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Risk Assessment of Heavy Metal Contamination in Soil for Sustainable Environmental Management in Urban and Rural Areas of Gujrat District, Pakistan

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Abstract
This study was conducted to assess the risk of heavy metal contamination in soils from the selected sampling areas. The study aimed to determine whether soil properties, including electrical conductivity (EC), pH, and organic matter (OM), affect heavy metal concentrations in soil. Composite soil samples were collected and analyzed using Atomic Absorption Spectroscopy (AAS) for heavy metal concentrations at a depth of 0–15 cm, following the order of Zn > Pb > Cd > Cu. In addition, human health risk assessments using Average Daily Dose (ADD), Hazard Index (HI), Total Hazard Quotient (THQ), and Carcinogenic Risk Assessment (CRA) were conducted for adults and children via dermal contact, ingestion and inhalation. The results showed no significant correlation between heavy metal concentrations and soil physicochemical properties. Although Zn and Cu ($r = 0.62$, $p < 0.01$) and Cu and Pb ($r = 0.57$, $p < 0.01$) showed a moderately positive relationship, representing common, familiar contamination sources probably from industrial activities and vehicular emissions. In addition, Zinc showed a weak negative correlation with pH ($r = -0.28$, $p < 0.01$), indicating reduced metal availability in alkaline soils. However, the health risk assessment revealed that children in urban areas face higher contamination risks, with a Hazard Index (HI) of 0.06, compared to 0.01 in rural children. Carcinogenic risk assessment revealed that lead (Pb) and Cadmium (Cd) pose the highest risks, with cumulative risk for urban children ($CR = 1.99 \times 10^{-4}$) reaching the upper threshold of the acceptable range. These results emphasize the urgent need for pollution control measures in urban environments. Future studies could explore specific contamination pathways and remediation strategies to minimize human health risks. This study contributes to sustainability by identifying soil contamination risks and providing baseline data to inform safer land use planning. The findings support sustainable agricultural practices and evidence-based policy decisions aimed at protecting ecosystems and human health.

Keywords:
carcinogenic risk; hazard index; health risk assessment; heavy metals; soil contamination; soil properties; urban pollution

1. Introduction

Soil pollution has emerged as a significant and persistent environmental issue globally, driven by rapid industrialization, urbanization, and insufficient waste management practices [1]. Additionally, heavy metal contamination has become a significant concern due to its long-lasting environmental and health impacts [2]. Heavy metals are naturally occurring elements that, at low concentrations, are important for biological processes [3]. However, when present in high concentrations, they become toxic and pose a significant threat to the environment and human health. Soil serves as a sink for these metals, accumulating pollutants over time [2]. The contamination of soil with heavy metals can have detrimental effects on agriculture, as crops grown in polluted soil absorb these metals, which then enter the food chain [4]. Long-term exposure

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to heavy metals can lead to chronic health consequences, including neurological disorders, cardiac diseases, and kidney damage [5]. Furthermore, once these metals are present in the soil, they are difficult to remove, leading to persistent soil contamination and long-term environmental issues [6].

In Pakistan, industrial activity has increased considerably over the past few years, contributing to economic growth but also causing severe environmental deterioration. Gujrat, a major industrial hub located in the central region of Punjab, Pakistan, hosts a diverse range of industries, including textiles, ceramics, electrical machinery, and steel manufacturing. These industries, although important to residents economically, are the primary sources of contaminants, including heavy metals such as cadmium (Cd), lead (Pb), nickel (Ni), and chromium (Cr) [7]. These metals enter soil through several pathways, including atmospheric deposition, solid waste disposal, and irrigation with contaminated water [8]. As a result, the soil in nearby areas, primarily in the city's peripheral regions, has become gradually polluted [9]. Although the Kalra Kalan and River Garden Housing Scheme are peripheral areas located near the industrial estate of Gujrat, they are in proximity to both agricultural lands and an industrial zone. Numerous people in these zones rely on locally grown crops for their livelihood and daily subsistence, raising concerns about the accumulation of heavy metals in their food chain [10].

Investigating the level of contamination in the study area is vital for improving effective mitigation plans. Thus, this study aimed to evaluate the level of heavy metal contamination in the soil of these two peripheral regions and assess the related hazards to human health and the surrounding environment. Additionally, the present study examines the concentrations of selected heavy metals in soil. It compares them with internationally recognized safety thresholds, such as those established by the United States Environmental Protection Agency (EPA) and the World Health Organization (WHO). According to WHO guidelines, the permissible soil limits for the selected metals are: lead (Pb) 10 mg/kg, cadmium (Cd) 0.8 mg/kg, zinc (Zn) 300 mg/kg, and copper (Cu) 100 mg/kg. Cd and Pb are strictly regulated due to their high toxicity [11]. This study is aimed not only at community representatives and environmental agencies but also at international frameworks concerned with environmental sustainability and public health.

Although the country faces numerous challenges in treating industrial waste, many industrial units lack adequate handling facilities. As a result, hazardous unused chemicals are frequently discharged directly into the environment, contaminating nearby soil, water, and air [12]. Thus, the present study of Kalra Kalan and the River Garden Housing Scheme areas is particularly important, as these regions are illustrative of many other peripheral areas located near industrial estates across Pakistan.

This study aims to address this gap by providing detailed information on heavy metal concentrations in the soil, as well as the potential risks they pose at the local level. Evaluating soil samples for heavy metal concentrations also aligns with international environmental protection standards and the study's objectives to assess pollution levels and their potential effects. The findings provide valuable insights for environmental regulators, industrial stakeholders, and local communities, enabling them to implement necessary measures to mitigate the risks of heavy metal contamination while safeguarding both the environment and human health.

The distinction of this study lies in its comparative evaluation of heavy metal contamination in both urban and rural soils surrounding the industrial estate area of Gujrat. By incorporating health risk assessments across different exposure pathways, the study provides a comprehensive understanding of pollution dynamics. The findings are focused on delivering specific contextual guidance for sustainable soil management and supporting effective pollution control strategies in the affected industrial areas of Pakistan.

