9 Potential health risk assessment based on ingestion, inhalation and dermal pathway

Sampling Location	Child					Adults				
	HQ_{ing}	HQ_{inh}	HQ_{der}	HI	Risk analysis	HQ_{ing}	HQ_{inh}	HQ_{der}	HI	Risk analysis
S1	1866.76	200.19	0.001	2066.94	High noncarcinogenic risk	200.01	112.15	0.000	**312.16**	High noncarcinogenic risk
S2	1376.38	139.53	0.001	1515.91	High noncarcinogenic risk	147.47	78.17	0.000	**225.64**	High noncarcinogenic risk
S3	1051.05	141.68	0.001	1192.73	High noncarcinogenic risk	112.61	79.37	0.000	**191.98**	High noncarcinogenic risk
S4	1099.35	135.90	0.001	1235.25	High noncarcinogenic risk	117.79	76.14	0.000	**193.92**	High noncarcinogenic risk

HQ_{ing} hazard quotient ingestion, HQ_{inh} hazard quotient inhalation, HQ_{der} hazard quotient dermal, *HI* health index

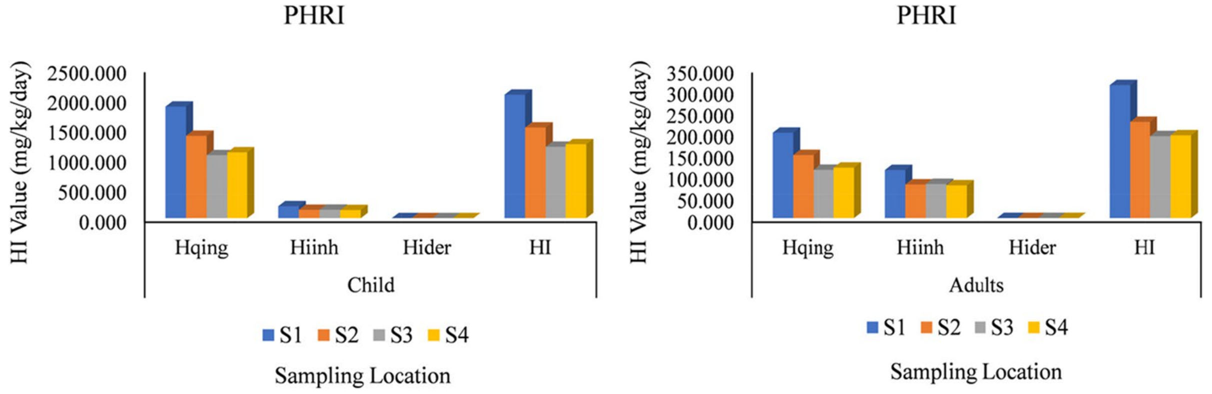


Fig. 8 Potential health risk index (PHRI) based on ingestion, inhelation, and dermal pathway in child and adult

reduced pollution levels. Various NGO and educational institutes such as IIT Roorkee and Gurukula Kangri University are working continuously to raise awareness about waste disposal and segregation. They are also working for waste minimization and resource recovery concept through techniques like vermicomposting.

