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Research Article

Comparative Assessment of Heavy Metal Contamination in Surface Soils across Industrial, Urban, Rural, and Agricultural Areas

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ABSTRACT

This study investigates heavy metal contamination in surface soils across industrial, urban, rural, and agricultural land use types in Nowshera District, Pakistan. The research addresses the critical issue of soil contamination resulting from anthropogenic activities such as industrial emissions, urban expansion, and agricultural intensification. A total of 76 soil samples were collected from 34 sites representing diverse land use types and analyzed for heavy metals, including lead (Pb), cadmium (Cd), zinc (Zn), copper (Cu), and nickel (Ni), using flame atomic absorption spectrophotometer. Physicochemical properties, including pH, organic matter content, and salinity, were also measured to understand their influence on heavy metal distribution. Results indicate significant variations in heavy metal concentrations across land use types, with industrial soils showing the highest contamination levels. For instance, the mean Pb concentration in industrial soils (175.6 mg/kg) was nearly four times higher than in rural soils (46.3 mg/kg). Similarly, Zn levels were significantly elevated in industrial areas, averaging 430.6 mg/kg compared to 122.7 mg/kg in rural soils. Urban soils exhibited moderate contamination, driven by vehicular emissions and construction activities, while agricultural soils showed lower overall contamination but localized hotspots due to agrochemical use. Pollution indices such as the Geo-accumulation Index (Igeo) and Pollution Load Index (PLI) confirmed anthropogenic contributions to heavy metal accumulation. Spatial analysis using GIS identified contamination hotspots, particularly in industrial and urban areas, highlighting the need for targeted remediation strategies. Multivariate statistical analyses, including Principal Component Analysis (PCA) and Cluster Analysis (CA), revealed distinct groupings of metals based on anthropogenic and lithogenic sources. These findings underscore the critical influence of land use practices on soil contamination dynamics. This study provides a comprehensive evaluation of heavy metal contamination in Nowshera's soils, offering valuable insights for sustainable land management and pollution mitigation strategies. The research emphasizes the importance of integrating scientific assessments with policy interventions to address the ecological and health risks posed by heavy metal pollution.

Keywords: Heavy Metals, Industrial, Urban, Rural, Agriculture, Nowshera.



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INTRODUCTION

The contamination of surface soils with heavy metals has emerged as a pressing environmental challenge, primarily driven by human activities such as industrialization, urbanization, and agricultural intensification. The heavy metals, including lead (Pb), cadmium (Cd), and nickel (Ni), are non-biodegradable and persist in the environment for extended periods, accumulating to levels that pose significant ecological and health risks (Adhikari et al., 2024). While certain metals, such as zinc (Zn) and copper (Cu), are essential nutrients, their excessive accumulation can have detrimental effects on soil and human health, necessitating a comprehensive understanding of their distribution and sources (Akter et al., 2023).

Heavy metal contamination in soils is intricately linked to land use patterns. Industrial areas, characterized by emissions and effluents from factories, often exhibit elevated levels of metals such as Pb, Cu, and Zn, largely attributed to metallurgical and chemical industries (Cao et al., 2024). Urban environments, dominated by vehicular traffic and construction activities, contribute significantly to the accumulation of heavy metals such as Cd and Ni through emissions and waste management issues (Bibi et al., 2023; Chudasama et al., 2024). Agricultural soils, although less industrially impacted, are not immune to contamination; the excessive use of fertilizers, pesticides, and irrigation with polluted water introduces metals such as arsenic (As) and Cd (Feng et al., 2024). Rural soils, often perceived as pristine, are increasingly impacted by anthropogenic activities, including the use of untreated wastewater and agricultural inputs (Herath et al., 2018). High concentration of heavy metals in untreated irrigation water not only deteriorate soil structure but also enhance concentration of these heavy metals in crops especially in case of rice as reported by Rehman et al 2024.

The distribution and levels of heavy metal contamination in soils vary significantly, as evidenced by comparative studies worldwide. For instance, industrial soils in Hyderabad, Pakistan, show elevated Pb and Cu concentrations due to localized industrial activities (Bux et al., 2021). Similarly, urban soils in Ado-Ekiti, Nigeria, are hotspots for Zn and Cd, reflecting the influence of vehicular emissions and construction debris (Emumejapor & Adewumi, 2023). Agricultural soils in peri-urban areas of Cangxi County, China, demonstrate the impact of prolonged agrochemical use, with high levels of Cu and Zn attributed to fertilizer and pesticide applications (Feng et al., 2024). These studies underscore the necessity of localized investigations to identify specific contamination sources and inform mitigation strategies.

The Nowshera District of Khyber Pakhtunkhwa province, Pakistan, with its diverse land use patterns encompassing industrial, urban, rural, and agricultural areas, provides a compelling case for analyzing heavy metal contamination. Industrial zones in Nowshera are typified by factories producing marble, textiles, and paper, which contribute significantly to heavy metal emissions (Bibi et al., 2023). Urban areas, characterized by dense populations and vehicular traffic, exhibit elevated levels of Pb and Zn due to traffic related emissions and improper waste disposal (Cao et al., 2024; Jiang et al., 2024). Agricultural lands in the district, primarily used for cultivating wheat, maize, and sugarcane, are subject to contamination from agrochemicals and irrigation with untreated wastewater (Rana et al., 2024). Furthermore, the open discharge of these waste water pollutants into the water bodies, and in the nearby fields cause water and soil pollution in Khairabad area of Nowshera district. It is due to inefficient environmental laws, financial resources, lack of wastewater treatment facilities and awareness of the concerned sectors and communities (Khan et al 2017). Rural soils, although less intensively used, face emerging contamination challenges from nearby industrial and urban activities. The persistence and mobility of heavy metals in soils are influenced by various physicochemical properties, including pH, organic matter (OM), and salinity. Alkaline soils, such as those prevalent in Nowshera, often exhibit reduced mobility of metals like Cd and Ni, which are retained through sorption processes (Hošek et al., 2024). However, the presence of organic matter can enhance the mobility of certain metals, complicating the contamination dynamics (Akter et al., 2023). Understanding these interactions is crucial for assessing contamination risks and developing targeted soil management strategies.