2. Materials and Methods

2.1. Study Area

The study was conducted in two peripheral areas of the industrial estate in Gujrat, Pakistan: Kalra Kalan agricultural land (rural) and the River Garden Housing Scheme (urban) (Figure 1). The district lies at an intersection of 74.07° E and 32.57° N, where the study areas extend between 32.57° N and 32.54° N; 74.01° E and 74.08° E. The temperature in the study area ranges from 20 °C to 50 °C, with an average annual precipitation of 670 mm. The urban study area (River Garden) is located 22.1 km from the central city of Gujrat, while the rural area (Kalra Kalan) is 16.4 km away.

2.2. Sampling Design

The study encompassed a total sampling area of 597 ha, comprising 331 ha from urban regions and 266 ha from rural regions. The areas were divided into 50 quadrants. A systematic random grid composite soil sampling approach was employed, consisting of 50 composite samples, with 25 from rural areas and 25 from urban areas, designed and mapped using ArcGIS.

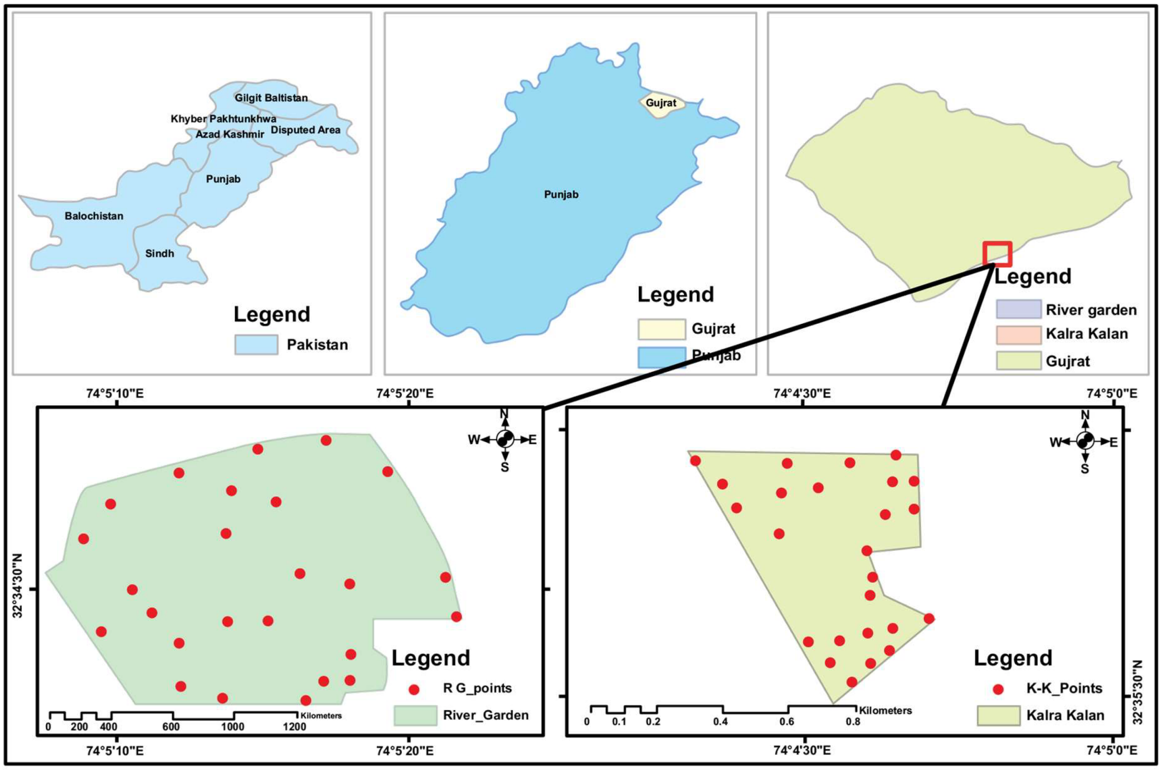


Figure 1: Study area to accurately describe the rural (Kalra Kalan) and urban (River Garden) sampling sites.

2.3. Collection of Soil Samples

Each of the 50 quadrats was further divided into five smaller units for sample collection. Soil samples were collected from a depth of 0–15 cm using a stainless-steel auger [13]. Samples from the five subunits in each quadrat were mixed. A total of 50 composite samples were collected and analyzed for heavy metal concentrations. The soil samples were stored in sealed plastic bags and transported to the laboratory for subsequent analysis. Prior to chemical examination, all samples were air-dried [14].

2.4. Analytical Techniques for Heavy Metal Detection (Cd, Cu, Zn, and Pb)

One gram of each air-dried and sieved soil sample was ashed in a muffle furnace at 460 °C for 24 hours. The resulting ash was digested in 10 mL of aqua regia (1:3 concentrated HNO_3: HCl) on a heating block using a sequential temperature program: 2 hours at 25 °C, 2 hours at 60 °C, and 5 hours at 125 °C. The process took a total of nine hours to complete. After digestion, the samples were first centrifuged and subsequently diluted to volume with 10% HNO_3. Additionally, standard solutions for each element were prepared in 10% HNO3. The concentrations of different heavy metals in diluted digests were measured by an atomic absorption spectrophotometer (Model No. AA-6300 SHIMADZU) [15]. Furthermore, portions of the remaining soil samples were used for physicochemical analyses after removal of coarse soil components. All samples were analyzed in triplicate to ensure the reliability, accuracy, and representativeness of the results, thereby minimizing random errors and accounting for small-scale heterogeneity within the samples [16].

