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Original Research Article

Assessment of heavy metal contamination and soil fertility in the industrial belt of Sandila, Uttar Pradesh: Implications for aromatic crop cultivation

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Abstract

Heavy metal pollution in agricultural soils due to anthropogenic activities like industries and agrochemicals is a major concern all over the world. This study aims to evaluate soil fertility and heavy metal pollution in selected sites of the Sandila area, Uttar Pradesh, India. The composite soil samples were collected in industrial sites (I), surrounding agricultural farmlands (F) in Sandila, and the CIMAP farm as a control (C). The physicochemical properties, heavy metal content, and soil pollution indices like the geo-accumulation index, single pollution index, enrichment factor, contamination factor, and ecological risk factor were analyzed. Soil pH varied across sites—acidic in industrial (I), alkaline in farmland (F), and neutral in control (C). Nutrient levels differed significantly: available nitrogen was low in I (188.16 kg/ha) but high in F (616.75 kg/ha) and moderate in C (292.7 kg/ha). Phosphorus (P_2O_5) and potassium (K_2O) ranged from high (99 kg/ha, 309.44 kg/ha) in I to medium (27.93–252.52 kg/ha) in F and lower (22.35–126.03 kg/ha) in C. The mean elemental concentration in soils was in decreasing order as Zn > Pb > Cu> Cr > Ni > Ba > Fe > Mn > Co. Pb and Cu were major heavy metals contaminated in I and F sites. To mitigate heavy metal contamination, phytoremediation using aromatic crops is recommended.

Keywords: Enrichment factor, Geo-accumulation index, Heavy metals, PCA, Single pollution index.

Introduction

Soil contamination by heavy metals poses a significant global environmental challenge, with particularly severe implications for agricultural lands. The contamination of arable soils through anthropogenic sources has become a critical concern in recent years (Angon *et al*., 2024; Adimalla *et al*., 2019). While heavy metals can occur naturally in soils, human activities, especially industrial processes, contribute disproportionately to their accumulation (Kumar *et al*., 2019). The gravity of this issue stems from its far-reaching consequences on human health and ecosystem stability. Heavy metals in contaminated soils can enter the agricultural food chain, accumulating in fruits, vegetables and grains, thereby posing substantial health risks to consumers. Moreover, these contaminants can percolate through soil pores, leading to groundwater pollution and further exacerbating health hazards associated with water consumption (Ismanto *et al*., 2023; Adimalla & Wang, 2018). The pervasive nature of soil pollution and its direct impact on human well-being have elevated it to a primary environmental concern (Munzel *et al*., 2023; Horvath *et al*., 2018).

The studies on the heavy metal contamination in agricultural soils reported the different sources of pollution. Kumar *et al*. (2019) reported that over 80% of heavy metal pollution in soil cover primarily originates from anthropogenic sources. Zheng *et al*. (2018) identified various contributors to soil heavy metal pollution, including natural processes and human activities such as agriculture, urbanization, residential waste disposal, industrialization and mining operations. The agricultural sector itself can be a significant source of heavy metal contamination. Xiaobing *et al*. (2020) demonstrated that long-term application of fertilizers increased heavy metal concentrations in the red soils of southeast China. Similarly, Chang *et al*. (2022) highlighted the potential environmental risks associated with biogas residues and livestock slurry, which, while rich in mineral nutrients, also contribute to heavy metal content in soils.

Heavy metal contamination in agricultural soils is due to the injudicious use of pesticides and fertilizers. Paul *et al*.

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(2015) reported significantly elevated levels of chromium (Cr), copper (Cu), zinc (Zn), lead (Pb) and cadmium (Cd) in the agricultural soils of Jajmau, India, exceeding background values. Machender *et al.* (2013) found high concentrations of various heavy metals in the Chinnaeru river basin, attributing these to excessive use of fertilizers and pesticides.

The Sandila industrial area, located in the Hardoi district of Uttar Pradesh, India, is known for its numerous large-scale industries. The region's agricultural lands are particularly vulnerable to heavy metal pollution. Local farming practices involve the use of agrochemicals, including chemical fertilizers, insecticides and fungicides for crops such as wheat, sesame, radish and potato. Despite the potential risks, there is a notable scarcity of comprehensive studies assessing soil fertility and heavy metal contamination in this area. To address this knowledge gap and provide crucial insights for soil management, the present study focuses on two primary objectives, *viz.*, to evaluate soil fertility in the agricultural lands surrounding the Sandila industrial area and to assess heavy metal content and calculate soil pollution indices for the region.

