



Research Article

Multivariate and statistical approaches for the evaluation of heavy metals pollution at e-waste dumping sites



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Abstract

Electronic waste pollution is a growing concern due to its hazardous effects on the environment and human health. Among many contaminants from e-waste, excessive levels of heavy metals in soil, which are far beyond the permissible limit, have led to many research studies at e-waste dumping sites majorly in the developing nations like India and China. The present study was conducted to assess the effect of e-waste dumping on the soil profile; therefore, the soil quality was analyzed for various physicochemical and heavy metals characteristics. The concentration of heavy metals in the soil samples was determined using inductively coupled plasma optical emission spectrometer. Soil samples were found to contain a higher amount of different heavy metals like copper, zinc, nickel, lead, manganese, chromium, cadmium, and iron. Correlation and principal component analysis were performed to establish a better insight into the degradation of soil quality. The contamination factor and pollution load index were evaluated statistically to assess the heavy metal pollution. The significant difference among the soil quality parameters inferred the hazardous impact of e-waste on the soil profile, and the pollution load index indicated that the sites are highly polluted with heavy metals. The present study contributes to a deeper understanding of the heavy metal contamination at e-waste dumping sites.

Keywords E-waste · Heavy metals · Principal component analysis · Contamination factor · Cluster analysis · Pollution load index

1 Introduction

With the rapid development in the information technology sector and fast-paced innovations in the electrical and electronics industry [36, 50], large quantities of electronic equipments are being discarded globally [77]. E-waste is one of the fastest growing sources of waste and now represents an emergent environmental concern [45].

Waste electronic equipments constitute over 5% of urban waste in developed countries and every year approximately 20–50 million tons of e-waste is produced globally and it is anticipated to increase 3–5% annually [22, 48]. The lethal impacts of recycling and discarding of e-waste on soil ecosystems have been reported in many

countries [29, 71, 72]. The rapid growth of e-waste has led to inappropriate management techniques in both developed and developing countries, resulting in multi-dimensional influences on the environment [52, 71].

Several research studies have revealed the significant influences of heavy metal pollution on the environment and human health [18, 21, 50]. E-waste is considered more hazardous than any other waste as it contains a huge variety of toxic elements, namely Pb, Cd, Cr, Hg, PVC, BFRs, beryllium, antimony, and phthalates. Long-term exposure to these materials can harm the sensory systems, kidney, bones, reproductive, and endocrine system [25].

Currently, heavy metals contamination has become one of the most hazardous environmental challenges due

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to their tendency for bioaccumulation and toxic effects on plants, animals, and human beings [8, 31, 37, 57]. The industrial activities, including mining, metallurgy, petroleum-producing, machine manufacturing, and metal finishing, affect the environment directly or indirectly [34]. The main concern is the discharge and accumulation of heavy metals into the soil, as metals are not degradable and largely affect the ecosystem. Most of the heavy metals are extremely toxic even at low concentrations. Cd, Cr, Pb, Hg, As, Ni, Zn, Cu, and Ag are not only poisonous but are even carcinogenic [53].

The principal objective of this study was to determine the origin, dispersal, and evaluation of the environmental risk associated with heavy metals contamination. The objective was attained, using various multivariate and statistical approaches including the soil physicochemical properties, nutrient status, and heavy metals distribution at the selected e-waste dumping sites. Despite the fact that numerous reports are available on heavy metal contaminations, an inclusive study correlating various parameters statistically to soil quality in the selected regions is largely unassessed.

2 Materials and methods

2.1 Site description

Ahmedabad, the largest industrial hub in Gujarat with a phenomenal growth record, has been an important base of trades and industries. Ahmedabad lies at 23.03°N 72.58°E in western parts of India at 53 meters above sea level in north-central Gujarat, which covers an area of 464 km². The climatic conditions are mostly semi-arid due to the closeness with the Arabian Sea. According to the Bureau of Indian Standards, the city comes under seismic zone 3. Typically, the climate stays dry, except during monsoon season. The present research study was carried out at three different e-waste dumping sites, which were close to Ahmedabad railway station. Five samples were obtained from each selected study site and the locations of sampling sites are shown in Fig. 1 with coordination given.

2.2 Sampling procedure and analytical methodology

Soil samples were collected from the depth of (15–30 cm) and immediately transferred to an airtight container. The soil samples then transported to the laboratory and samples were prepared to analyze the physicochemical and heavy metals properties. pH was estimated (1:2.5 w/v) by digital pH meter [70]. Electrical conductivity was determined (1:2.5 w/v) by conductivity

meter. Organic carbon and organic matter were estimated as per the method recommended by Osuji and Adesiyun [46]. Sulfate was estimated by the turbidimetric method [13], available phosphorus was determined according to Kovar et al. [24], and nitrate was assessed according to Cataldo et al. [9]. Similarly, soil moisture content, water holding capacity, alkalinity, and potassium concentrations were analyzed as per the standard methods.

2.3 Heavy metals analysis in e-waste contaminated samples

Soil samples were prepared for heavy metal quantification using the method suggested by the State Environmental Protection Administration [31]. Air-dried and sieved samples were digested with HCl–HNO₃–HF–HClO₄ solution for the analysis of Pb, Zn, Cd, Cu, Mn, Fe, and Ni [14], and for the analysis of Cr, the samples were digested with HNO₃–HClO₄–HF solution [20, 78]. The obtained solution was heated for 4–6 h at 120 °C on hot plate and filtered using Whatman filter paper no. 42. The filtrate was then diluted with distilled water till the total volume reached to 20 ml. The concentrations of Cr, Pb, Cd, Fe, Cu, Ni, Mn, and Zn were calculated using Perkin Elmer Optima 7300 DV ICP-OES. The samples were analyzed in triplicate, and the concentration of the metals was reported in mg/kg.