2.5. Statistical Analysis

All statistical analyses were conducted using SPSS (Version 20, IBM Inc., Chicago, IL, USA) and Microsoft Excel (Version 16). The normality of data distribution was tested using the Shapiro-Wilk test, which is more appropriate for small to medium sample sizes ($n < 200$). As the dataset satisfied the assumption of normality, parametric tests were applied for subsequent analyses [17]. Descriptive statistics (mean and standard deviation) were calculated to summarize heavy metal concentrations and soil properties. To compare mean differences in metal concentrations across different sampling points, a one-way Analysis of Variance (ANOVA) was conducted, followed by Tukey's post hoc test to identify pairwise differences [18]. To examine relationships between soil properties and heavy metal contents, we used Pearson's correlation coefficient, which is a parametric measure suitable for normally distributed data. For each correlation, statistical significance (p-value) was computed to test the null hypothesis that $r = 0$ [19]. Non-parametric tests (such as the Mann-Whitney U test) were initially considered as alternatives if normality assumptions were not met. However, since the data met assumptions, they were not applied in the final analyses.

2.6. Extraction of Soil Physicochemical Properties

The soil pH was measured with a calibrated pH meter (HANNA PH Meter Hi98106). 10 g of air-dried soil and 25 mL of deionized water were combined in a soil-to-water ratio (1:2.5) for every composite sample [20]. Soil organic matter (SOM) content was determined using the Loss on Ignition (LOI) method. This procedure involved weighing approximately 5 g of air-dried soil, followed by heating at 550 °C for 4 hours in a muffle furnace. The weight loss after combustion represented the amount of organic matter burned off. The percentage of Soil Organic Matter (SOM) was calculated by;

$$\text{SOM\%} = ((\text{Wcs} - \text{Wf})/\ \text{Wcs} - \text{Wc})) \times 100 \quad (1)$$

where,

Wcs = The weight of oven-dried soil as well as the crucible

Wf = The weight of the fire sample of the furnace and crucible

Wc = The weight of the crucible

All samples were run in triplicate to ensure the reliability, accuracy, and representativeness of the results, thereby minimizing random errors and accounting for small-scale heterogeneity within the sample [16]. An EC meter (WTW inoLab Cond 720) was used to measure soil electrical conductivity (EC) and determine soil salinity levels, which affect the mobility of heavy metals. Accordingly, 10 g of soil was combined with 50 mL of deionized water to prepare a 1:5 soil-to-water suspension for the measurement of electrical conductivity (EC). After stirring, the mixture was left to settle for 30 minutes. The conductivity (dS/m) was then recorded by submerging the EC meter probe in the solution [20]. The hand-texture method was used to assess soil texture for samples collected from urban and rural areas [21].

2.7. Human Health Risk Assessment

The human health risks in both rural and urban areas were evaluated by calculating the Average Daily Dose (ADD), Hazard Quotient (HQ), Hazard Index (HI), and Lifetime Carcinogenic Risk (LCR) [22–24].

2.8. Average Daily Dose

The average daily dose (ADD) for three exposure pathways was calculated, including ingestion (ADDing), inhalation (ADDinh), and dermal contact (ADDderm), in mg/kg/day for the heavy metals Cu, Zn, Pb, and Cd.

$$\text{ADDing} = \text{C} \times (\text{IR} \times \text{EF} \times \text{ED})/(\text{BW} \times \text{AT}) \times 10^{-6} \quad (2)$$

$$\text{ADDinh} = \text{C} \times (\text{InhR} \times \text{EF} \times \text{ED})/(\text{PEF} \times \text{BW} \times \text{AT}) \quad (3)$$

$$\text{ADDderm} = \text{C} \times (\text{SA} \times \text{AF} \times \text{ABF} \times \text{EF} \times \text{ED})/(\text{BW} \times \text{AT}) \times 10^{-6} \quad (4)$$

where,

C = The concentrations of heavy metals (mg/kg)

IngR = The rate of Ingestion in mg/day (100 for adults, also 200 for children)

ED = A duration of exposure (24 years for adults and 6 years for children)

Bw = The average body weight (children 15 kg and adults 70 kg)

AT = The average time (365 × ED)

InhR = The inhalation rate in mg/kg/day (20 for both adults and children)

PEF = The particles emission factor in m^3/kg (1.36 × 109; both for adult and children)

SA = The surface area of exposed skin in cm^2 (2145 for adult and 1150 for children)

AF = The skin adherence factor for soil in mg/cm^2 (0.007 for children and 0.20 for adults)

ABF = The dermal absorption factor (As = 0.03 and 0.001 for other metals)

EF = Exposure frequency (days per year)

IR = Inhalation Rate

CSF = Cancer slope factor

THQ = Total hazard quotient

Pb, Cd, Zn, and Cu were designed by using the formula mentioned above for soil.

However, the Ingestion Rate (IngR) of water was 2.2 L/day for adults and 1.5 L/day for children, with EF of 365 days/year and SA of 5700 cm^2 [24,25]. The remaining parameters were identical to those specified in the preceding equation.

2.9. Total Hazard Quotient and Index

$$\text{THQ} = (\text{ADD (Ingestion, Inhalation, or Dermal)})/\text{RfD} \quad (5)$$

The THQ ratio represented the ADD across all three phases of exposure. The Reference Dose (RfD) for each metal, expressed in mg/kg/day, was used to estimate the non-carcinogenic risk. A Hazard Quotient (HQ) value > 1 indicates a potential health risk.

The Hazard Index (HI), calculated as the sum of all HQs, was used to assess the total non-carcinogenic risk potential of different contaminants in the three phases. However, there was a chance of carcinogenic effects happening if the (HI > 1), and the chance increased with an increasing value of HI. Rfd in mg/kg body weight (BW)/day for Cu, Pb, Cd, and Zn, whereas a significant THQ > 1 health risk (Table 1).

$$HI = \sum HQ\ (HQing + HQinh + HQderm) \quad (6)$$

2.10. Risk Assessment of Carcinogenic

Lifetime exposure to cancer risk from Cd, Cu, Pb, and Zn was calculated as a health risk through the cumulative life cancer risk rating, using a formula for each phase's exposure. The cancer slope factor (CSF) for each metal, corresponding to the three exposure pathways, is presented in Table 1. Whereas LCR < 10^{-6} indicates a negligible carcinogenic risk; LCR > 1×10^{-4} indicates a high risk; and a value between 1×10^{-6} and 1×10^{-4} is generally considered an acceptable or tolerable risk [26].

$$LCR = ADD\ (\text{Ingestion, inhalation, or dermal}) \times CSF \quad (7)$$

$$LCR = \sum \text{Cancer RISK (CANCER RISKing1} + \text{CANCER RISKing2} + \text{CANCER RISKier3)} \quad (8)$$

The mean of three replicates for each treatment in the experiment was calculated. Statistical analyses were performed using Statistics version 10.0. Analysis of variance (ANOVA) was conducted, and Tukey's post hoc test was applied to compare treatment means and identify significant differences (Tables 2 and 3).