To quantify the extent of heavy metal contamination, indices such as the Geo-accumulation Index (Igeo), Pollution Load Index (PLI), and Enrichment Factor (EF) are widely used (Khalid et al., 2016). These indices provide a standardized approach for evaluating contamination levels and identifying anthropogenic contributions. For instance, the application of Igeo in industrial soils of Laizhou, China, revealed significant Pb enrichment, consistent with observations in Nowshera's industrial zones (Cao et al., 2024). Similarly, PLI values in urban soils of Shizuishan, China, highlighted moderate to severe contamination, comparable to urban areas in Nowshera (Bai et al., 2023). Pb enriched sewage water was also reported in the surroundings of marble factories of Nowshera district (Khan et al 2017). In addition to quantifying contamination, spatial analysis tools such as Geographic Information Systems (GIS)

offer valuable insights into the distribution patterns of heavy metals. GIS-based mapping of contamination hotspots enables the identification of priority areas for remediation. For example, GIS analysis of urban soils in Hyderabad, Pakistan, revealed distinct contamination gradients, guiding targeted interventions (Bux et al., 2021). Similar approaches in Nowshera could provide actionable data for addressing heavy metal pollution.

Multivariate statistical methods, including Principal Component Analysis (PCA) and Cluster Analysis (CA), further elucidate the relationships between heavy metals and their sources. PCA conducted in Changchun, China, identified industrial and agricultural activities as dominant contributors to soil contamination (Li et al., 2024). The environmental and health implications of heavy metal contamination necessitate urgent attention. Elevated Pb levels in soils have been linked to cognitive impairments and developmental delays in children, while excessive Cd exposure is associated with kidney damage and osteoporosis (Pujari & Kapoor, 2020). The ingestion of contaminated crops or water further exacerbates these risks, emphasizing the need for sustainable soil management practices. Studies from Bangladesh and China highlight the role of regulatory frameworks and community awareness in mitigating contamination risks (Rana et al., 2024).

This study compares heavy metal contamination in the surface soils of Nowshera District across industrial, urban, rural, and agricultural areas. By analyzing the results from these different land uses, it identifies key pollution sources and trends. The goal is to understand how land use affects contamination and to provide insights that can help reduce heavy metal pollution. The study aims to support sustainable land management practices and inform policymakers to manage soil contamination.

MATERIALS AND METHODS

The study sites lies between 33°5'94.51 to 34°4'47.47"N and 71°5'40.68 to 72° 8'52.21"E, with a range of 111375 m². The study area is located in the north of Nowshera district, covering Nowshera city and four other small towns i.e. Rashakai, Sherin Kot, Risalpur and Amanghar as well as almost eight villages i.e. Hassan-e-Abal, Sabat Keli, Zandobanda, Ghaladair, Barabanda, Khat keli, Pir sabaq and Sultan gari. A total of 76 surface soil samples were collected from 34 sites, ensuring comprehensive representation across all land use types. In industrial areas, samples were taken from factories producing marble, textiles, and paper. Urban areas were sampled at roadsides, playgrounds, and residential zones. Rural areas were sampled near village peripheries, while agricultural sites included fields growing wheat, maize, and sugarcane. Sites were selected based on proximity to potential contamination sources. Soil samples were collected using a standardized protocol to ensure consistency across all sites. A hand auger and plastic scoop were used to collect samples from the top 0-20 cm soil layer. The samples were air dried for 24 hours, sieved through a 2mm mesh to remove debris, and stored in labeled polyethylene bags to prevent cross contamination. Laboratory preparation involved grinding the soil samples into a fine powder (<0.15 mm) using a porcelain mortar and pestle to ensure uniform chemical analyses.

Physicochemical properties

Parameters including pH, EC, TDS and Salinity were determined in the Laboratory according to SFRI Guide Soil Fertility Research Institute, Punjab, Lahore. pH was determined by pH meter (Thermo Scientific). EC (ORION STAR A0151), TDS and Salinity were determined by using conductivity meter, Alkalinity (acid-base titrometry), chlorides (Silver nitrate titrometry), phosphates (ammonium molybdate method), nitrate-nitrogen (phenol-disulphonic method) were determined by their respective methods (APHA, 1998 and Garg et al., 2002) (Qazi et al, 2021). All chemical reagents used in the soil analyses were of analytical grade and procured from Merck, Germany or BDH, England with 99.9% certified purity. The analysis was done in Soil & Water Testing Laboratories of Jhelum & Mandi Baha ud Din. The analysis was done at laboratories in Jhelum and Mandi Baha ud Din.