2.4 Multivariate and statistical analysis

The data obtained through the laboratory experiments (physicochemical and heavy metals concentration) were analyzed, tabulated into tables, and shown in the form of Mean ± SD. Principal component and cluster analysis, the most suitable multivariate approaches for environmental-based research studies [38], were performed to analyze the acquired data. Principal component analysis (PCA) bi-plot: standardized PC1 and PC2 scores were plotted to decrease the data and to extract a lesser number of independent factors for analyzing relations among experimental variables [79], starts with the correlation matrix defining the distribution of the original variables and extracting the eigenvalues and eigenvectors [5]. PCA and Pearson correlation used to determine the relationship among the soil characteristics at each sampling point and to explore the homology of soil contamination. Correlation and principal component were executed by Origin software. Cluster analysis was instigated to find out the similarity index among all the sampling points of e-waste sites, based on their physicochemical and heavy metals properties using Bray–Curtis cluster analysis (Single Link) by Biodiversity Professional software. Cluster analysis classifies the

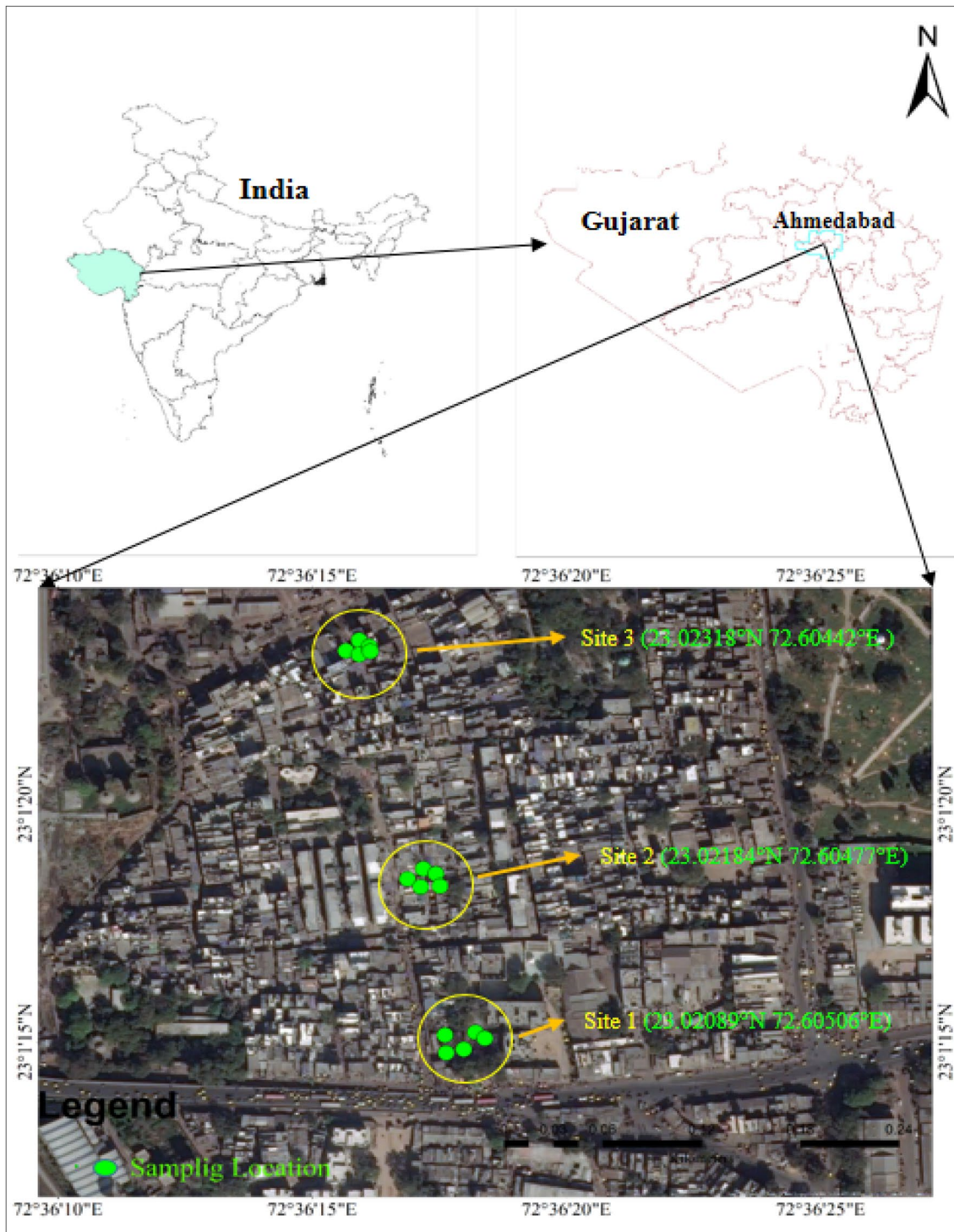


Fig. 1 Study area

contamination status and possible sources of heavy metal pollution in the study area [32, 49, 73, 74]. A Dendrogram is commonly used for summarizing classified clustering.