Table 1: Standard reference dose factor and cancer slope factor for both study areas.

Metals	Rfd (mg/kg/day)	CSF (mg/kg/day)
Zn	0.3	N/A
Pb	0.0035	0.0085
Cd	0.001	0.38
Cu	0.04	1.7
Metals	**Urban**	**Rural**
Zn	13.54	1.24
Pb	23.47	5.63
Cd	1.91	0.06
Cu	16.99	4.36

Table 2: Urban river garden (average concentration of heavy metals (mg/kg).

Site	Zn	Pb	Cd	Cu
1	7.23 p	17.88 p	0.42 b	7.05 u
2	7.55 p	18.45 o	1.02 ab	7.79 uv
3	8.37 o	19.04 n	1.61 ab	8.62 tu
4	9.22 n	19.69 m	2.15 ab	9.45 st
5	9.53 n	20.15 m	2.81 ab	10.28 rs
6	10.54 m	20.92 l	2.61 ab	11.11 qr
7	11.12 l	21.59 k	1.27 ab	11.94 pq
8	11.54 l	22.34 j	2.17 ab	12.77 op
9	12.29 k	22.72 j	1.78 ab	13.60 no
10	13.03 j	23.56 i	2.09 ab	14.43 mn
11	13.55 ij	24.28 h	2.41 ab	15.27 lm
12	14.11 i	24.85 g	2.15 ab	16.10 kl
13	14.70 h	25.42 f	2.02 ab	16.93 jk
14	15.31 g	26.13 e	2.57 ab	17.76 ij
15	15.81 fg	26.39 e	2.05 ab	18.59 hi
16	16.37 f	27.30 d	2.06 ab	19.42 gh
17	17.10 e	28.0 c	2.10 ab	20.25 fg
18	17.62 e	28.18 bc	3.01 a	21.08 ef
19	18.35 d	28.66 ab	2.07 ab	21.91 de
20	18.85 cd	29.02 a	2.05 ab	22.74 cd
21	19.36 bc	17.96 op	2.03 ab	23.58 c

Table 2: *Cont.*

Site	Zn	Pb	Cd	Cu
22	19.72 ab	19.15 n	1.76 ab	23.74 c
23	20.00 a	21.45 k	1.07 ab	25.24 b
24	7.64 p	24.99 fg	0.37 b	26.29 b
25	9.51 n	28.75 a	2.04 ab	28.80 a

Representing the means of three replicates (HSD) of the urban area at (0–15 cm soil depth); small letters indicate significance ($p < 0.05$) level.

Table 3: Rural kalra kalan (average concentration of heavy metals (mg/kg).

Site	Zn	Pb	Cd	Cu
1	1.53 a	4.27 a	0.03 c	0.23 p
2	1.45 a	4.25 a	0.04 bc	0.59 op
3	0.88 a	4.51 a	0.04 bc	1.05 no
4	1.66 a	4.86 a	0.06 abc	1.53 mn
5	0.68 a	5.29 a	0.07 abc	2.05 lm
6	0.53 a	5.14 a	0.08 abc	2.65 jkl
7	0.68 a	5.60 a	0.09 abc	3.35 hij
8	1.06 a	5.87 a	0.07 abc	3.43 hi
9	1.89 a	6.10 a	0.08 abc	4.05 gh
10	1.78 a	6.34 a	0.09 ab	4.48 g
11	1.05 a	6.29 a	0.06 abc	5.45 f
12	1.04 a	6.93 a	0.03 c	5.60 f
13	1.26 a	6.17 a	0.04 bc	6.05 ef
14	2.40 a	4.46 a	0.03 bc	6.52 de
15	0.85 a	5.01 a	0.04 bc	7.05 d
16	1.35 a	5.65 a	0.05 abc	7.25 d
17	1.55 a	5.03 a	0.05 abc	8.04 c
18	1.27 a	5.45 a	0.06 abc	8.68 bc
19	1.36 a	5.97 a	0.08 abc	9.05 ab
20	1.66 a	7.21 a	0.08 abc	9.42 a
21	1.99 a	6.58 a	0.07 abc	0.56 op
22	1.05 a	5.86 a	0.11 a	1.43 mn
23	0.96 a	6.57 a	0.03 bc	2.60 kl
24	0.61 a	6.12 a	0.04 bc	3.25 ijk
25	0.59 a	5.27 a	0.06 abc	4.57 g

Representing the means of three replicates (HSD) of the rural area at (0–15 cm soil depth), small letters indicate significance ($p < 0.05$) level.

3. Results

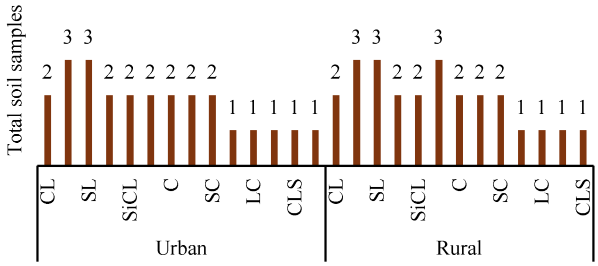
The soil in urban areas exhibited a pH of 7.70 ± 0.25 SD, whereas rural soils had a pH of 6.87 ± 0.30 SD, which is close to neutral. In addition, the Electrical Conductivity (EC) value in urban soil was 2.20 dS/m ± 0.08 SD. Rural soils had a slightly lower EC (2.06 dS/m ± 0.08 SD. The soil organic matter (SOM) content in urban soils was 3.71% ± 0.05 SD, whereas rural soils exhibited 3.43% ± 0.08 SD, slightly lower than that observed in urban areas (Table 4).