Materials and Methods

Study area

Sandila is a tahsil of the Hardoi district of Uttar Pradesh, located between 27.0765° N and 80.5179° E (Figure 1). The region has a humid subtropical climate, with the lowest average temperature of 10°C in January and the maximum average temperature of 47°C in the month of June. The region is characterized by extreme winters, hot summers and rainy seasons. The rainfall occurs between April and September, with an average annual rainfall of 690 mm. Sandila is an important industrial area of Uttar Pradesh, known for the industries of pesticides, fertilizers, chemicals, food processing industries, *etc.* Agricultural crops like wheat, paddy, sesame, radish and potato are the major crops cultivated in the area.

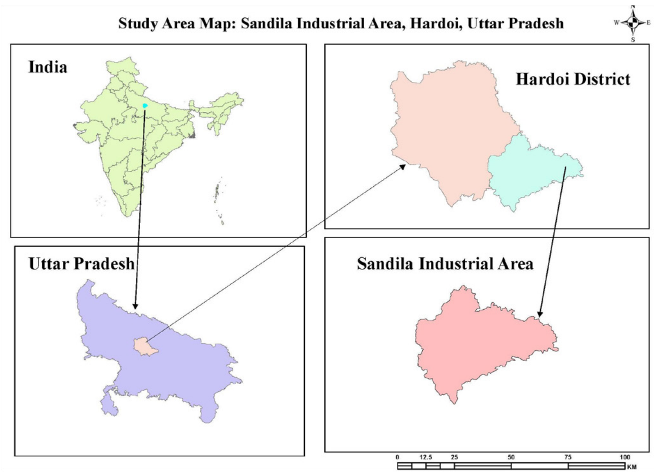

Figure 1: Location map of the study area

Soil sampling

The soil samples were collected from three separate locations: (i) Sandila industrial soil (I) from the industrial area of Sandila, (ii) Sandila farm soil (F) from the agricultural area of Sandila and (iii) from the farm area of CSIR-CIMAP (C). From each site, the composite soil samples were taken from 5 different locations in triplicate. The collected soil samples were immediately transported to the CSIR-CIMAP research laboratory, dried in the shade and sieved through a 2 mm stainless steel mesh. Each sieved sample was homogenized.

For trace element analysis, 1 g of weighed powdered soil samples was digested using a 1:5 mixture of perchloric acid ($HClO_4$) and nitric acid (HNO_3). The mixture was evaporated to dryness, and the resulting filtrates were diluted to 25 mL using Milli-Q water, following the procedure outlined by Loring & Rantala (1992). The total trace metal concentrations were then determined using inductively coupled plasma optical emission spectroscopy (ICP-OES), using a Perkin Elmer Optima 2500 model.

Physical and chemical analysis

Soil pH and Electrical conductivity were determined in a 1:2.5 soil water suspension using a pH meter and conductivity bridge (Jackson, 1958). Soil organic carbon was determined by the chromic acid wet oxidation method (Walkley & Black, 1934). The available nitrogen in the soil was determined by the alkaline potassium permanganate method (Subbiah &Asija, 1956). The available phosphorus in soil was determined by the colorimetric method (Bray & Kurtz, 1945). Available potassium in soils was determined by the neutral normal ammonium acetate method (Hanway & Heidel, 1952). The sulphur content in soil was determined by the turbidometric method (Williams & Steinberg, 1959).

Soil pollution indices

Soil pollution levels of different trace metals in the soil samples of three different study areas were evaluated using various soil pollution indices such as geo-accumulation index, single pollution index, enrichment factor and contamination factor, which are widely used to estimate the contamination levels of heavy metals (Adimalla & Wang, 2018).

Geoaccumulation index

The geo-accumulation index (GAI) is a widely used tool for assessing the degree of heavy metal pollution in soils and sediments. It was introduced by Muller (1969), primarily applied to evaluate contamination by comparing current concentrations of heavy metals in soils with pre-industrial levels, providing a quantitative measure of anthropogenic influence. The equation for the calculation of GAI is represented below.

GAI = log2* (Cn/1.5*Bn)
where,
Cn = Concentration of the element in the soil.
Bn = Geochemical background for the element.
1.5 = Constant

Single pollution index (SPI)

The single pollution index (SPI) is a simple and widely used indicator for assessing the contamination level of a specific pollutant in a given environmental medium, such as soil and sediment. The SPI provides a quantitative measure of the concentration of a specific pollutant compared to a geochemical background (Wei &Yang, 2010). It can be calculated using the equation below.
SPI = Cn/Bn

Where,

Cn = Heavy metal content in soil.
Bn = concentration of heavy metal (n) geochemical background.