Heavy metal quantification

Concentrations of 6 heavy metals, including cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn), were determined using microwave-assisted acid digestion with nitric acid (HNO₃) and hydrochloric acid (HCl). The resulting solutions were analyzed using atomic absorption spectrophotometer (AAS - iCE 3000 series Thermo Scientific) following the U.S. EPA Method 3051A. Calibration standards and strict quality control procedures were followed throughout the process (U.S. EPA, 2007).

Pollution indices calculation

To assess contamination levels, several pollution indices were calculated. The Geo-accumulation Index (I_{geo}) was computed for each land use type using the formula:

$$I_{geo} = \log_2 (C_n / 1.5B_n)$$

where C_n is the measured concentration of the element in the sample and B_n is the geochemical background value for the element in the soil. The constant 1.5 accounts for natural variations and minor anthropogenic influences (Muller, 1969). The Pollution Load Index (PLI) was calculated as:

$$PLI = (C_{f1} \times C_{f2} \times C_{f3} \dots C_{fn}) \text{ and } C_{f \text{ metal}} = C_{\text{metal}} / C_{\text{background}}$$

Where C_f = concentration factor, n = no. of metals, C_{metal} = metal concentration in the soil and $C_{\text{background}}$ = background concentration of element in the shale (Turekian and Wedepohl, 1961). A PLI value greater than 1 indicates pollution, while values below 1 suggest no pollution (Tomlinson et al., 1980).

The Enrichment Factor (EF) was used to identify anthropogenic contributions to heavy metal contamination. This factor compares the metal concentration in the soil to a reference element (e.g., magnesium) with low variability. EF is calculated as:

$$EF = \frac{C_n(\text{sample}) / C_{\text{ref}}(\text{sample})}{B_n(\text{background}) / B_{\text{ref}}(\text{background})}$$

Where C_n (sample) is the concentration of the element in the study area. C_{ref} (sample) is the concentration of the reference element in the environment, B_n (background) is the concentration of examined element in the reference environment and B_{ref} (background) is the concentration of the reference element in the reference environment (Buat-Menard et al., 1979).

Heavy Metal and Land use Correlation

To analyze the correlation between heavy metal concentrations and land use types, Pearson correlation coefficients were calculated. Metals such as Pb, Cu, Zn, and Ni were correlated with soil physicochemical parameters including pH, EC, and OM. Statistical software (e.g., SPSS v20) was used to ensure robust and reproducible results. Data were analyzed separately for each land use category (industrial, urban, agricultural, and rural) to identify specific relationships.

Spatial Analysis (GIS)

The spatial distribution of heavy metal concentrations was mapped using ArcGIS v9.2 software. The Inverse Distance Weighting (IDW) method was applied to incorporate data across un-sampled regions, generating higher resolution maps for each metal. These maps highlighted contamination hotspots and spatial variability. Data layers were integrated to visualize combined pollution risks across different land use types.

Multivariate Statistical Analysis

Principal Component Analysis (PCA) and Cluster Analysis (CA) were performed to explore the relationships between heavy metals and soil properties. Factor loading results were interpreted to distinguish anthropogenic from natural sources of contamination. Statistical significance was assessed using a threshold eigen value of >1 , with varimax rotation applied for clarity (Facchinelli et al., 2001).

Table 1. Statistical Summary of Physicochemical Properties along Different land Types.

Land use	Statistics	pH	EC (dS/m- 1)	TDS (mg/Kg- 1)	Salinity (mg/Kg)	PO ₄ ⁻³ (mg/Kg)	Alkalinity (mg/Kg)	Cl ⁻¹ (meq L ⁻¹)	O.M (%)	NO ₃ ⁻¹ - N(mg/Kg)
Industrial	Mean	8.8	1.0	662.0	48.0	1.1	196.8	199.2	4.3	33.2
	Range	7.6- 10.2	0.07- 2.64	40-810	3.5-132	0.449- 1.41	120-300	29.82- 564	1.48- 4.28	0-84.26
Rural	Mean	8.8	0.7	476.7	13.4	1.1	200.0	96.4	4.1	22.7
	Range	8.4- 9.0	0.17- 2.8	120- 1970	8.5-18	0.234- 2.55	140-260	25.844- 337.9	2.729- 5.09	2.104- 44.74
Urban	Mean	8.7	0.9	711.7	30.8	1.3	246.0	141.5	3.1	27.1
	Range	7.8- 10.10	0.07- 2.87	270- 1870	3.5-56	0.366- 3.5	72-480	39.76- 437.36	0.992- 5.58	7.087- 38.82
Agricultural	Mean	9.0	0.2	135.3	8.0	2.2	262.6	64.2	4.2	16.0
	Range	8.5- 9.5	0.03- 1.2	30-810	1.5- 59.5	1.06- 3.7	100-520	19.88- 437.4	2.23- 7.6	2.745- 82.5

Quality Assurance and Quality Control (QA/QC)

Throughout the study, stringent QA/QC measures were implemented to ensure data reliability. Calibration curves were prepared for each metal, reagent blanks were analyzed for contamination, and duplicate samples were

processed to assess reproducibility. Recovery rates were maintained above 95%, minimizing errors and enhancing the credibility of the findings.

RESULTS

Concentrations by Land Use

The analysis of heavy metal concentrations across industrial, urban, rural, and agricultural soils in Nowshera District reveals distinct variations driven by land use practices. These variations are critical for understanding the extent of contamination and identifying sources of heavy metals. The data visualized in Figures 1, 2, 3, and 4 provide a comprehensive overview of the spatial and quantitative distribution of metals in the study area.