Variations in soil texture distribution also differed between urban and rural regions at a depth of 0–15 cm (Figure 2). Urban soils exhibited a higher frequency of clay loam and silt loam compared to rural soils, as silt loam was three times more common, and clay loam appeared twice as often in urban samples. Similarly, in rural areas, both soil types occurred at approximately the same frequency.

The same order of average metal concentrations was observed in both rural and urban areas (Zn > Pb > Cd > Cu); however, the concentrations in urban areas were significantly higher-ranging from at least (13.53 mg/kg ± 4.19 SD)-(Zinc (Zn)) up to (23.47 mg/kg ± 3.72 SD, 16.98 mg/kg ± 6.23 SD) (Pb (Lead, Cu, Copper) the mean Cadmium (Cd) showed similar concentration in urban soils (urban = 1.90 mg/kg ± 0.65 SD and rural = 0.06 mg/kg ± 0.02 SD) compared to rural areas (Cu,4.35 mg/kg ± 2.83 SD, Pb, 5.63 mg/kg ± 0.82 SD) (Table 5).

An independent samples t-test showed that the total heavy metal concentration in urban soil (M = 138.03

± 13.02) was significantly higher than in rural soil (M = 62.97 ± 6.51), $p < 0.001$ (Table 6).



Soil texture distributions

Figure 2: Count of soil texture in urban and rural areas within 0–15 cm depth; (SL = Sandy loam, SiCL = Silt clay loam, CL = Clay loam, CLS = Sandy clay loam).

The correlation analysis revealed a significant moderate positive relation ($r = 0.46$, $p < 0.05$) between Cu and SOM content in rural areas (Table 7). However, Pb and Zn showed a weak positive relation ($r = 0.18$, $p = 0.00$). In addition, Soil Organic Matter and Electrical Conductivity indicated a weak positive relation ($r = 0.33$, $p = 0.00$). A significant moderate positive correlation was observed between Cu and Zn ($r = 0.62$, $p < 0.01$). Similarly, a significant positive relation was found between Cu and Pb ($r = 0.57$, $p < 0.01$). While pH showed a weaker relationship than other variables, a positive relationship between EC and pH ($r = 0.28$, $p = 0.00$) was observed, indicating that regions with high salinity typically have slightly more alkaline soils. Zinc and pH showed a weak negative relationship ($r = -0.28$, $p = 0.00$), indicating that heavy metal concentrations decrease in more alkaline soils. However, the relation between Zinc and Soil Organic Matter was observed to be weakly negative ($r = -0.29$, $p = 0.00$), indicating that organic matter limits the availability or mobility of Zinc in rural soil.

Table 4: Soil physicochemical properties of the two study areas.

Depth	Test	Urban (N = 25) (Mean ± SD)	Rural (N = 25) (Mean ± SD)
0–15 cm	pH	7.70 ± 0.25	6.87 ± 0.30
	EC (dS/m)	2.20 ± 0.08	2.06 ± 0.11
	SOM (%)	3.71 ± 0.05	3.43 ± 0.08

Table 5: Concentration of heavy metals in the soil in both rural and urban areas (mg/kg).

Depth	Test	Urban (N = 25) (Mean ± SD)	Rural (N = 25) (Mean ± SD)
0–15 cm	Zn	13.53 ± 4.19	1.24 ± 0.48
	Pb	23.47 ± 3.72	5.63 ± 0.82
	Cd	1.90 ± 0.65	0.06 ± 0.02
	Cu	16.98 ± 6.23	4.35 ± 2.83

Table 6: Comparison of heavy metal concentration in urban and rural areas.

Area	*Mean*	*p*
Rural	62.97 ± 6.51	0.00
Urban	138.03 ± 13.02	

Table 7: Correlation matrix between soil physicochemical properties and heavy metal concentration of rural areas (N = 25).

Parameters	pH	EC	SOM	Zn	Cd	Cu
pH	1					
EC	0.05	1				
SOM	0.33	0	1			
Zn	0.18	0.18	−0.19	1		
Pb	0.05	0.31	0.29	0	1	
Cd	0.126	0.14	−0.14	−0.03	0.33	1
Cu	0.11	0.30	0.46 *	0.16	0.31	0.02

* Correlation is significant at 0.05 level (2-tailed).

Similarly, Cu and Cd ($r = 0.36$, $p = 0.00$), and Pb and Cd ($r = 0.34$, $p = 0.00$) showed weak positive correlations.

A correlation between heavy metal concentrations and soil physicochemical properties was observed in the urban area (Table 8). A significant, moderate positive correlation was found between Cu concentration and Zn ($r = 0.62$, $p < 0.01$) in urban soil in Gujrat. Furthermore, a significant moderate positive correlation was observed between Cu and Pb concentrations ($r = 0.57$, $p < 0.01$) in the study area.

The calculated Hazard Index (HI), representing the cumulative non-carcinogenic risk, was 0.06 for children and 0.01 for adults (Table 9).

The human health risks associated with heavy metal pollution were measured in both rural and urban areas. The contact risks for adults and children were assessed by calculating the Average Daily Dose (ADD), Hazard Quotient (HQ), Hazard Index (HI), and the Carcinogenic Risk calculation (CR). The ADD for metals was estimated using three exposure phases, expressed in mg/kg/day. HI values for any assumed metal overall soil contact pathways were less than 1, indicating significant health risks. However, urban children (0.0606) exhibited a markedly higher HI value compared to rural children (0.0119) (Table 10).

Table 8: Correlation matrix between soil physicochemical properties and heavy metal concentration of urban areas (N = 25).

Parameters	pH	EC	SOM	Zn	Cd	Cu
pH	1					
EC	0.28	1				
SOM	0.27	0.07	1			
Zn	−0.28	0.00	−0.30	1		
Pb	−0.03	0.04	0.22	0.39	1	
Cd	−0.19	−0.20	−0.05	0.34	0.36	1
Cu	0.10	0.18	0.08	0.62 **	0.57 **	0.02

** Correlation is significant at 0.05 level (2-tailed).

Table 9: The Reference Doses (RfD) and Cancer Slope Factors (CSF) for various heavy metals, along with values for urban and rural areas.