Enrichment factor (EF)

The enrichment factor is a widely used geochemical tool to assess the degree of influence on the concentrations of elements in soils and sediments. The EF helps to differentiate between natural and human-induced contributions of heavy elements by comparing their current concentrations to a reference element that is typically of crustal origin and not significantly affected by human activities (Reimann & Caritat, 2000).

EF = {Cn (sample)/ Cref (sample)}/ {Bn (background)/Bref (background)}.

Where,
Cn (sample) = content of the examined element in the examined environment
Cref (sample) = content of the reference element in the examined environment
Bn (background) = content of the examined element in the reference environment.
Bref (background) = is the content of the reference element in the reference environment.

Contamination factor (CF)

The contamination factor (CF) is a widely used indicator to assess the level of contamination of a specific pollutant in soils or sediments. It is used to evaluate the extent to which the concentration of a particular contaminant has increased in comparison to its background level. CF is particularly useful for identifying anthropogenic contributions to pollution and comparing contamination levels across different locations or time periods. The CF is calculated using the equation as given by Weissmannova & Pavlovsky (2017).

CF=Cm/Bn

Where,
Cm = Mean metal concentration.
Bn = Background metal concentration.

Ecological risk factor (ER)

Ecological risk factor is the ratio of the toxic response factor to the contamination factor for a given contaminant (Hakanson 1980). It is the quantitative expression of the potential ecological risk of a given contaminant. The following equation calculates it.
Er = Tr × CF
Where,
Tr = Toxic-response factor for a given contaminant.
CF = Contamination factor.

Statistical analysis

Correlation analysis and principal component analysis (PCA) were performed to study the relationship between various variables. SPSS version 27.0 was used for analyzing the data.

Results and Discussion

The analysis of soil samples from Sandila Industrial area (I), Sandila farm soil (F) and CIMAP soil (C) revealed significant variations in physicochemical properties (Table 1). The pH analysis showed a wide variation, ranging from acidic to alkaline. It ranged from 5.63 to 6.87, 9.2 to 9.26, and 7.2 to 7.23 in Sandila Industrial soil (I), Sandila farm soil (F) and CIMAP soil (C). It was found that soils of I are acidic, F is alkaline and C is neutral. This wide range of pH values suggests diverse soil conditions, which can significantly impact nutrient availability and heavy metal mobility. The acidic nature of industrial soil (I) is particularly concerning, as it may enhance the solubility and bioavailability of heavy metals (Chuan *et. al.,*1996). The electrical conductivity of soils varied from 1.65 to 1.73 mS/cm (average of 1.69 mS/cm), 2.19 to 2.54 mS/cm (average of 2.35 mS/cm) and 0.57 to 0.77 mS/cm (average of 0.64 mS/cm) in I, F and C, respectively. The total soluble salts of the soils of F were higher, followed by I and C. The higher EC in F and I soils indicates a higher concentration of soluble salts, which could be due to excessive fertilizer use or industrial contamination. In contrast, the decrease in CIMAP farm soil may be attributed to the plant uptake and leaching by rainfall and irrigation (Geetha *et al*., 2017). The results show a complex nature of soil health and contamination in the Sandila area. The contrasting pH levels between industrial and farm soils suggest different management

Table 1: Physico-chemical properties of three different soils in Uttar Pradesh

Parameters	*Sandila industrial soil (I)*		*Sandila farm soil (F)*		*CIMAP farm soil (C)*	
	Range	*Mean*	*Range*	*Mean*	*Range*	*Mean*
pH	5.63–6.87	6.39	9.2–9.26	9.23	7.2–7.23	7.21
EC (mS/cm)	1.65–1.73	1.69	2.19–2.54	2.35	0.57–0.77	0.64
OC (%)	0.41–0.42	0.42	0.72–0.75	0.74	0.57–0.62	0.59
Available N (kg/ha)	156.8 – 219.2	188.16	595.84–627.2	616.75	282.24–313.6	292.7
Available P (kg/ha)	96.46–101.77	99.00	26.16–29.29	27.93	21.12–24.39	22.35
Available K(kg/ha)	295.43–323.89	309.44	249.36–254.78	252.52	112.48–136.88	126.03
Available S (kg/ha)	21.12–23.39	22.4	6.05–9.36	7.71	10.0–10.12	10.14
Iron (mgkg^{-1})	46–51	48.33	13–17	15	4.2–5.4	4.7
Manganese (mgkg^{-1})	40.6–49.6	45.27	14.6–18.6	16.6	5.6–7.6	6.63
Copper (mgkg^{-1})	307–313	309.67	270–283	277.33	11–13.6	12.97
Zinc (mgkg^{-1})	630–636	633.00	589–611	602.67	83–95	88.67