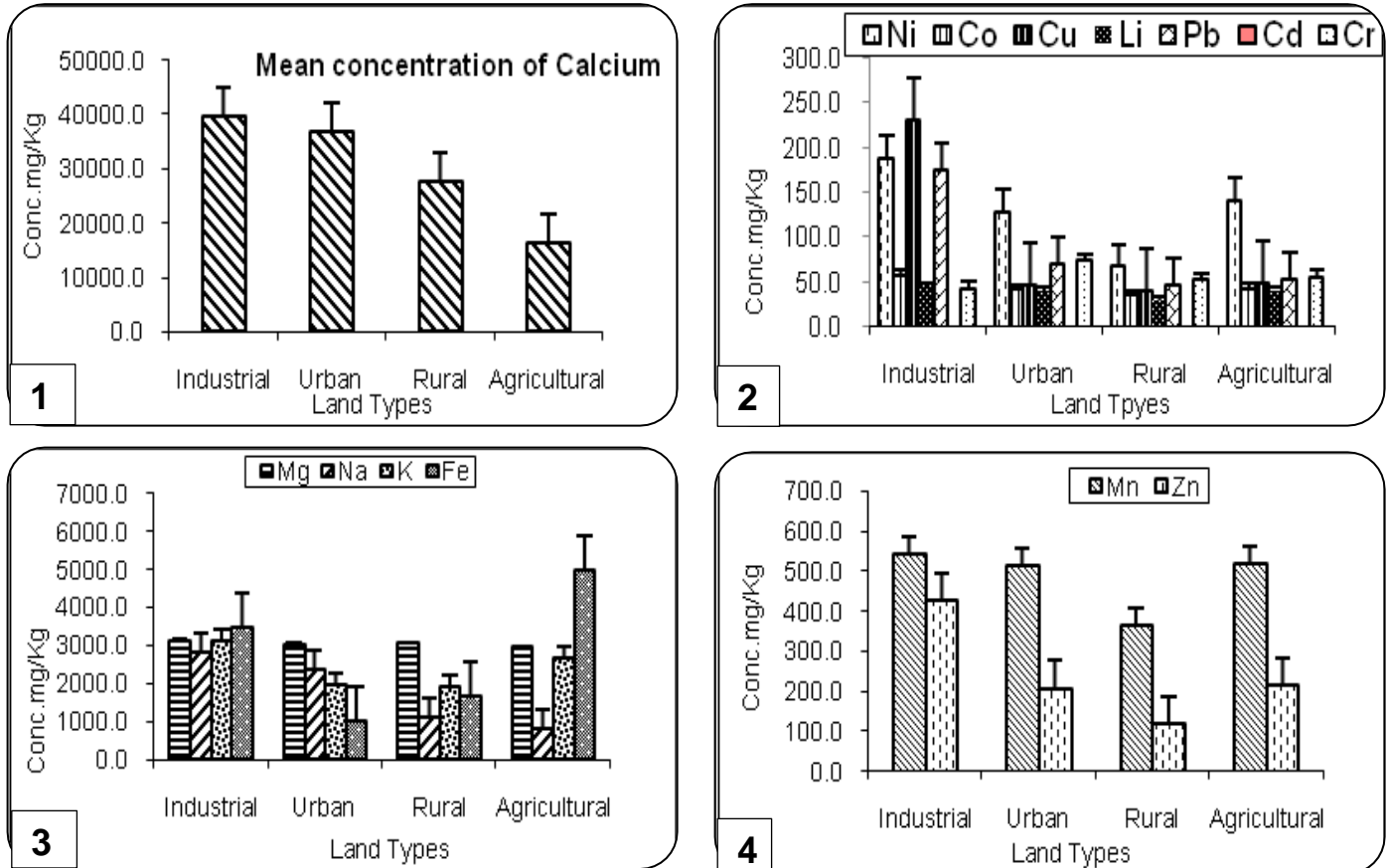


Figure 1: Calcium concentration (mg/Kg) along all four land types. Figure 2. Mean Concentration of Ni, Co, Cu, Li, Pb, Cd and Cr (mg/Kg). Figure 3. Mean Concentration of Mg, Na, K, and Fe (mg/Kg). Figure 4. Mean Concentration of Mn and Zn (mg/Kg).

Industrial Soils: Dominance of Anthropogenic Sources

Industrial soils exhibited the highest concentrations of heavy metals, underscoring significant anthropogenic influence from industrial emissions and waste discharge. For instance, the mean concentration of lead (Pb) in industrial soils was 175.6 mg/kg, which was nearly four times higher than in rural soils (46.3 mg/kg) and three times higher than in agricultural soils (52.6 mg/kg). Copper (Cu) concentrations followed a similar trend, with industrial soils recording a mean value of 231.8 mg/kg, significantly higher than rural soils (40.3 mg/kg) and urban soils (46.4 mg/kg).

Zinc (Zn) levels were particularly elevated in industrial soils (mean: 430.6 mg/kg), approximately three times higher than in rural soils (122.7 mg/kg). The high concentrations of Pb, Cu, and Zn in industrial soils, as shown in Figure 2 and 4 highlight the contribution of industrial activities, including emissions, improper waste disposal, and proximity to industrial zones.

Urban Soils: Moderate Contamination from Urbanization

Urban soils showed moderate contamination levels compared to industrial soils but higher than rural and agricultural soils. The mean Zn concentration in urban soils was 210.6 mg/kg, double that of rural soils and slightly higher than agricultural soils (218.5 mg/kg). Lead concentrations in urban soils averaged 69.8 mg/kg, also higher than rural and agricultural soils. Figure 1, 2, 3 and 4 highlights the contribution of urban sources such as vehicular emissions,

construction activities, and waste management issues to the contamination of urban soils. While urban soils are less polluted than industrial areas, their elevated heavy metal levels pose ecological concerns.