2.5 Contamination factor and degree of contamination

The contamination factor is the ratio of the concentration of metal (C_M) to the background values (C_B). Contamination

degree (C_{deg}) is the sum of contamination factors for all the elements. Hakanson [17] suggested four classes of contamination factor and contamination degree. $CFs < 1$ refers to low contamination factor; $1 \leq CFs < 3$ means moderate contamination factor; $3 \leq CFs < 6$ indicates considerable contamination factor and $CFs \geq 6$ indicates very high contamination factor; and $C_{deg} < 8$ refers to low contamination degree; $8 \leq C_{deg} < 16$ means moderate contamination degree; $16 \leq C_{deg} < 32$ indicates considerable contamination degree; and $32 \leq C_{deg}$ refers to very high degree of contamination.

$$Cf = \frac{C_M}{C_B}$$

where C_M is the measured concentration in the soil for the metal, and C_B is the background value for the metal.

2.6 Pollution load index

An integrated pollution load index of metals is calculated to assess the soil quality [31, 62]. The PLI determined as the n th root of the product of the n CF:

$$PLI = \sqrt[n]{CF1 \times CF2 \times CF3 \times CF4 \times \dots \times CFn}$$

where n is the total number of metals analyzed, the PLI values higher than 1 implies metal pollution, otherwise ($PLI < 1$), there is no metal pollution [55].

2.7 Geoaccumulation index (I_{geo})

The geoaccumulation index (I_{geo}) commonly evaluates the pollution by comparing the obtained heavy metals concentration to background concentration. It is calculated by the equation

$$I_{geo} = \log_2 [C_n / 1.5 * B_n]$$

where C_n is the obtained concentration for the metal n , and B_n is the background value for the metal n in the soil [66], and the factor 1.5 used due to the possible variations in the background data. Müller [43] has reported six classes of I_{geo} (Table 1). Class 6 is an open class and includes all values of the geoaccumulation index greater than class 5.

3 Results and discussion

3.1 Physicochemical characterization of contaminated soil

The physicochemical properties of the contaminated soil samples were highly diversified in nature (Table 2). The

Table 1 Classes of the geoaccumulation Index (I_{geo})

Class	Value	Soil quality
0	$I_{geo} \leq 0$	Practically uncontaminated
1	$0 < I_{geo} < 1$	Uncontaminated to moderately contaminated
2	$1 < I_{geo} < 2$	Moderately contaminated
3	$2 < I_{geo} < 3$	Moderately to heavily contaminated
4	$3 < I_{geo} < 4$	Heavily contaminated
5	$4 < I_{geo} < 5$	Heavily to extremely contaminated
6	$5 < I_{geo}$	Extremely contaminated

significance level among the three different sampling sites could be attributed to the composition of e-wastes, structure of the soil, e-waste disposal methods, and management techniques.

The soil samples belong to fine to very fine sandy soil, having a distinctive smell with unnatural colors. The variations in the color might be due to the higher quantity of organic matter and metals composition of the soil [68].

The temperature of the dumping sites was observed 21.64 ± 0.94 °C for site 1, 21.99 ± 1.06 °C for site 2 and 26 ± 1.21 °C for site 3. The soil temperature is the most significant property, which affects the various biological activities and regulates the nutrient conversion in the soil [61, 76]. The pH of the polluted sites perceived slightly basic, which suggested that the dumping sites were marginally alkaline and predominantly related to the metabolite's accretion and the availability of nutrients in the soil [54]. Electrical conductivity was found highest at site 2 followed by site 1 and site 3. The electrical conductivity of soil influenced by the presence of metallic scraps which are the main components of the dumping sites and specified the quality of the soil and offered a suitable way to estimate the whole quantity of ionizable salts in the soil [4, 23, 41]. Similar results were reported by Uba et al. [67] at waste dumping sites at Zaira, Nigeria.

The soil moisture was found to be higher in site 3 as compared to site 1 and site 2. Several physicochemical properties including pH and nitrogen of the soil are mainly reliant on the higher soil moisture [35]. The organic carbon ranged from $1.55 \pm 0.06\%$, 1.47 ± 0.8 , and 1.32 ± 0.09 at the three sites, respectively, which specified the burning of various organic and inorganic compounds found in e-waste [2]. The organic matter found more in sites 1 followed by site 3 and site 2. The organic matter ($> 2.0\%$) in soils is favorable for metal chelation [65] and decreases the mobility of metals in soil [10, 11, 21]. The quantity of organic matter at the selected dumping sites was significantly higher due to the variety of disposed waste materials. Similar results were found by Uba et al. [67] at the dumping sites of Zaria Metropolis, Nigeria. The current findings also supported by Oyedele et al. [47], described

Table 2 Physicochemical characterization of soil from different sampling sites

Parameters	Site 1 Mean ± SD	Site 2 Mean ± SD	Site 3 Mean ± SD
Color	Dark brown	Brown	Black
Texture	Sandy-loamy	Sandy-loamy	Sandy-loamy
Temperature (°C)	21.64±0.94	21.99±1.06	26.36±1.21
pH	7.22±0.04	7.44±0.26	7.72±0.17
EC (ms/cm)	2.30±0.13	4.16±0.16	0.91±0.11
Soil moisture (%)	3.58±0.51	5.88±0.74	8.04±0.67
Water holding capacity (%)	41.48±2.19	39.99±0.43	37.02±1.03
Organic carbon (%)	1.55±0.06	1.47±0.08	1.32±0.09
Organic matter (%)	2.67±0.10	2.52±0.14	2.27±0.15
Alkalinity (mg/l)	68.66±0.60	71.15±0.65	79.52±1.67
Sulfate (mg/kg)	31.78±0.55	35.17±0.25	19.68±0.32
Nitrate (mg/kg)	24.16±0.25	26.91±1.20	32.71±0.59
Nitrite (mg/kg)	1.29±0.14	1.58±0.09	1.48±0.32
Available phosphorus (mg/kg)	1.82±0.09	1.51±0.08	1.89±0.05
Potassium (mg/kg)	58.65±0.58	79.91±0.52	44.03±0.57

that dumping sites had significantly higher pH and organic matter as compared to the control soil.