(Note: I-Sandila industrial soil, F -Sandila farm soil C -CIMAP farm soil; <0- un contamination, (0-1)- uncontaminated -moderately contaminated, (1-2)- moderately contaminated, (2-3)-moderately to strongly contaminated, (3-4)- strongly contaminated, (4-5)- Strongly- extremely contaminated, >5- extremely contaminated.)

practices or contamination sources. The acidic nature of industrial soil is particularly concerning as it may enhance heavy metal mobility and bioavailability. The organic carbon content varied from 0.4 to 0.42% (0.42%), 0.72 to 0.75% (0.74%), and 0.57 to 0.62% (0.59%) in I, F, and C, respectively. The higher organic carbon content was observed in F, followed by I and C. The higher organic carbon content was found in F, indicating improved soil health and a higher potential for nutrient retention due to organic matter accumulation.

The available nitrogen content varied from 156.8 to 219.2 kg/ha (188.16 kg/ha), 595.84 to 627.2 kg/ha (616.75 kg/ha), and 282.24 to 313.6 kg/ha (292.7 kg/ha) in I, F, and C, respectively. The higher available N was observed in F, followed by C and I. The higher nitrogen content was recorded in F, suggesting enhanced microbial activity and mineralization from organic residues (Kaleem Abbasi *et al*., 2015).

The available phosphorus content in three different soils varied from 96.46 to 101.77 kg/ha (99 kg/ha), 26.16 to 29.29 kg/ha (27.93 kg/ha), and 21.12 to 24.39 kg/ha (22.35 kg/ha) in I, F, and C, respectively. The highest available phosphorus was found in I, followed by F and C. Elevated phosphorus in industrial soil may result from phosphatic pollutants and industrial waste accumulation (Villalba & Gara *et al*., 2008). Farm and CIMAP soils exhibited lower phosphorus levels, likely due to crop uptake and limited phosphorus amendments (Agegnehu *et al*., 2016).

Available potassium varied from 295.43 to 323.89 kg/ha (309.44 kg/ha), 249.36 to 254.78 kg/ha (252.52 kg/ha), and 112.48 to 136.88 kg/ha (126.03 kg/ha) in I, F, and C. The higher available K_2O was found in I, followed by F and C. High potassium in industrial soil could be attributed to inorganic residue accumulation, whereas farm soil retained moderate potassium levels due to fertilization practices. Available sulphur in three different soils ranged from 21.12 to 23.39 mg/kg (22.4 mg/kg), 6.05 to 9.36 kg/ha (7.71 mg/kg), and 10 to 10.12 kg/ha (10.14 mg/kg) in I, F, and C, respectively. The higher available sulphur was found in I, followed by F and C. The higher sulfur levels in industrial soil suggest possible contamination from industrial emissions.

Plant-available micronutrients such as Cu, Fe, and Mn present in the three different soils are estimated through laboratory analysis by the DTPA method using ICP-OES. The copper content varied from 6.75 to 6.87 mg/kg (6.81 mg/kg), 1.05 to 1.15 mg/kg (1.11 mg/kg), and 0.61 to 0.64 mg/kg (0.62 mg/kg) in I, F, and C. The higher copper content was found in I, followed by F and C. The Fe content varied from 10.26 to 11.58 mg/kg (10.88 mg/kg), 7.12 to 8.68 mg/kg (7.72 mg/kg), and 1.52 to 2.48 mg/kg (1.98 mg/kg) in I, F, and C, respectively. The highest Fe was found in I, followed by F and C. The manganese content varied from 15.53 to 16.35 mg/kg (16.04 mg/kg), 9.99 to 10.91 mg/kg (10.57 mg/kg), and 2.01 to 2.83 mg/kg (2.43 mg/kg) in I, F, and C. The higher Mn content was found in I, followed by F and C.

The descriptive statistics of the heavy metal concentrations in representative samples are presented in Table 2. The mean values of elemental contents in soils follow in decreasing order as Zn > Pb > Cu> Cr > Ni > Ba > Fe > Mn > Co (Table 2). The Barium content was found to be higher in Sandila Industrial, Sandila farm area, followed by CIMAP farm soil. The Ba content ranged from 110.8 to 124.8 mg/kg, 60 to 75.7 mg/kg, and 7.8 to 8.8 mg/kg,

Table 2: Descriptive statistic for heavy metal concentrations in Industrial soil (mg/kg)