Rural Soils: Lower Levels Reflecting Minimal Anthropogenic Influence

Rural soils exhibited relatively lower levels of heavy metal contamination, reflecting reduced exposure to industrial and urban activities. For example, the mean concentration of Pb in rural soils was 46.3 mg/kg, which was significantly lower than in urban and industrial soils. Similarly, Cu concentrations in rural soils averaged 40.3 mg/kg, much lower than the levels recorded in industrial areas. While rural soils generally exhibited lower contamination, the presence of certain metals such as Mn and Co suggests localized influences, possibly from agricultural practices or natural lithogenic sources.

Agricultural Soils: Predominantly Lithogenic Sources

Agricultural soils demonstrated the lowest levels of contamination for most heavy metals, indicating minimal industrial or urban influence. However, certain metals, such as iron (Fe), were significantly elevated in agricultural soils, with a mean concentration of 49,714.6 mg/kg, as depicted in Figure 1. This is likely due to lithogenic contributions rather than anthropogenic sources.

The concentrations of Cu, Zn, and Pb in agricultural soils were lower than in industrial and urban soils, reflecting limited exposure to contamination. Despite this, localized hotspots may arise from the use of fertilizers, irrigation with contaminated water, or other agricultural inputs.

The comparison of heavy metal concentrations by land use highlights industrial soils as the most contaminated, followed by urban, rural, and agricultural soils. These variations underscore the influence of anthropogenic activities, including industrial emissions and urbanization, in shaping soil contamination. The data from Figures 1, 2, 3 and 4 provide valuable insights for identifying contamination sources and informing management strategies to mitigate heavy metal pollution.

Distribution of Key Metals

The distribution of key heavy metals, including lead (Pb), zinc (Zn), and copper (Cu), across industrial, urban, rural, and agricultural soils in Nowshera District reveals distinct spatial patterns influenced by anthropogenic and natural factors. Figures 1, 2, 3 and 4 provide a comprehensive visual representation of these metals' distribution and their variations across land use types.

Lead (Pb): Elevated Levels in Industrial and Urban Soils

Lead (Pb) concentrations were notably higher in industrial and urban soils compared to rural and agricultural areas. As depicted in Figure 2, industrial soils exhibited a mean Pb concentration of 175.6 mg/kg, significantly exceeding the levels observed in urban (69.8 mg/kg), rural (46.3 mg/kg), and agricultural (52.6 mg/kg) soils. This pattern is indicative of localized sources of pollution in industrial and urban zones, such as emissions from factories, vehicular exhaust, and improper waste disposal.

The relatively lower Pb levels in rural and agricultural soils reflect minimal exposure to industrial activities. However, agricultural soils may still be impacted by the use of fertilizers or irrigation water containing trace amounts of lead. This variability underscores the influence of both anthropogenic and lithogenic factors on Pb distribution.

Zinc (Zn): Significant Anthropogenic Influence in Industrial Soils

Zinc (Zn) concentrations were highest in industrial soils, with a mean value of 430.6 mg/kg, as shown in Figure 4. This level was nearly double that of urban soils (210.6 mg/kg) and approximately three times higher than rural soils (122.7 mg/kg). The elevated Zn levels in industrial soils are likely attributed to industrial emissions, galvanization processes, and waste disposal practices. Urban soils demonstrated moderate Zn concentrations, influenced by vehicular emissions and urban runoff, while rural and agricultural soils showed comparatively lower levels. The mean Zn concentration in agricultural soils was 218.5 mg/kg, slightly higher than in rural soils, potentially due to the use of zinc-containing fertilizers.

Copper (Cu): Industrial Dominance with Localized Variations

Copper (Cu) distribution also showed significant variability across land use types, with industrial soils recording the highest mean concentration of 231.8 mg/kg, as depicted in Figure 2. Urban soils followed with a mean Cu concentration of 46.4 mg/kg, while rural and agricultural soils exhibited mean values of 40.3 mg/kg and 49.7 mg/kg, respectively. The elevated Cu levels in industrial soils are attributed to industrial discharges and waste from manufacturing processes. In agricultural soils, Cu distribution may be influenced by the application of copper-based pesticides or fertilizers. Despite their generally lower levels, rural soils exhibited some localized variations, likely due to natural sources or minor anthropogenic inputs.

Spatial Patterns and Key Insights

The spatial patterns of Pb, Zn, and Cu distribution across land use types, as illustrated in Figures 2 and 4, highlight the dominance of industrial and urban activities in driving heavy metal pollution. The significant contamination in industrial soils underscores the need for stringent regulations and remediation efforts. Urban soils, while less contaminated than industrial areas, still show considerable pollution from urbanization-related sources. Rural and agricultural soils demonstrated lower contamination levels, but localized hotspots highlight the potential impact of agricultural inputs and natural lithogenic factors. This analysis emphasizes the importance of tailored management strategies to address heavy metal contamination across different land use types. In conclusion, the distribution trends of Pb, Zn, and Cu provide valuable insights into the sources and extent of heavy metal pollution in Nowshera District, offering a foundation for targeted mitigation and sustainable soil management practices.