The alkalinity was found highest at site 3 as compared to other sites and ranged from 68.66 ± 0.60 mg/l at site 1, 71.15 ± 0.65 mg/l at site 2, and 79.52 ± 1.67 mg/l at site 3, respectively. The high alkalinity indicated the age of the dumping site, association of higher pH and availability of nutrients in the soil [1, 4]. The soils of e-waste dumping sites have been reported to be alkaline, with increased pH [6, 19]. The sulfate content was significantly varied and found highest at site 2 followed by site 1 and site 3, respectively. The concentration of nitrate did not vary significantly and found higher at site 3 as compared to site 1 and site 2. Similarly, the nitrite content was found more at site 2 followed by site 3 and site 1, respectively. Available phosphorus in the contaminated soil sample significantly varied 1.82 ± 0.09 mg/kg at site 1, 1.51 ± 0.08 mg/kg at site 2, and 1.89 ± 0.05 mg/kg at site 3. The blazing of e-waste might affect the presence

of phosphorus in soil and some quantity of phosphorous may have been lost to the air by volatilization [12]. Similar trend of phosphorus content was reported by Liu et al. [35] at e-waste recycling sites in Guiyu town, China. The potassium was found to be higher at site 2 followed by site 1 and site 3. The availability of potassium was influenced by the favorable soil environment and organic matter [44].

A two-tailed test of significance level of $P < 0.05$ was used to analyze the correlation coefficient among the various physicochemical characteristics of the soil samples (Table 3). The EC was positively correlated with sulfate and potassium. Organic carbon showed a highly positive correlation with organic matter. Alkalinity and sulfate positively correlated with nitrate and potassium, respectively. However, pH showed marginally optimistic correlation with alkalinity and nitrate and sulfate also exhibited a positive correlation with organic carbon and organic matter to a slight extent.

Table 3 Pearson correlation coefficient (*r*) among the physicochemical properties of soil samples

	pH	EC	OC	OM	Alkalinity	Sulfate	Nitrate	Nitrite	K	P
pH	1									
EC	-0.401	1								
OC	-0.556*	0.450	1							
OM	-0.559*	0.445	0.999*	1						
Alkalinity	0.733*	-0.655*	-0.765*	-0.765*	1					
Sulfate	-0.613*	0.918*	0.682*	0.679*	-0.891*	1				
Nitrate	0.727*	-0.585*	-0.735*	-0.735*	0.952*	-0.842*	1			
Nitrite	0.503	0.231	-0.240	-0.245	0.22	0.024	0.200	1		
K	-0.361	0.994*	0.445	0.440	-0.642*	0.911*	-0.57*	0.249	1	
P	0.21	-0.890*	-0.115	-0.109	0.416	-0.708*	0.359	-0.279	-0.888*	1

3.2 Characterization of heavy metals

Heavy metal contents in the study sites were found higher than the USEPA and European soil screening standards. The predominant toxic contaminants in the soil of dumping sites were zinc, iron, manganese, copper, cadmium, chromium lead, and nickel ranging between 110–126 mg/kg, 11–18 mg/kg, 5–25 mg/kg, 148–158 mg/kg, 12–17 mg/kg, 109–200 mg/kg, 61–70 mg/kg, and 11–18 mg/kg, respectively (Fig. 2). The order of occurrence of heavy metals in the contaminated soil was Cr > Cu > Zn > Pb > Fe > Mn > Cd > Ni. The reference values were: 95 mg/kg for Zn, 0.7 mg/kg for Cd, 36 mg/kg for Cr, 28 mg/kg for Cu, 31 mg/kg for Ni, and 28 mg/kg for Pb [42].

The findings revealed that electronic waste dumping sites were extremely polluted from the high concentration of copper, cadmium, zinc, lead, and chromium, whereas iron, manganese, and nickel were relatively detected with moderate concentrations. The variations among the heavy metal concentrations probably showed the metal's vertical transference capabilities, as heavy metals mainly preferred to transfer from surface soils to subsoils [51]. Different recycling activities including plastic melting, recovery of copper from the wires, burning of circuits, and using acidic substances to recover gold and other metals may cause the metal pollution at the e-waste sites [30]. Heavy metal pollution at e-waste dumping sites generally found due to the use of many metals in the production of electronic products, e.g., lead and cadmium in circuit boards, copper in electrical wiring, cadmium in computer batteries [21, 58, 60, 75, 80, 81].

The elevated concentration of Cd was recorded at selected dumping sites due to the disposal of NiCd or NiCad rechargeable batteries, which are generally manufactured by nickel oxide hydroxide and metallic

cadmium. The high fraction of Mn was found because of the indefinite leaching of hydrous oxides of manganese at the selected sites [59]. Lead was detected exceptionally high concentration due to the discarding of lead–acid batteries as lead is mainly used in the manufacturing of batteries and assembling of other electronic equipments [15]. An earlier research on heavy metal pollution has identified copper, lead, chromium, and manganese as the major contaminants at three e-waste dumping sites in Nigeria [3]. Tang et al. [64] also reported that chromium, zinc, and lead are the most abundant heavy metals in e-waste recycling city in China. Ha et al. [16] performed a study in Bangalore city and recorded very high concentration of different heavy metals at e-waste recycling unit at slum area (Cr 73 mg/kg, Cu 592 mg/kg, Zn 326 mg/kg, Cd 2.33 mg/kg, Hg 1.8 mg/kg, Pb 29 mg/kg), and concentration in city recycling unit (Cr 57 mg/kg, Cu 22.8 mg/kg, Zn 41 mg/kg, Cd 0.165 mg/kg, Hg 0.05 mg/kg, Pb 22.8 mg/kg).