Metals	*Sites*	*Mean*	*Median*	*SD*	*Skewness*	*Kurtosis*
Ba	I	116.42	115.5	6.212	0.470	-1.758
	F	68.3	68.8	5.744	-0.355	0.931
	C	8.26	8.5	0.527	-0.495	-2.562
Co	I	26.98	29.5	6.668	-1.843	3.577
	F	20.08	20.5	1.846	-0.925	1.618
	C	2.58	2.5	0.192	1.517	2.608
Cr	I	212.5	213.5	7.550	0.219	-0.017
	F	163.02	165.5	8.178	-1.236	1.179
	C	22.94	21.6	5.243	0.875	1.106
Cu	I	309.8	309	2.414	0.386	-1.445
	F	277.64	278.4	5.460	-0.566	-1.247
	C	12.32	12.2	1.163	0.073	-2.668
Fe	I	48.74	49.5	2.220	-0.431	-2.619
	F	15.3	4.6	0.522	0.541	-1.441
	C	4.68	15.9	1.655	-0.647	-1.488
Mn	I	45.14	45.4	3.660	-0.071	-1.693
	F	16.6	16.6	1.614	0.000	-1.566
	C	6.64	6.6	0.792	-0.125	-1.170
Ni	I	181.38	181.4	5.140	0.068	-1.191
	F	154.8	153.4	5.393	0.466	-1.733
	C	15.66	15.8	1.195	-0.454	-0.947
Pb	I	515.32	512.5	4.996	0.843	-1.214
	F	461.6	462	3.399	0.427	0.238
	C	41.58	41.5	3.235	0.618	1.858
Zn	I	633	633	2.372	0.000	-1.200
	F	602.6	604	8.735	-1.047	0.785
	C	89	88.5	4.677	0.046	-0.915

with a mean value of 116.8, 68.27, and 8.45 mg/kg in I, F, and C. The content of Ba in soils was found to be below the threshold limit of 750 mg/kg (CEPA, 2007). The Cr content ranged from 203 to 223 mg/kg, 150 to 170 mg/kg, and 17 to 31 mg/kg, with mean values of 212, 163.33, and 22 mg/kg in I, F and C, respectively. The content of Cr in Sandila soils was found to be above the threshold limit of 64 mg/kg soil. This indicates the contamination of soils by chromium. The Co content ranged from 27.2 to 32.2 mg/kg, 17.2 to 22.2 mg/kg, and 2.5 to 2.9 mg/kg, with a mean value of 29.87, 20.53, 2.73 mg/kg in I, F, and C, respectively. The total Co content was found to be lower than the threshold limit of 40 mg/kg (CEPA, 2007). The Cu content ranged from 307 to 313 mg/kg, 270 to 283 mg/kg, and 11 to 13.6 mg/kg mg/kg with mean values of 309.67, 277.33, and 12.97 mg/kg in I, F, and C, respectively. The Cu content in both Sandila soils was found to be higher than the threshold limit of 63 mg/kg (CEPA 2007). The Fe content ranged from 46 to 51 mg/kg, 13 to 17 mg/kg, and 4.2 to 5.4 mg/kg, with a mean value of 48.33, 15, and 4.7 mg/kg in I, F, and C, respectively. The Pb content ranged from 512.5 to 522.5 mg/kg, 457.5 to 466.5 mg/kg, and 37.5 to 46.5 mg/kg, with the mean value of 515.83, 461.5, and 41.17 mg/kg in I, F, and C, respectively. The Pb content in both Sandila soils was found to be higher than the threshold limits of 70 (CEPA, 2007). The Mn content ranged from 40.6 to 49.6 mg/kg, 14.6 to 18.6 mg/kg, and 5.6 to 7.6 mg/kg, with mean values of 45.27, 16.6, and 6.63 mg/kg in I, F, and C, respectively. The Ni content ranged from 175 to 188 mg/kg, 149 to 162 mg/kg, and 14 to 17 mg/kg, with mean values of 180.67, 154, and 15.67 mg/kg in I, F, and C, respectively. The Ni content in both Sandila soils were found to be higher than the threshold limits of 70 (CEPA, 2007) The Zn content ranged from 630 to 636 mg/kg, 589 to 611 mg/kg, 83 to 95 mg/kg with mean value of 633, 602.67, 88.67 mg/kg in I, F, and C, respectively. These elevated levels indicate significant heavy metal contamination, likely due to industrial activities and potentially excessive use of agrochemicals in the farm area (Alengebaw *et al*., 2021). Barium (Ba) and cobalt (Co) were found to be below their respective threshold limits, suggesting these metals may not be of immediate concern in the study area. The high levels of available phosphorus and potassium in industrial soil, coupled with lower organic carbon and nitrogen, indicate potential imbalances in nutrient cycling. This could be due to industrial pollution altering soil chemistry or the use of contaminated water for irrigation. The strong correlations among heavy metals in the industrial soil provide evidence for common sources of contamination. This information is crucial for developing targeted remediation strategies and for identifying and mitigating the primary sources of pollution in the area. Given the elevated heavy metal contamination (Cr, Cu, Pb, Ni, Zn) in Sandila's industrial (I) and farm (F) soils, coupled with imbalanced nutrient profiles, phytoremediation strategies using aromatic crops such as lemongrass (*Cymbopogon citratus*) and palmarosa (*Cymbopogon martinii*) are strongly recommended. These crops are well-suited for metal-stressed environments due to their tolerance to heavy metals, low metal translocation to harvestable parts (essential oils), and ability to thrive in diverse pH conditions (acidic to alkaline) (Pandey & Singh, 2017).