Relationships Between Variables

The analysis of relationships between heavy metal concentrations and soil properties provides valuable insights into the factors influencing metal distribution across industrial, urban, rural, and agricultural soils in Nowshera District. Table 2 summarizes the correlations among key variables, highlighting the interplay between heavy metals and soil physicochemical parameters.

Correlation Among Heavy Metals

Strong positive correlations were observed among certain heavy metals, indicating common sources or similar behaviors in soil environments. For instance, nickel (Ni) showed significant correlations with cobalt (Co; $r = 0.65$), lithium (Li; $r = 0.70$), and lead (Pb; $r = 0.54$), suggesting shared lithogenic or anthropogenic origins. Similarly, copper (Cu) exhibited a robust correlation with Pb ($r = 0.75$) and sodium (Na; $r = 0.58$), reflecting their co-association with industrial activities and urban emissions.

Zinc (Zn) and Pb also displayed a strong positive correlation ($r = 0.62$), underscoring their common presence in urban and industrial waste. These relationships, as depicted in 2, suggest overlapping contamination sources such as vehicular emissions and industrial discharge, particularly in urban and industrial soils.

Interaction Between Metals and Soil Properties

Soil properties, such as pH, organic matter (OM), electrical conductivity (EC), and total dissolved solids (TDS), significantly influenced the distribution of heavy metals. Sodium (Na) exhibited positive correlations with EC ($r = 0.49$), TDS ($r = 0.48$), and salinity ($r = 0.53$), reflecting its association with ionic mobility in saline soils. Potassium (K), on the other hand, showed a moderate positive correlation with organic matter ($r = 0.48$), indicating its retention in organic-rich soils.

Interestingly, pH demonstrated a negative correlation with several parameters, including EC ($r = -0.38$) and Cd ($r = -0.36$). This suggests that alkaline soil conditions may reduce the mobility and bioavailability of certain metals. These findings underscore the role of soil physicochemical properties in modulating heavy metal behavior.

Principal Component Analysis (PCA)

The PCA results, as summarized in Table 3, further validate these findings. Factor 1, dominated by Ni, Co, Li, and Cr, explained 28.9% of the variance, indicating the influence of lithogenic sources. Factor 2, which included Cu, Cd, Na, and Ca, accounted for 17.5% of the variance, reflecting industrial and agricultural pollution.

The relationships between heavy metals and soil properties emphasize the dual role of natural and anthropogenic factors in shaping soil contamination. While lithogenic elements like Ni and Co are primarily derived from parent material, anthropogenic activities significantly contribute to the distribution of Pb, Cu, and Zn in urban and industrial areas. In conclusion, the correlations, clusters, and PCA findings presented in Table 2 offer a comprehensive understanding of the variables influencing heavy metal distribution, providing a framework for targeted remediation and soil management strategies.

DISCUSSION

Concentrations of Heavy Metals Across Land Uses

As presented in Figures 1, 2, 3, and 4, industrial soils exhibited significantly higher concentrations of metals such as Pb, Cu, Zn, and Ni compared to urban, rural, and agricultural soils. The average Pb concentration in industrial soils (175.6 mg/kg) was almost four times higher than in rural soils (46.3 mg/kg), indicating the profound impact of industrial pollution on the local environment (Adhikari et al., 2024; Bibi et al., 2023). The findings are consistent with previous studies, which show that industrial activities, particularly those related to vehicle emissions, manufacturing, and waste disposal, are major contributors to elevated Pb levels (Basir et al., 2024).

Table 2: Correlation matrix between heavy metal contents in all land Use types. $P < 0.05$.

j	Ni	Mn	Co	Cu	Li	Pb	Zn	Cd	Cr	Mg	Na	Ca	K	Fe	pH	EC	TDS	Sal	PO ₄ ³⁻	ALK	Cl ⁻	OM	NO ₃ ⁻
Ni	1.00																						
Mn	0.20	1.00																					
Co	0.65	0.16	1.00																				
Cu	0.35	0.17	0.53	1.00																			
Li	0.70	0.16	0.89	0.26	1.00																		
Pb	0.54	0.02	0.43	0.75	0.28	1.00																	
Zn	0.44	0.16	0.07	0.24	0.10	0.62	1.00																
Cd	-0.16	0.08	0.01	0.08	-0.05	-0.05	-0.04	1.00															
Cr	0.42	0.19	0.58	-0.14	0.70	-0.04	-0.18	-0.21	1.00														
Mg	-0.02	0.13	0.15	0.11	0.11	0.13	0.20	-0.09	-0.05	1.00													
Na	0.24	0.29	0.36	0.58	0.24	0.50	0.10	0.20	0.02	0.15	1.00												
Ca	0.04	0.00	0.22	0.63	-0.04	0.35	-0.13	0.26	-0.12	-0.15	0.44	1.00											
K	0.31	0.05	0.30	0.28	0.20	0.20	-0.03	0.02	-0.03	0.30	0.16	0.04	1.00										
Fe	0.24	-0.20	0.15	-0.06	0.15	-0.04	-0.07	-0.13	0.10	0.02	-0.34	-0.23	0.53	1.00									
pH	0.36	0.01	0.22	0.14	0.28	0.17	-0.08	-0.36	0.16	-0.08	0.07	0.04	0.39	0.12	1.00								
EC	-0.06	0.04	0.08	0.18	-0.02	0.06	-0.17	0.25	0.22	0.09	0.49	0.27	-0.12	-0.24	-0.38	1.00							
TDS	-0.05	0.04	0.09	0.17	0.00	0.05	-0.16	0.24	0.25	0.06	0.48	0.26	-0.13	-0.23	-0.38	0.99	1.00						
Sal	0.03	0.37	0.31	0.35	0.15	0.18	-0.04	0.37	0.07	0.21	0.53	0.32	0.06	-0.18	-0.47	0.72	0.71	1.00					
PO ₄	-0.09	0.32	-0.21	-0.22	-0.06	-0.26	0.07	0.10	0.00	-0.07	-0.36	-0.33	-0.15	-0.07	-0.12	-0.06	-0.09	-0.17	1.00				
ALK	-0.11	0.20	-0.07	0.07	-0.08	-0.06	0.16	0.08	-0.11	0.04	-0.09	0.16	0.04	0.06	0.14	-0.20	-0.14	-0.20	0.29	1.00			
Cl ⁻	0.05	0.20	0.23	0.21	0.17	0.12	-0.10	0.30	0.24	0.05	0.51	0.32	-0.04	-0.20	-0.18	0.80	0.79	0.67	-0.10	0.04	1.00		
OM	0.01	0.22	0.21	0.14	0.09	-0.08	-0.34	-0.19	-0.08	0.14	0.04	0.06	0.48	0.14	0.27	0.06	0.02	0.15	-0.19	-0.29	0.05	1.00	
NO ₃ ⁻ _N	-0.07	0.08	0.23	0.16	0.19	0.00	-0.07	0.27	0.12	0.13	0.34	0.12	0.03	-0.07	-0.50	0.50	0.50	0.78	-0.20	-0.28	0.40	0.02	1.00