Brigden et al. [7] have reported high concentrations of heavy metals in the soil of e-waste handling areas in Delhi, India [56]. Brandl et al. [6] also performed a research study at e-waste contaminated site for heavy metals and recorded very high concentration of these metals, (Al 237 g/kg, Cu 80 g/kg, Pb 20 g/kg, Ni 15 g/kg, Sn 23 g/kg, Zn 26 g/kg). Singh et al. [56] also supported the current findings, as they recorded a high concentration of different heavy metals (As, Ba, Cd, Cr, Fe, Cu, Mn, Ni, Co) at e-waste recycling sites of Chandigarh and Ludhiana, Punjab, India.

Luo et al. [39] have reported a study at Guangdong province of South China and recorded very high contamination level of various heavy metals (Cd 17.1 mg/kg, Cr 68.9 mg/kg, Cu 11,140 mg/kg, Ni 60.1 mg/kg, Pb 4500 mg/kg, and Zn 3690 mg/kg). The comparison of current findings with earlier research studies is presented in Table 4. The severity of contamination not only depends on the

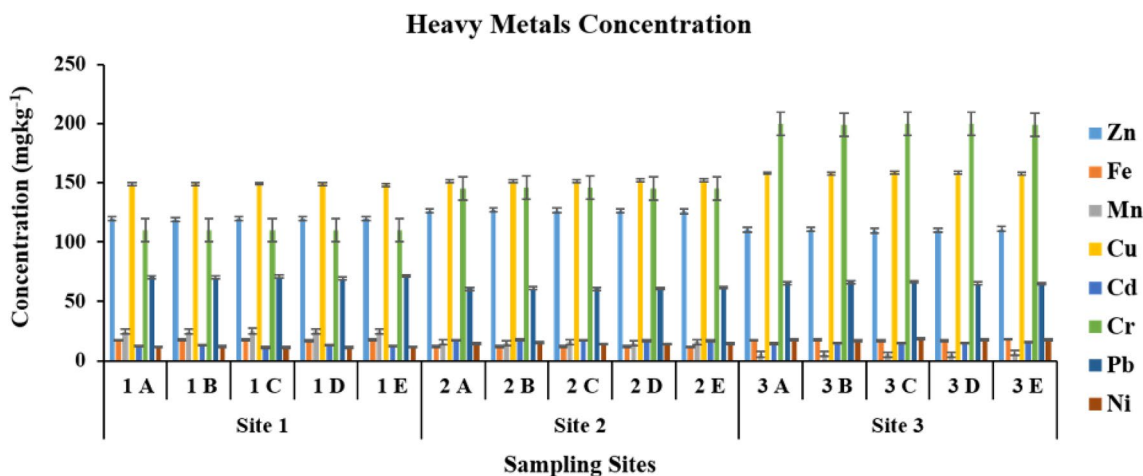


Fig. 2 Concentration (mg kg⁻¹) of heavy metals at different sampling points

Table 4 Comparison of present results with earlier reports

Sites	Heavy metals concentrations (mg/kg)								Sources
	Zn	Fe	Mn	Cu	Cd	Cr	Pb	Ni	
e-waste dismantling Sites	110–126	11–18	5–25	148–158	12–17	109–200	61–70	11–18	Current study
Site of e-waste dismantling	258	–	–	496	1.7	28.6	104	155	[28]
Dust inside PCB processing	4420	–	–	8360	–	–	110,000	1500	[27]
Open-burning site	2922	–	–	7814	24.2	307	3947	403.6	[71]
Qingyuan soil, site of e-waste dismantling	1016.7	–	–	4850.6	10.3	63.3	1714.5	100.3	[40]
Site of e-waste dismantling	343.2	–	–	180.7	3.0	101.3	187.3	49	[64]
Site of e-waste dismantling	4737.74	–	–	14,534.4	8.34	287.19	1615.8	130.24	[56]

total concentration of metal, but also on the fraction of their movable and bioavailable forms, which generally controlled by the pH, organic matter, and other soil properties [63].

Similarly, a two-tailed test of significance level of $P < 0.05$ was used to analyze the correlation coefficient among the various heavy metals. A significant positive correlation was found between some pairs of heavy metals (Table 5). The correlation analysis revealed that copper showed a positive correlation with chromium and nickel, and chromium also positively correlated with nickel. A positive correlation was also observed between iron and lead. The correlation analysis clearly specified that the origination of different heavy metals is possibly electronic waste.

3.3 Principal component analysis (PCA)

Multivariate techniques such as principal component analysis can provide an easy mode of discussing the correlated data sets [73] and clarifying the relations between the specific variables and various controlling features by classifying associations among the particular parameters [33, 69]. PCA used an orthogonal transformation to change a set of observations of possibly correlated multiple variables (different sites and parameters of contaminated soil) into a set of values of linearly uncorrelated variables called principal components.

Principal component analysis of contaminated sites showed a total variability of 59.58% (Eigenvalue 11.91) for PC 1 and 28.58% (Eigenvalue 5.70) for PC 2, respectively (Fig. 3). Site 1 showed a negative relation at PC1 and PC 2, whereas sites 2 showed positive relation at PC 2 and negative relation at PC 1. Site 3 showed a negative relation at PC 2 and positive relation at PC 1. Bi-plot factors analysis of different parameters of selected contaminated sites was varied from 0.05 to 0.27 coefficients variances at PC1.