Correlation matrix

The correlation matrix (Figure 2) for heavy metals in the industrial area reveals strong positive correlations among several metals. Zinc shows a perfect positive correlation (r = 1.000) with nickel, indicating a possible common source or similar behavior in the soil. Very strong positive correlations (r > 0.9) were observed between Cr, Cu, Mn, Ni, and Zn, suggesting these metals may have similar sources or are influenced by similar factors in the industrial environment. Lead (Pb) showed strong positive correlations with most other metals, particularly with Cu (r = 0.906) and Ni (r = 0.889), further supporting the idea of common contamination sources. These strong correlations suggest that the heavy metal contamination in the Sandila Industrial area likely originates from similar anthropogenic sources, possibly from industrial effluents, and the use of contaminated water for irrigation.

Principal component analysis

PC1 accounts for 96.22% of the total variance in the dataset, while PC2 explains an additional 3.72%. Together, these two principal components capture 99.94% of the total variance (Figure 3). Most variables cluster on the positive side of PC1, suggesting a strong positive correlation among many elements and soil properties. A clear separation exists between the two groups of variables along PC1.

PC1 includes most heavy metals (Fe, Mn, Ni, Pb, Zn, and Cu) and several soil properties (EC, N, P, K, and S) that exhibit positive relationships, while pH, OC, and Ba show negative associations. Cr and Co are positioned between these two main groups. The exceptionally high variance explained by the first two PCs (99.94%) indicates a simple underlying structure in the dataset, suggesting that most variables are strongly interrelated and can be effectively represented by just two principal components. The clustering of heavy metals (Fe, Mn, Ni, Pb, Zn, and Cu) alongside soil nutrients (N, P, K, and S) implies that these elements may share common sources or exhibit similar behaviors in the soil. Lower pH (more acidic conditions) is associated with higher concentrations of heavy metals and nutrients, which aligns with known soil chemistry, where acidic conditions often enhance the solubility and bioavailability of many elements. Additionally, higher organic carbon content correlates with lower concentrations of most elements, indicating that organic matter may play a role in immobilizing or complexing these elements, thereby reducing their detectability or availability.

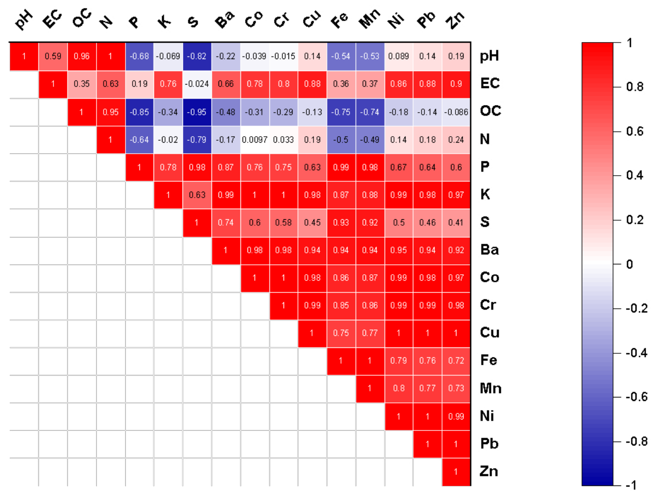

Figure 2: Correlation matrix for the chemical properties and metals in industrial soils