The concentration of copper (Cu) in industrial soils was also notably high (231.8 mg/kg), reflecting the contribution of industries like electroplating and metal processing, which are known to release copper into the environment (Emumejapkor & Adewumi, 2023). Similarly, zinc (Zn) levels in industrial soils (mean 430.6 mg/kg) were significantly higher than in agricultural (218.5 mg/kg) or rural soils (122.7 mg/kg), emphasizing the association between industrial pollution and heavy metal contamination (Chudasama et al., 2024). The comparatively higher concentrations of these metals in urban areas, as shown in Figures 2 and 3, further point to the contribution of vehicular emissions and urban activities, although at lower levels than industrial soils (Feng et al., 2024).

Comparison to Global Studies and Risk Evaluation

In order to contextualize the observed contamination levels, a comparison was made with studies from other parts of the world. The concentrations of Pb, Cu, Zn, and Ni in urban soils from Nowshera were found to be lower than those in Manila, Macedonia, and Hangzhou but higher than those found in places like Bangkok and Ireland (Adhikari et al., 2024; Bai et al., 2023). This comparison suggests that while urban pollution in Nowshera is substantial, it remains relatively moderate compared to some highly industrialized regions. However, the continued growth of industrial activities and vehicular traffic in Nowshera suggests that contamination levels may continue to rise if appropriate measures are not taken (Chen et al., 2024).

Interestingly, rural soils, which generally showed lower levels of contamination compared to industrial and urban soils, exhibited higher concentrations of certain metals (such as Ni and Co) than rural areas in other parts of the world, such as Taizhou, China (Bai et al., 2023). This could be attributed to localized agricultural practices or natural lithogenic sources that contribute to the elevated levels of metals like nickel and cobalt (Basir et al., 2024).

Agricultural soils in Nowshera, although generally less contaminated, had higher concentrations of certain metals like Cu, Ni, and Pb than in Spain. This is likely due to the use of agrochemicals such as copper-based pesticides and fertilizers, which contribute to the accumulation of metals in agricultural soils (Chudasama et al., 2024).

Additionally, the observed elevated concentrations of Fe in agricultural soils (mean 49,714.6 mg/kg, as shown in Figure 3) are likely attributed to the presence of iron-rich parent material, a common feature in many agricultural soils (Feng et al., 2024).

Table 3 Principal Component Analysis. Factor Loadings (Varimax normalized) Clusters of loadings are marked in bold.

Parameters	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
Ni	0.684	0.070	0.533	0.184	0.044
Mn	0.080	0.130	0.033	-0.190	0.759
Co	0.852	0.331	0.122	0.196	0.125
Cu	0.151	0.791	0.420	0.172	0.056
Li	0.939	0.053	0.102	0.091	0.152
Pb	0.179	0.487	0.797	0.100	-0.013
Zn	-0.042	-0.081	0.891	-0.095	0.214
Cd	-0.151	0.456	-0.318	-0.051	0.156
Cr	0.870	-0.190	-0.161	-0.073	-0.197
Mg	-0.21	-0.076	0.126	0.300	0.661
Na	0.210	0.710	0.134	-0.135	0.335
Ca	-0.022	0.865	-0.019	-0.055	-0.236
K	0.107	0.189	0.015	0.862	0.223
Fe	0.121	-0.266	0.001	0.831	-0.203
Eigen value	4.049	2.458	1.64	1.454	1.225
Total Variance Explained(%)	28.918	17.557	11.712	10.385	8.747
Cumulative Eigen Value	4.049	6.507	8.146	9.600	10.825
Cumulative %	28.918	46.475	58.187	68.572	77.319

Spatial Distribution and Hotspot Identification Using GIS

The spatial distribution of heavy metals in the study area was assessed through GIS mapping, which provided a clear visualization of contamination hotspots. The southern parts of the study area, which are closer to urban and industrial centers, exhibited the highest metal concentrations, with significant hotspots in the Amanghar industrial area (Bibi et al., 2023; Chudasama et al., 2024). The observed correlation between high traffic density and elevated metal concentrations is consistent with studies that link vehicular emissions to soil contamination (Chen et al., 2024).