PC score values for pH, soil moisture, alkalinity, nitrate, nitrite, copper, cadmium, chromium, and nickel revealed a positive relation at PC1 and PC2 (Fig. 3). However, PC score values for water holding capacity, organic carbon, organic matter, manganese, and lead were perceived as highly negative at PC1 and PC2. The score values for electrical conductivity, sulfate, zinc, and potassium were found positive at PC2 and negative at PC1. The loading value of phosphorus and iron was observed positive for PC1 and negative for PC2. A strong relationship was observed among chromium, copper, nickel, and nitrate for PC1 and PC2. Scores for most of the heavy metals (Cu, Ni, Fe, and Cr) indicated, more loading at site 3, due to uninhibited dumping of e-waste, whereas the PC score values for Mn and Pb indicated additional loading at Site 1. The PC loading values for Zn and Cd showed deposition toward site 2. Hence, very less heavy metal contents were observed at site 2, thus a separate group was formed by site 2.

Table 5 Pearson correlation coefficient (r) among the heavy metals

	Zn	Fe	Mn	Cu	Cd	Cr	Pb	Ni
Zn	1							
Fe	−0.801*	1						
Mn	0.578*	0.007	1					
Cu	−0.745*	0.212	−0.970*	1				
Cd	0.363	−0.812*	−0.518*	0.313	1			
Cr	−0.661*	0.102	−0.993*	0.987*	0.431	1		
Pb	−0.422	0.857*	0.482	−0.275	−0.973*	−0.388	1	
Ni	−0.608*	0.035	−0.989*	0.967*	0.487	0.986*	−0.43	1

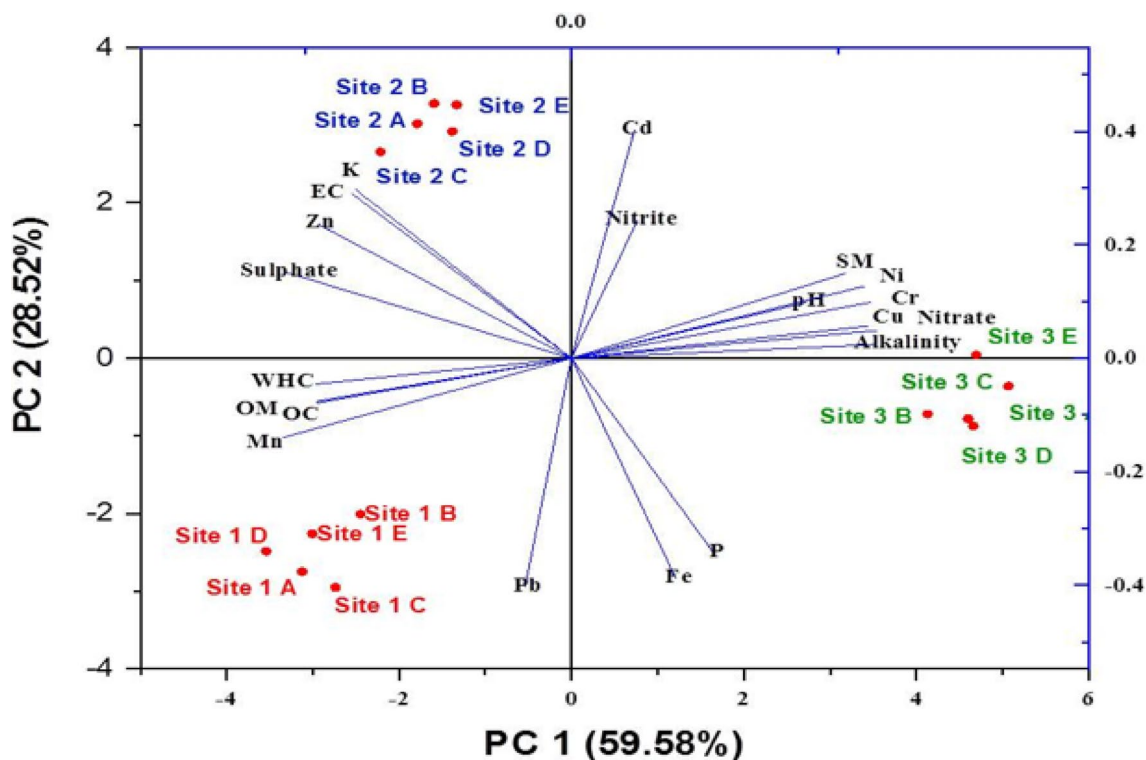


Fig. 3 Principle component analysis (PCA) correlation bi-plot of different physicochemical characteristics of contaminated soil and selected sites. Symbol represents the standardized scores on PC1

(x-axis) and PC2 (y-axis) for the soil parameters. Vector coordinates represent the correlations between standardized variables and principle components (PCs)

3.4 Cluster analysis

Cluster analysis, a prevalent approach for determining the multiple-parameter problems [26, 63, 73], was used to determine the spatial similarity matrix among sampling points based on the physicochemical and heavy metals characterization of selected sites. The single linkage method for distance measures was carried out to obtain the clusters, providing much useful information to study the soil contamination. Dendrogram described 14 clusters among the sampling points (Fig. 4).

Sampling point S1A formed four clusters with S1B, S1C, S1D, and S1E with 99.46%, 99.33%, 99.34%, and 99.55% of similarity, respectively. Similarly, point S2A also created four clusters with S2B, S2C, S2D, and S2E with 99.56%, 99.67%, 99.49%, and 99.36% of similarity, respectively. Sampling point S3B established two clusters with S2D and S3A with 89.63% and 99.30% similarity, respectively. One cluster was formed between S1B and S2E with 93.16% similarity. Another cluster showed 99.27% similarity between S2C and S2E. Sampling point S3D created a cluster with S3C with 99.35% similarity and S3A and S3C formed a cluster with 99.36% similarity (Table 6).