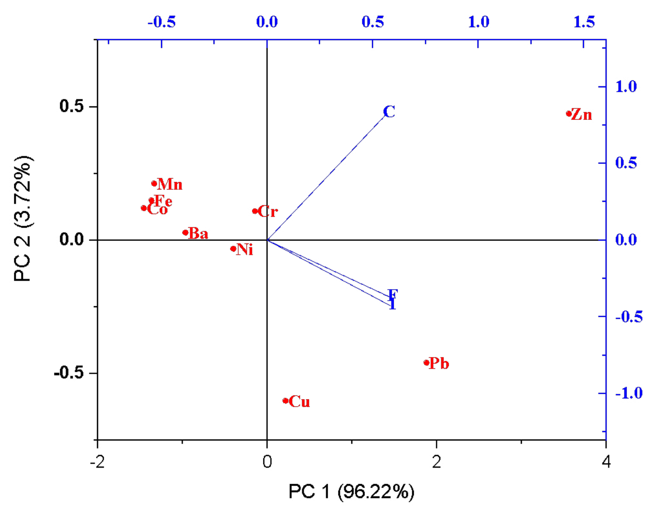

Figure 3: Principal component analysis of chemical properties and heavy metals in the industrial soils

Figure 4: Geo-accumulation index of different metals in different soils

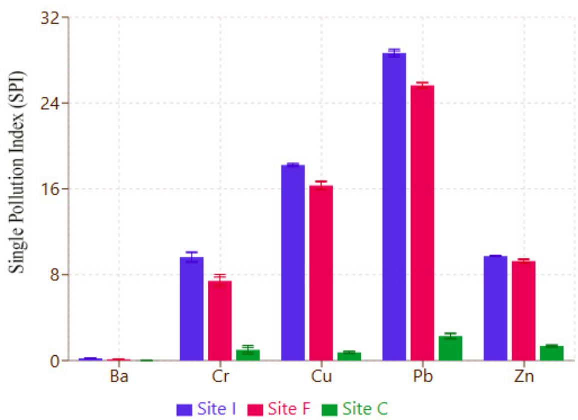

Figure 5: Single pollution index of different metals in different soils

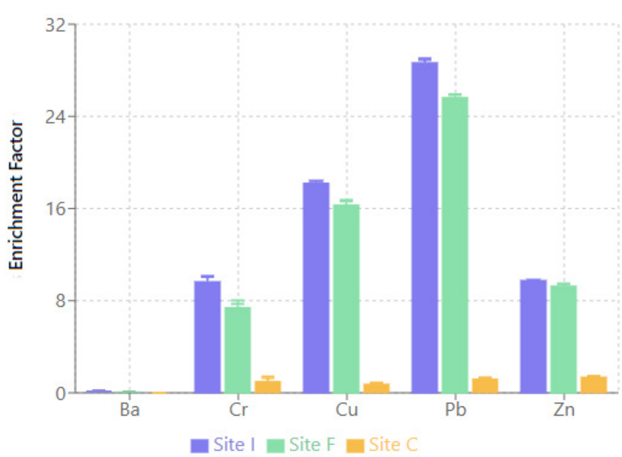

Figure 6: Enrichment factor of different metals in different soils

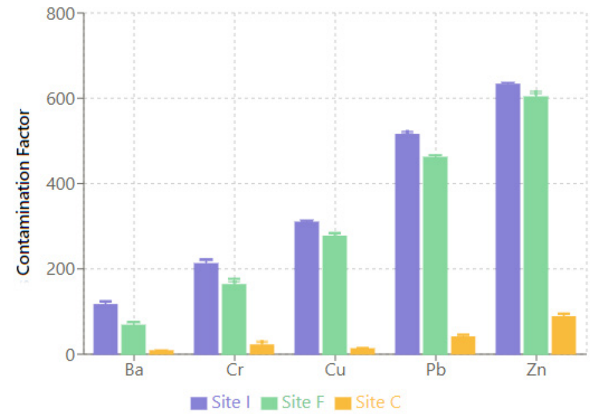

Figure 7: Contamination factor of different metals in different soils

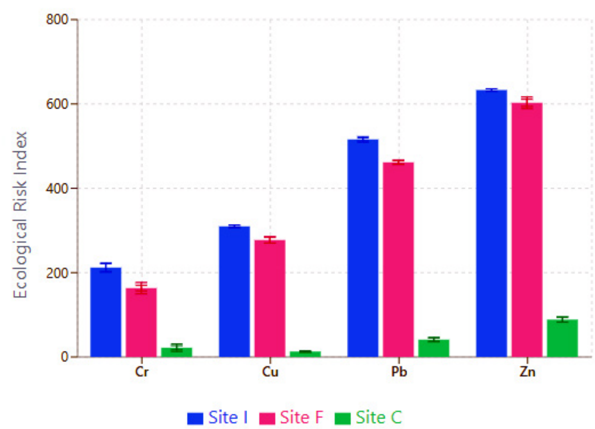

Figure 8: Ecological risk of different metals in different soils.