Conclusion

In the present study, soil samples were collected from the four municipal solid waste dumping sites in Haridwar City to assess the soil contamination through open dumping of solid waste. Initially, physico-chemical properties and heavy metal concentrations were assessed, and later various soil pollution indices were applied to measure the contamination. The result of soil texture clearly revealed sandy loam soil of all dumping sites and it is a major concern because such soil has a higher leaching problem. The obtained results illustrated that the maximum parameters were higher in S4 in comparison to S1, S2, and S3 because of the higher quantity of miscellaneous waste from Haridwar city. In addition, soil pollution indices found the heavy metals contribution pattern is in order of Zn > Mn > Fe > Cu in all dumping sites. The predominant contamination sources for Zn and Mn metals contamination may be attributed to Zn-coated waste material, burning of e-waste, and dry cells dumped in the solid waste dumping sites. The CD and PLI indicate high pollution level in S1, S2, S4 and moderate pollution level in S3. However, PCA results depicted the higher factor loadings of N, P, K in soil samples of S3 and S4. It has been concluded that the waste of agricultural and rural area is dumped into these two sites that enhance the N, P, K. The PHRA analysis shows that only ingestion pathway is primarily responsible for the noncarcinogenic effect of local peoples mainly child and adult in comparison to inhalation and dermal pathways. This research recognizes potential health risks posed by soil pollution from open waste dumping, particularly for local groups in Haridwar municipality and also underscores the importance of adopting sustainable waste management practices. Whereas the study focused on analyzing the concentrations of four heavy metals (Fe, Cu, Zn, and Mn) due to their detectability using atomic absorption spectroscopy (AAS). This method can accurately assess soil contamination, but it might not catch other potentially dangerous metals or pollutants. A more thorough picture of soil pollution in the research area may be obtained by talking about the limits of this selective heavy metal analysis. According to the study, open garbage dumping has significantly contaminated the soil, mostly in sandy loam soil, which increases the danger of leaching. In order to support sustainable environmental management and policy decisions in urban areas such as the Haridwar municipality, further study could broaden the scope of heavy metal analysis, investigate alternate methods of detection, and pinpoint specific sources of contamination.

Recommendations

The obtained results clearly show that it is essential to set up a methodical and frequent monitoring protocol for determining the extent of heavy metal pollution in the soil at municipal solid waste disposal sites. Authorities can detect new pollution hotspots, monitor changes in contamination levels over time, and take prompt corrective action to reduce hazards to the environment and human health by conducting regular evaluations. To address the identified contamination sources and mitigate long-term impacts, it is essential to implement effective waste management strategies. This includes initiatives to reduce the deposition of non-biodegradable waste in dumping sites and the introduction of landfill construction measures to contain and manage waste effectively. Also, guidelines mandating proper waste disposal practices should be enforced, including sorting, recycling, and safe disposal of hazardous materials. Municipal authorities can introduce fines or penalties for non-compliance to deter illegal dumping and promote responsible waste management practices.

Abbreviations *AAS*: Atomic absorption spectroscopy; *ANOVA*: Analysis of variance; *B*: Boron; *BD*: Bulk density; *Ca*: Calcium; *CD*: Degree of contamination; *CF*: Contamination factor; *cm*: Centimeter; *Cu*: Copper; *EC*: Electrical conductivity; *EF*: Enrichment factor; *ERI*: Ecological Risk Index factor; *ERI*: Ecological Risk Index factor; *Fe*: Iron; *g*: Gram; *GPS*: Global positioning system; H_2SO_4: Sulfuric acid; $HClO_4$: Perchloric acid; *HI*: Hazard Index; HNO_3: Nitric acid; *HQ*: Hazard quotient; *Igeo*: Geo-accumulation index; *IIT*: Indian Institutes of Technology; *K*: Potassium; *kg*: Kilogram; *K-W*: Kruskal-Wallis; *MC*: Moisture content; *Mg*: Magnesium; *mg*: Microgram; *Mn*: Manganese; *N*: Nitrogen; *NGO*: Non-government organization; *No.*: Number; *ºC*: Degree centigrade; *OC*: Organic carbon; *OM*: Organic matter; *P*: Phosphorus; *PCA*: Principal component analysis; *PERI*: Potential ecological risk index; *PHRA*: Potential health risk assessment; *PLI*: Pollution load index; *S*: Sulphur; *S1 to S4*: Selected sites; *THQ*: Total hazard quotient; *Tr*: Toxic response factor; *w/v*: Percent weight in volume; *WHO*: World health organization; *Zn*: Zinc

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Declarations

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Consent to participate and publish All authors have agreed to participate and publish in this article.

Competing interests The authors declare no conflict of interest.

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