Metal	RfD	CSF	Urban	Rural
Zn	0.3	N/A	13.54	1.24
Pb	0.0035	0.0085	23.47	5.63
Cd	0.001	0.38	1.91	0.06
Cu	0.04	1.7	16.99	4.36

Table 10: Reference Doses (RfD) and Cancer Slope Factors (CSF) of heavy metals used in the risk assessment study of (Zn, Pb, Cd, and Cu).

Zn	Pb	Cd	Cu
Average Daily Dose (for children)			
9.03×10^{-5}	0.00015654	1.27×10^{-5}	0.00011332
8.27×10^{-6}	3.76×10^{-5}	4.00×10^{-7}	2.91×10^{-5}
Average Daily Dose (for adults)			
9.48×10^{-6}	1.64×10^{-5}	1.34×10^{-6}	1.19×10^{-5}
8.68×10^{-7}	3.94×10^{-6}	4.20×10^{-8}	3.05×10^{-6}
Total Hazard Quotient (for children)			
0.00030104	0.04472711	0.0127397	0.00283308
2.76×10^{-5}	0.01072917	0.0004002	0.00072703
Total Hazard Quotient (for adult)			
3.16×10^{-5}	0.004694	0.001337	0.00029733
2.89×10^{-6}	0.001126	0.000042	0.0000763

Table 10: *Cont.*

Zn	Pb	Cd	Cu
Carcinogenic Risk Assessment (for children)			
N/A	1.33×10^{-6}	4.84×10^{-6}	0.00019265
N/A	3.19×10^{-7}	1.52×10^{-7}	4.94×10^{-5}
Carcinogenic Risk Assessment (for adults)			
N/A	1.40×10^{-7}	5.08×10^{-7}	2.02×10^{-5}
N/A	3.35×10^{-8}	1.60×10^{-8}	5.19×10^{-6}
Hazard Index		Cancer Risk	
HI (for children)	HI (for adult)	CR (for children)	CR (for adult)
0.06060094	0.00635992	0.00019882	2.09×10^{-5}
0.01188397	0.00124719	4.99×10^{-5}	5.24×10^{-6}

4. Discussion

4.1. Soil Physicochemical Properties

Overall, the pH level in the urban area was slightly alkaline. However, the pH of rural soil was marginally lower than in urban zones at the same depth. The pH levels showed a notable difference between urban and rural regions, representing potential variations in soil chemistry. In alkaline soils, the availability of heavy metals such as lead (Pb) decreases, reducing their mobility and potential for bioaccumulation. However, the near-neutral pH of rural-area soils may promote a balanced nutrient profile, enhancing agricultural yields and biodiversity [27]. The lower pH in rural soil may be attributed to reduced human influence, allowing natural soil-forming processes to prevail [28]. However, a relatively high pH in urban soil may also impact the solubility and mobility of heavy metals [29].

Furthermore, higher EC levels were observed in urban soils, which could be attributed to various urban activities, including road construction, industrial waste, and atmospheric deposition of pollutants. Thus, greater EC may affect soil bacterial groups, inducing nutrient cycling and the breakdown of organic matter [30]. Additionally, higher EC in the soil can influence the availability and mobility of heavy metals, which can induce osmotic stress in plants, thereby inhibiting their growth [31]. High EC measurements revealed that soil salinity has adverse effects on plants and soil fertility [32]. Furthermore, urban areas, characterized by reduced vegetation cover and increased impermeable surfaces, hinder the natural leaching of salts, potentially leading to elevated soil salinity. Conversely, elevated SOM in polluted urban soils can form soluble complexes with heavy metals, potentially increasing their mobility and bioavailability to plant roots [33].

Urban soils exhibited higher soil organic matter (SOM), which may be attributed to the accumulation of organic waste and reduced microbial decay in compacted soils. Organic matter can also enhance metal mobility in contaminated soils, raising concerns in urban settings with heavy metal pollution [34]. In rural soils, adequate organic matter supports sustainable agricultural practices by improving soil fertility and stability and by promoting plant growth and microbial communities [24]. The urban soil texture is characterised by a higher proportion of sand, resulting in quicker drainage and lower water-holding capacity [35]. Rural soils had higher silt and clay content, thereby enhancing their water-retention and nutrient-holding capacity [36]. Several soil surveys in Gujrat have revealed that the soil texture is predominantly clay loam across both rural and urban landscapes. Therefore, the physicochemical properties of the soil provided valuable insights into the soil texture within the study area.

4.2. Heavy Metal Concentration in the Soil

The selection of Zn, Pb, Cd, and Cu was based on their prevalence in industrial emissions, persistence in soils, and well-documented toxicity. In the Gujrat district, industries such as ceramics, metal plating, and battery manufacturing are major sources of these metals. While Zn and Cu are essential micronutrients, they become toxic at elevated levels. In contrast, Pb and Cd are highly toxic even at low concentrations and pose serious risks to human health. Their persistence and potential transfer into the food chain further justify their inclusion in the assessment of ecological and human health risks, thereby directly supporting the study's objectives.

These results demonstrated transparent urban-rural gradients, with both Cd and Cu showing their highest concentrations in urban soil. However, the rural soil samples were collected from areas dominated by agricultural practices and subject to agricultural runoff, whereas heavy metal concentrations were higher in urban soils [37]. The high concentration of these metals in urban soil is likely due to proximity to industrial sites and high traffic, with pollutants originating from sources such as automobile tire wear and brake lining degradation [38]. Rural soil samples exhibited lower Zn concentrations, likely due to reduced exposure to primary Zn sources [39]. However, Zinc (Zn) may only be available from natural soil resources or in small quantities supplied by fertilisers in rural soils [40]. Although Zn is an essential element for flora, fauna, and ecological processes, excessive exposure can also pose health risks. Thus, elevated concentrations can be poisonous, such as high Zn levels, which disrupt nutrient cycling and alter soil microbial communities, affecting ecosystem sustainability [41,42]. Previous studies reported Zn concentrations ranging from 0.07 to 5.60 mg/kg in the area, which are significantly lower than those observed in the present study.