Geo-accumulation index

The GAI is a widely used metric to assess heavy metal contamination in agricultural soils (Adimalla & Wang, 2018; Muller, 1969). Our analysis revealed a range of contamination levels across the study area (Figure 4): Uncontaminated (GAI < 0): Ba in all soils (I, F, C); Cr, Cu, and Zn in CIMAP soil (C), uncontaminated to moderately contaminated (GAI = 0-1): Pb in CIMAP soil (C), moderately contaminated (GAI = 1-2): Cr in Sandila Industrial (I) and farm (F) soils, moderately to strongly contaminated (GAI = 2-3): Zn in I and F soils, strongly contaminated (GAI = 3-4): Cu in I and F soils, strongly to extremely contaminated (GAI = 4-5): Pb in I and F soils. The order of GAI values (Pb > Cu > Zn > Cr > Ba) indicates that lead is the most significant contaminant, followed by copper and zinc. This pattern suggests a gradient of contamination severity and potential sources.

Single pollution index

The single pollution index (SPI) provides insights into the relative degree of contamination in soils (Stevanovic *et al.*, 2018; Zheng *et al.*, 2018). SPI values greater than 1 indicate soil contamination. From the results, it was observed that low contamination (SPI ≤ 1): Ba in all soils; Cr and Cu in CIMAP soil (C), medium contamination (1 < SPI ≤ 3): Pb and Zn in CIMAP soil (C) and High contamination (SPI > 3): Cr, Cu, Pb, and Zn in Sandila Industrial (I) and Farm (F) soils. (Figure 5.). The decreasing order of mean SPI values (Pb > Cu > Zn > Cr > Ba) aligns with the GAI results, further emphasizing the severity of lead and copper contamination.

Enrichment factor

The enrichment factor (EF) assesses the intensity of anthropogenic contaminant deposition on surface soil (Keshavarzi *et al.,* 2018). Our analysis revealed that deficiency to minimal enrichment (EF < 2): Ba in all soils; Cr and Cu in CIMAP soil (C), moderate enrichment (EF = 2-5): Pb and Zn in CIMAP soil (C), significant enrichment (EF = 5-20): Cr, Cu, Pb, and Zn in Sandila industrial (I) and farm (F) soils, very high enrichment (EF = 20-40): Cu and Pb in Sandila industrial (I) and farm (F) soils (Figure 6). The decreasing order of mean EF values (Cu > Pb > Zn > Cr > Ba) highlights copper as the most enriched metal, closely followed by lead and zinc.

Contamination factor

The contamination factor (CF) evaluates the intensity of heavy metal contamination in soil (Kumar & Singh, 2018). From the obtained results, it was observed that, low contamination (CF < 1): Ba in all soils; Cu in CIMAP soil (C), moderate contamination (1 ≤ CF ≤ 3): Cr, Pb, and Zn in CIMAP soil (C), very high contamination (CF ≥ 6): Cr, Cu, Pb, and Zn in Sandila Industrial (I) and Farm (F) soils (Figure 7). The decreasing order of mean CF values (Pb > Cu > Ni > Zn > Cr > Co > Mn > Ba > Fe) provides a comprehensive ranking of contamination intensity across all analyzed metal

Ecological risk

The ecological risk index (ER) (Figure 8) revealed a distinct spatial contamination pattern. CIMAP soil exhibited mild ecological risk across all analyzed metals, reflecting minimal environmental threats. However, industrial and farm soils posed ecological risks, particularly for Cu and Pb (Er = 80–160), underscoring their potential to disrupt soil microbial communities and impact plant health. Cr and Zn presented mild ecological risks, consistent with previous findings suggesting their lower bioavailability in contaminated soils. The high Cu and Pb contamination in industrial and farm soils raises significant concerns regarding agricultural sustainability.

Conclusion

The research findings revealed soil contamination patterns under different land use systems characterized by significant variations in physicochemical properties. Heavy metal analysis showed elevated concentrations following the pattern Zn > Pb > Cu > Cr > Ni > Ba > Fe > Mn > Co, with Pb, Cu, Cr, and Ni in industrial soils. The soil pollution indices, including geo-accumulation index (GAI), single pollution index (SPI), enrichment factors (EF), contamination factors (CF), and ecological risk (ER) assessment, indicated significant contamination levels for Cu and Pb. The cultivation of aromatic crops such as lemongrass and palmarosa is recommended as a sustainable phytoremediation strategy for the contaminated soils.

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Author Contribution

Shivanna B: Actual experimentation and manuscript draft preparation; Akanksha Singh: Data collection and draft preparation; Jnanesha, A C: Data analysis and Review; Ranjith Kumar S: Review; Anandakumar T M: Review; and Yogendra N D: Review, Puja Khare: Review.

Conflict of Interest

The authors declare no conflict of interest.

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