These clusters indicated that contaminants seem to be associated with the other variables, showing a very high

degree of contamination, which suggested that the heavy metals (Cu, Pb, Ni, Zn, Cd, Cr, Mn, and Fe) might have a common source of pollution and influenced by the indiscriminate dumping of e-waste.

3.5 Assessment of heavy metal contamination

The heavy metal pollution of the selected dumping sites was assessed by contamination factor (C_f), degree of contamination (C_{deg}), pollution load index (PLI) (Table 7), and geoaccumulation index (I_{geo}) (Table 8).

3.5.1 Contamination factor

The spatial distribution of CFs for heavy metals (Zn, Cu, Cd, Cr, and Pb) in selected e-waste dumping sites is demonstrated in Table 7. The CFs gradient of selected metals established a similar pattern along all the sampling sites. The selected sites (sites 1, sites 2, and sites 3) were highly contaminated ($C_f \geq 6$) with cadmium and moderately contaminated ($1 \leq C_f < 3$) with Zinc and Lead. In the case of chromium and copper, the sites were considered contaminated as the CFs were found ($3 \leq C_f < 6$).

The findings again confirmed that soils of e-waste dumping sites act as a sink for heavy metals and showed

Bray-Curtis Cluster Analysis (Single Link)

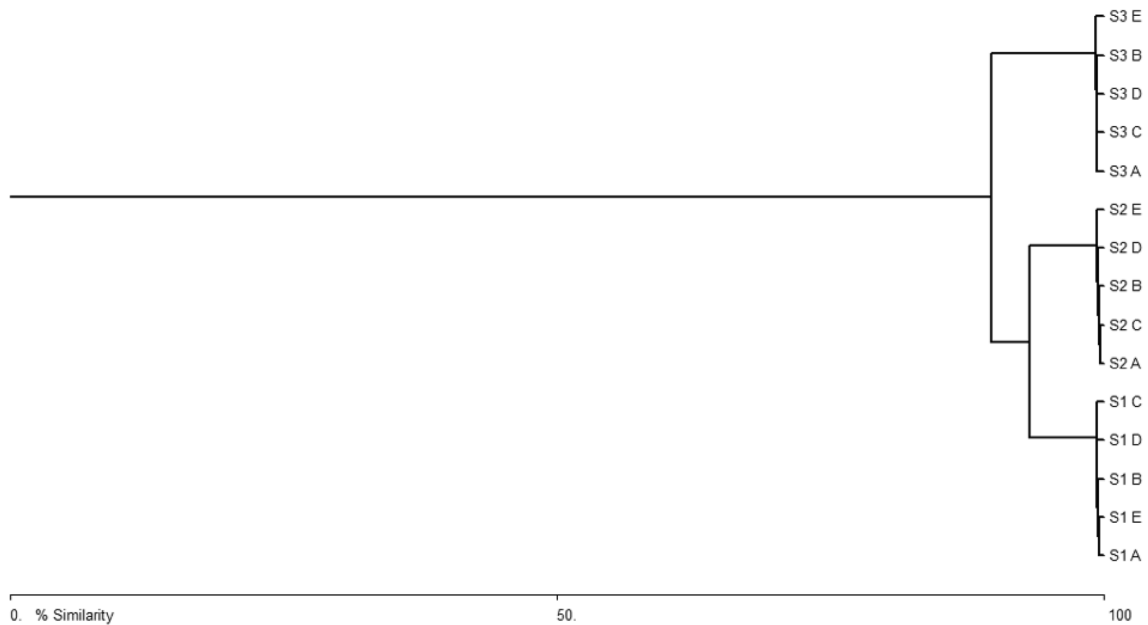


Fig. 4 Dendrogram showing similarity index among all sampling points

Table 6 Similarity matrix among the sampling points

	S1 A	S1 B	S1 C	S1 D	S1 E	S2 A	S2 B	S2 C	S2 D	S2 E	S3 A	S3 B	S3 C	S3 D	S3 E
S1 A	*	99.46	99.33	99.34	99.55	92.71	92.71	92.71	92.68	93.00	87.37	87.67	87.32	86.93	87.33
S1 B	*	*	99.05	99.26	99.40	92.87	92.89	92.83	92.82	93.16	87.74	88.07	87.69	87.28	87.72
S1 C	*	*	*	98.88	99.24	92.75	92.62	92.74	92.64	92.94	87.40	87.74	87.35	86.94	87.45
S1 D	*	*	*	*	99.23	92.55	92.56	92.55	92.51	92.83	87.41	87.70	87.38	87.00	87.35
S1 E	*	*	*	*	*	92.65	92.66	92.64	92.62	92.94	87.41	87.73	87.37	86.95	87.39
S2 A	*	*	*	*	*	*	99.56	99.67	99.49	99.36	89.19	89.44	89.07	88.85	89.37
S2 B	*	*	*	*	*	*	*	99.53	99.33	99.29	89.26	89.51	89.14	88.92	89.44
S2 C	*	*	*	*	*	*	*	*	99.43	99.27	89.21	89.47	89.09	88.87	89.39
S2 D	*	*	*	*	*	*	*	*	*	99.28	89.38	89.63	89.27	89.04	89.58
S2 E	*	*	*	*	*	*	*	*	*	*	89.02	89.32	88.93	88.71	89.27
S3 A	*	*	*	*	*	*	*	*	*	*	*	99.30	99.36	99.33	99.22
S3 B	*	*	*	*	*	*	*	*	*	*	*	*	99.21	99.08	99.18
S3 C	*	*	*	*	*	*	*	*	*	*	*	*	*	99.35	99.19
S3 D	*	*	*	*	*	*	*	*	*	*	*	*	*	*	99.27
S3 E	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

high contamination from these toxic elements. The sources of contamination at selected dumping sites are (1) haphazard dumping of e-waste, and (2) uncontrolled recycling activities of e-waste in the selected study area.