Lead (Pb) contamination in urban areas was often linked to vehicular emissions, particularly from older automobiles that had used leaded gasoline, as well as emissions from industrial activities. In addition, Pb can be found in urban dust, construction debris, and waste disposal areas, all of which contribute to soil contamination [43]. In rural soils, Pb concentrations were comparatively low, possibly due to the use of agricultural fertilizers or limited atmospheric deposition. Lead (Pb) is highly toxic and poses significant environmental and health risks, particularly to children and pregnant women. Additionally, the accumulation of heavy metals in plants and animals that enter the food chain leads to long-term health effects [44].

The elevated cadmium (Cd) concentrations observed in urban soils are likely attributable to industrial activities, including metal refining, battery manufacturing, and waste disposal [45]. Although Cd is usually introduced into the soil through industrial processes and the use of several fertilisers [46]. Cadmium (Cd) concentrations in rural soils were lower than those in urban soils. Plants can absorb Cd, particularly leafy vegetables, where the human body accumulates Cd from plants, which affects sensitive parts of the human body, such as the kidneys and bone [47,48]. Cadmium (Cd) is highly toxic and may pose health risks to humans through the consumption of untreated products and commodities.

The elevated copper (Cu) concentrations observed in urban areas may be attributed to industrial effluents and automobile brake wear. Although rural soils have low concentrations, over time, copper can be added to agriculture through certain fungicides and fertilisers. Copper (Cu) is an essential micronutrient for both plants and animals; however, excessive concentrations can be toxic, adversely affecting plant growth and soil organisms [49]. Excessive levels of Cu in the human body, caused by the intake of impure soil production substances, cause kidney and liver damage [50].

4.3. Comparison of Heavy Metal Concentration

The normality tests of the data revealed a greater deviation from normality (p = 0.00) in rural samples than in urban samples. Although urban areas showed less variability due to more evenly distributed sources (vehicular releases and construction activities), the rural regions exhibited greater variability due to inconsistent application of fertilisers or pesticides [51].

4.4. Concentration of Heavy Metals Between Urban and Rural Areas

A gradual increase in variation among Zn, Pb, Cd, and Cu is observed at soil depths of 0–15 cm in urban areas. However, Zn, Pb, Cd, and Cu in rural soil showed less variation at the 0–15 cm soil depth than in urban areas [52].

4.5. Correlation Between Soil Physicochemical Properties and Heavy Metal Concentration of Rural Area

Although organic matter plays a crucial role in retaining heavy metals and binding them, it can increase their bioavailability while reducing metal mobility in the soil [53]. The results suggested that a high organic matter content in rural soil was associated with high salinity levels [54]. Also reported that high EC values affect soil fertility and water retention capacity. However, the pH of rural soil did not significantly affect the behaviour of heavy metals. The relatively stable pH in the region exerted a direct limiting effect on the mobility and solubility of metals [55]. In rural areas, Zinc, Lead, and Cadmium appear less influenced by soil properties than organic matter. The overall effect of pH and EC is not stronger on heavy metals than on other soil properties. In the urban area, it was suggested that there is no significant relationship between OM and EC, but rather a weak one. It also showed that organic content has a limited influence on metal mobility or retention in urban areas [56].

4.6. Correlation Between Soil Physicochemical Properties and Heavy Metal Concentration of Urban Area

However, Cadmium concentration was found to be more pronounced than other soil chemical properties, which could be due to urban contamination sources having a greater influence on Cadmium. It was indicated that pH and organic matter exerted a weak influence on heavy metal concentration. On the other hand, there was a notable relationship between Zinc and lead, which may have shared the same sources of contamination, such as industrial automobile pollution.

4.7. Risk Index Assessment of Heavy Metals in the Rural and Urban Areas

The Assessment of non-carcinogenic health risks indicated that the studied areas are currently somewhat safe from adverse effects stemming from the combined exposure to Cu, Cd, Pb, and Zn. Both values are substantially below the safety threshold of 1.0, a limit established by regulatory bodies [57], suggesting that non-carcinogenic health impacts are unlikely for either population group [58]. The individual Total Hazard Quotients further support this conclusion for each metal, which also remained below the risk threshold, indicating a low probability of harm from any single contaminant.

4.8. Human Health Risk Assessment in Rural and Urban Areas

The contact risks for adults and children were assessed by calculating the Average Daily Dose (ADD), Hazard Quotient (HQ), Hazard Index (HI), and the Carcinogenic Risk calculation (CR). The ADD for metals was estimated using three exposure phases, expressed in mg/kg/day. For both children and adults, the average daily dose (ADD) followed the order of ingestion > dermal contact > inhalation. However, among children, the highest dose of all metals in the soil was found in the Ingestion and Dermal Absorption route, whereas Ingestion was greater in adults. This may be a result of children's unique behaviour through skin contact, notably hand-to-mouth contact [24].

4.9. Total Hazard Quotient and Index

The hazard quotient (HQ) followed the same trend in both children and adults, with ingestion > dermal exposure > inhalation. For all exposure pathways, the HI values for both children and adults were less than 1, indicating that significant non-carcinogenic health risks are unlikely. However, urban children (0.0606) exhibited a markedly higher HI value compared to rural children (0.0119). The HI for adults remains below hazardous levels, but is higher in urban areas.

4.10. Assessment and Comparison of Carcinogenic Risk in Urban and Rural Areas

Lifetime cancer risk from Cd, Cu, Pb, and Zn was calculated using cumulative lifetime cancer risk estimates, providing valuable information from a health perspective. The Cancer Slope Factor (CSF) for each metal provided valuable insights across the three phases of exposure pathways.