The Pb and Zn concentrations were particularly high near major intersections and industrial zones, highlighting the influence of industrial waste and traffic emissions on soil quality. These findings emphasize the need for targeted remediation efforts in these hotspot areas, particularly around industrial zones and busy roads where heavy metal concentrations are disproportionately high (Basir et al., 2024).

In contrast, agricultural and rural areas showed fewer hotspots, and the distribution of metals like Fe, Mg, and K, as depicted in Figure 3, aligned with their natural presence in the soil. These areas were less impacted by anthropogenic activities, with the contamination levels largely reflecting the natural variability of these elements in the soil (Adhikari et al., 2024). However, localized contamination was still observed, likely due to agricultural practices and the use of metal-containing fertilizers and pesticides.

Multivariate Statistical Analysis: Correlation and Grouping of Metals

To further understand the relationships between different metals and their sources, multivariate statistical techniques, such as cluster analysis and principal component analysis (PCA), were employed. The results, shown in Table 3, identified four five distinct groups of metals with shared sources or behaviors. The first group, including Ni, Co, Li, and Cr, was primarily linked to natural sources, although anthropogenic influences, particularly from industrial activities, contributed to elevated concentrations in urban and industrial areas (Emumejakpor & Adewumi, 2023). The second group, consisting of Fe and K, was predominantly natural in origin, derived from parent material, with Fe showing particularly high concentrations in agricultural soils due to lithogenic factors (Feng et al., 2024).

The third group, including Cd, Zn, Mg, and Mn, was influenced by both natural and anthropogenic sources, with the higher concentrations of Zn and Cd likely resulting from industrial discharges and the use of agricultural chemicals (Bibi et al., 2023). The fourth group, containing Cu, Na, Ca, and Pb, was dominated by anthropogenic sources,

particularly from industrial activities and vehicular emissions, as seen in the elevated concentrations of Pb and Cu in industrial soils (Chudasama et al., 2024).

The clustering of metals based on their origin provides a better understanding of the contamination sources in the region and emphasizes the need for differentiated management strategies. Metals with natural origins, such as Fe and K, require less immediate attention than those with anthropogenic origins, such as Pb, Cu, and Zn, which pose significant environmental risks in industrial and urban areas (Adhikari et al., 2024).

Implications for Environmental Management

This study highlights the complex interplay between natural and anthropogenic factors in shaping the distribution of heavy metals across different land uses in Nowshera District. The significant differences in metal concentrations across land types reflect the influence of industrial activities, vehicular emissions, and agricultural practices. The spatial distribution maps and pollution indices confirm that industrial and urban soils are most heavily contaminated, with the highest ecological risks associated with these areas. In contrast, rural and agricultural soils, while exhibiting lower contamination levels, still require monitoring and management to prevent future contamination from agricultural inputs.

The findings emphasize the need for targeted remediation efforts in industrial and urban hotspots, along with stricter regulations on industrial emissions and agricultural chemical use. Furthermore, the spatial mapping and statistical analysis provide valuable tools for identifying contamination hotspots and prioritizing areas for intervention. The results of this study underscore the importance of ongoing monitoring and the implementation of sustainable land use practices to mitigate the risks posed by heavy metal contamination in Nowshera District.

CONCLUSION

This study provides a comprehensive evaluation of heavy metal contamination in surface soils across diverse land use types in Nowshera District, Pakistan. The findings reveal significant variations in contamination levels, with industrial soils exhibiting the highest concentrations of heavy metals such as lead (Pb), zinc (Zn), and copper (Cu), primarily due to emissions and improper waste disposal. Urban soils showed moderate contamination influenced by vehicular emissions and construction activities, while agricultural soils, though less impacted, presented localized hotspots due to agrochemical usage and irrigation with untreated wastewater. Rural soils were the least contaminated, reflecting minimal industrial and urban influences.

The research underscores the critical need for targeted soil management strategies. Industrial zones require stringent regulations to control emissions and implement effective waste disposal mechanisms. Urban areas would benefit from improved traffic management and waste recycling initiatives. In agricultural regions, promoting the use of organic fertilizers and treated irrigation water can minimize contamination risks. Spatial analysis and pollution indices further highlight contamination hotspots, providing a roadmap for focused remediation efforts. Similarly some advance techniques for the treatment of waste water e.g, anaerobic continuously stirred tank reactor and sequencing batch reactor (CSTR-SBR) coupled with magnesium-ammonium-phosphate (MAP)-precipitation for treating swine wastewater um-Ammonium- Phosphate(MAP-precipitation) could be the better approaches to address the problem of waste water contamination in Pakistan.(Zhang et al, 2021)

For farmers, adopting sustainable practices such as reduced reliance on chemical inputs and regular soil testing can mitigate heavy metal accumulation, ensuring safer agricultural production. Implementing these findings can enhance soil health and reduce contamination risks, supporting long-term agricultural sustainability and food safety. The Government agencies should be responsible for the implementation of rules & regulations as framed by concerned departments. Sustainable Development Goals of the United Nations about environment especially SDG 6 must be included in the text books of school and higher level educational institutes to guide students about the future perspective of environment and climate change of our region.

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AUTHOR CONTRIBUTIONS

All authors contributed equally to this research.

COMPETING OF INTEREST

The authors declare no competing interests.

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