The degree of contamination for Zn, Cu, Cd, Cr, and Pb at each sampling point listed in Table 7, which clearly showed that the selected sites were highly contaminated from these metals. At site 2 and site 3, all the elements contributed to the high degree of contamination ($32 \leq C_{deg}$), whereas

a considerable degree of contamination was observed at site 1 ($16 \leq C_{deg} < 32$). Therefore, the findings suggested that all the sampling points at site 2 and 3 showed a high degree of contamination as compared to site 1.

3.5.2 Pollution load index (PLI)

The pollution load index was calculated for every sampling point using the five elements (Zn, Cu, Cd, Cr, and

Table 7 Contamination factor and pollution load index value

Sampling sites		CFs Zn	CFs Cu	CFs Cd	CFs Cr	CFs Pb	Contamination degree (C_{deg})	Pollution load index
Site 1	S1A	1.26	5.31	17.37	3.05	2.52	29.51	3.89
	S2B	1.25	5.32	18.47	3.05	2.51	30.6	3.93
	S3C	1.26	5.32	15.84	3.05	2.54	28.01	3.82
	S4D	1.26	5.31	18.59	3.06	2.48	30.7	3.93
	S5E	1.26	5.29	17.84	3.07	2.56	30.02	3.92
Site 2	S2A	1.33	5.40	25	4.03	2.2	37.96	4.36
	S2B	1.34	5.40	25.21	4.06	2.19	38.2	4.38
	S2C	1.33	5.39	24.30	4.05	2.17	37.24	4.33
	S2D	1.33	5.43	24.27	4.04	2.17	37.24	4.33
	S2E	1.33	5.43	24.29	4.02	2.21	37.28	4.35
Site 3	S3A	1.16	5.65	20.71	5.55	2.34	35.41	4.45
	S3B	1.16	5.64	21.51	5.52	2.37	36.2	4.49
	S3C	1.15	5.67	20.97	5.54	2.38	35.71	4.47
	S3D	1.16	5.66	21.39	5.56	2.34	36.11	4.49
	S3E	1.17	5.63	22.70	5.52	2.32	37.34	4.53

Table 8 Geoaccumulation index (I_{geo})

Sampling sites		I_{geo} Zn	I_{geo} Cu	I_{geo} Cd	I_{geo} Cr	I_{geo} Pb
Site 1	S1A	-0.25	1.822	3.533	1.022	0.748
	S2B	-0.26	1.825	3.622	1.021	0.741
	S3C	-0.24	1.83	3.40	1.025	0.758
	S4D	-0.25	1.824	3.631	1.026	0.723
	S5E	-0.25	1.816	3.572	1.031	0.771
Site 2	S2A	-0.171	1.847	4.058	1.427	0.527
	S2B	-0.166	1.846	4.071	1.435	0.544
	S2C	-0.170	1.845	4.017	1.434	0.531
	S2D	-0.173	1.855	4.016	1.428	0.533
	S2E	-0.178	1.855	4.017	1.423	0.558
Site 3	S3A	-0.366	1.912	3.787	1.886	0.643
	S3B	-0.364	1.911	3.842	1.879	0.659
	S3C	-0.378	1.917	3.805	1.885	0.664
	S3D	-0.373	1.914	3.833	1.889	0.640
	S3E	-0.359	1.908	3.919	1.88	0.632

Pb) and presented in Table 7. The average pollution load indices indicated that the sites are highly polluted with heavy metals ($PLI > 1$). The pattern for highly to least polluted sites was Site3 > Site2 > Site1. The results revealed that all the selected sites suffered from the degradation of soil quality due to heavy metal pollution.

3.5.3 Geoaccumulation index (I_{geo})

According to the classification suggested by Muller [43], the geoaccumulation index (I_{geo}) was used to measure the soil quality of selected e-waste dumping sites at Ahmedabad. Based on I_{geo} analysis, the selected sites were

practically uncontaminated by Zinc, as the I_{geo} values were found negative. Further, the sites were found uncontaminated to moderately polluted by Pb as the I_{geo} values for lead were found between 0 and 1.

The sampling points at site 1 and site 3 were heavily contaminated by Cd, as the I_{geo} values were found between 3 and 4, whereas site 2 was heavily to extremely contaminated by Cd, as the I_{geo} values were observed more than 4. Copper and chromium showed moderately contamination at all the sampling points, as the obtained values for I_{geo} were found between 1 and 2 for Cu and Cr. The results indicated that these metals are the major components of e-waste.

4 Conclusion

The findings of the current research work revealed high concentrations of Pb, Zn, Cd, Ni, Cr, Cu, and Fe in the soil at the e-waste dumping sites, which points to e-waste as a source of heavy metals pollution. The analysis of CFs, PLIs, and I_{geo} identified these metals as the main pollutants in the soil of the study area. However, further assessment is required to validate the pollutant relation. The current research work highlighted the unregulated dumping of e-waste, which leads to a significant increase in concentrations of heavy metals. The pollution assessment approaches and cluster analysis empowered us to determine the significant contents of heavy metals at an alarming rate at e-waste dumping sites. The levels of heavy metals found in the study area can largely affect human health since the groundwater from the region of e-waste dumping sites is used for human consumption mostly without purification. An extensive assessment needs to be carried out, in the selected region which can establish the e-waste dumping impact on the environment and human health.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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