In contrast, the carcinogenic risk assessment revealed a notable concern, particularly for children. While the lifetime cancer risk for adults was calculated to be 4.99×10^{-5}, falling within the generally acceptable risk range of 10^{-6} to 10^{-4}, the risk for children was significantly higher [59]. This could be due to industrial development, road traffic discharges, and waste removal practices in urban environments. In addition, Children in urban areas showed a higher cancer risk, particularly from Lead and Cadmium [26]. The cumulative Cancer Risk (CR) for children reached 1.99×10^{-4}, a value that lies at the upper boundary of the acceptable range. This elevated risk, corresponding to approximately two additional potential cancer cases per 10,000 children, underscores their heightened vulnerability to carcinogenic substances. It also highlights a potential public health concern that may require preventative action, a finding consistent with global child health concerns [60].

5. Conclusions

This study provided a critical risk assessment of heavy metal contamination in the soil of two peripheral areas of Gujrat, Pakistan, revealing a significant disparity between urban and rural environments. The research confirmed that urban soil in the River Garden Housing Scheme is significantly more polluted than the agricultural soil in Kalra Kalan, with markedly higher concentrations of Zinc (Zn), Lead (Pb), Cadmium (Cd), and Copper (Cu). The contamination pattern in both areas followed the sequence Zn > Pb > Cd > Cu, with urban concentrations of Pb and Cd approximately 4 and 3 times higher, respectively, than those in rural areas. These results suggest that industrial activities and vehicular emissions are the primary drivers of the contamination gradient, as evidenced by correlations among specific metals.

The human health risk assessment yielded divergent outcomes for non-carcinogenic and carcinogenic risks.

The non-carcinogenic Hazard Index (HI) for the studied metals was 0.06 for children and 0.01 for adults, both well below the safety threshold of 1.0, suggesting that adverse non-carcinogenic health effects are unlikely for the population. However, the Carcinogenic risk (CR) assessment reveals a significant public health concern, particularly for children, whose cumulative risk (CR = 1.99×10^{-4}) reached an unacceptable level. This elevated risk, equivalent to two potential cancer cases per 10,000 children, is predominantly driven by exposure to Pb and Cd in the urban environment, with Ingestion being the primary exposure pathway. In conclusion, while immediate non-carcinogenic threats appear minimal, the unacceptable level of carcinogenic risk for children highlights the urgent need for targeted interventions to control pollution sources and mitigate human exposure in the urban periphery of Gujrat.

Given the significantly higher heavy metal concentrations in urban areas, primarily attributed to industrial and traffic sources, it is recommended that local and national environmental protection agencies enforce stricter regulations on industrial waste disposal and emissions in Gujrat. Continuous monitoring of soil quality in areas adjacent to industrial estates and high-traffic roads should be institutionalised to track pollution trends and ensure compliance. Due to the elevated carcinogenic risk for children, particularly through Ingestion, public health initiatives are crucial. It is recommended to implement awareness programs for communities in high-risk areas, such as the River Garden Housing Scheme, to educate residents about the risks of heavy metal exposure. These programs should promote simple mitigation practices, including handwashing, thorough cleaning of locally grown vegetables, and minimizing children's direct contact with contaminated soil. The study identified Lead (Pb) and Cadmium (Cd) as the primary drivers of carcinogenic risk. Therefore, it is recommended that site-specific remediation strategies be explored for hotspots within the urban area. Techniques such as phytoremediation, which use plants to extract or stabilise metals, could be investigated as a cost-effective, environmentally friendly approach to reduce the bioavailability of these toxic elements in soil. To develop more effective mitigation plans, further research is recommended to precisely identify the specific contamination pathways from industrial and urban sources to the soil. Future studies should also analyse the concentration of heavy metals in locally grown food crops to quantify the dietary risk to residents, as this is a primary route for heavy metals to enter the human food chain. The results highlight the importance of sustainable soil management and pollution control in industrial and rural areas. By guiding policymakers and communities, this research contributes to achieving long-term environmental sustainability and public health protection.

5.1. Limitations of Study

- Only four heavy metals (Zn, Pb, Cd, Cu) were analyzed, excluding others.
- Dietary exposure through crops and water was not included.
- Sampling was limited to surface soils (0–15 cm) and selected sites.
- Seasonal and temporal variations in contamination were not considered.
- Risk assessment relied on standard models, not fully capturing local conditions.

5.2. Practical Implications

- Provides baseline data to guide soil quality monitoring and management in industrial and rural areas.
- Helps policymakers design effective regulations to control industrial heavy metal emissions.
- Supports development of targeted soil remediation and risk reduction strategies.
- Informs local communities and farmers about potential health risks, promoting safer agricultural practices.

5.3. Future Recommendations

- The findings highlight the urgent need for stricter regulatory monitoring of heavy metal emissions from industrial estates.
- Results can guide policymakers in developing soil remediation and waste management strategies.
- Awareness campaigns and community engagement are essential to reduce human exposure risks.
- Future research should explore crop uptake pathways and long-term ecological impacts to support sustainable land use planning.

List of Abbreviations

AAS	Atomic Absorption Spectroscopy
ADD	Average Daily Dose
CR	Carcinogenic Risk
CSF	Cancer Slope Factor
EC	Electrical Conductivity
EPA	Environmental Protection Agency
HI	Hazard Index
HQ	Hazard Quotient
HSD	Honestly Significant Difference

IR	Inhalation Rate
pH	Potential of Hydrogen
RFD	Reference Dose
SD	Standard Deviation
SOM	Soil Organic Matter
SPSS	Statistical Package for the Social Sciences
THQ	Total Hazard Quotient
WHO	World Health Organization

Author Contributions

All authors contribute equally to the research paper. M.N.: Experimental design, formal analysis, data curation, data validation, writing original draft, visualization. B.S.: supervision, data validation, review of write-up of draft. M.F.: supervision, statistical analysis, review, and write-up of draft. All authors have read and agreed to the published version of the manuscript.

Availability of Data and Materials

The data will be made available on request.

Consent for Publication

No consent for publication is required, as the manuscript does not involve any individual personal data, images, videos, or other materials that would necessitate consent.

Conflicts of Interest

The authors declare no conflicts of interest

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AI Declaration

The authors confirm that no AI tools were used to generate any content of this manuscript.

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