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EVALUATION OF SOIL HEAVY METAL POLLUTION RESULTING FROM UNTREATED INDUSTRIAL EFFLUENT DISCHARGE AND ITS IMPACT ON ENVIRONMENT

Izhar Nazir[1], Humaira Shaheen[2], Muhammad Jawad Umar[3], Muhammad Azhar Khan[*4], Dr. Zill-E-Huma[5], Dr. Sajid Mahmood[6]

[1]*School of Science, Engineering & Environment, University of Salford, Manchester, United Kingdom*
[2,5]*Department of Botany, University of Sargodha, Sargodha, Pakistan*
[3]*Department of Chemistry, Quaid-e-Azam University, Islamabad, Pakistan*
[*4,6]*Department of Botany, Hazara University, Mansehra, Pakistan*

[1]izharnazir224@gmail.com, [2]humairakhaan86@gmail.com, [3]jawadumarsaggu@gmail.com, [*4]azharfinal@gmail.com, [5]humashah690@gmail.com, sajid_sbs12@hu.edu.pk

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Corresponding Author: *
Dr. Sajid Mahmood

Abstract

Industrial activities are a major source of heavy metal contamination in soils and wastewater, posing potential risks to environmental and human health. This study assessed the concentrations and ecological risks of selected heavy metals (Fe, Cu, Zn, and Ni) in soils and industrial effluents from three industrial sites (ghee, tannery, and textile industries) located in Faisalabad, Pakistan. Soil samples were collected and processed to obtain composite samples, while wastewater samples were collected in acid-treated polypropylene bottles and preserved at 4 °C prior to analysis. All samples were digested using standard acid digestion procedures and analyzed for metal concentrations using atomic absorption spectrophotometry. Soil contamination was evaluated using the Pollution Index (PI), Pollution Load Index (PLI), and Potential Ecological Risk (ER) model to determine contamination levels and ecological hazards associated with these metals. The indices provided a comprehensive assessment of soil pollution status and the potential ecological impact of industrial activities in the study area. The findings contribute to understanding heavy metal contamination in industrial zones of Faisalabad and highlight the importance of continuous environmental monitoring and improved waste management practices to protect soil quality and ecosystem health.

Introduction

Soil pollution is a global challenge caused by toxic concentrations of pollutants added into the soil by anthropogenic activities and proved to be a serious threat to environment as well as public health (Hou et al., 2025). The presence of toxic levels of pollutants in soil can lead to soil toxicity and cause harm to human health. Various anthropogenic sources including fertilizers, herbicides, pesticides, organic manure as well as contaminated irrigation water can cause soil pollution in agricultural soils and crops cultivated in these soils can be the source of serious health risks in humans (Taghavi et al., 2024). In order to maintain the environmental sustainability and human wellbeing, it is necessary to improve the soil health by mitigating the effects of pollution (Nuruzzaman et al., 2025). Soil pollution is a matter of concern and it should not be ignored because pollutants from soil can contaminate the environmental components including air and water and enter into the food chain and cause multiple diseases to humans because humans and environment are closely linked. The efforts to minimize or prevent the soil pollution are not sufficient and there is need to take actions and aware the people because most

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of the causes of soil pollution are anthropogenic (Raimi et al., 2022). The identification of soil pollutants and determination of their impact on environment play an important role in preventing the soil pollution (Shi et al., 2024).

With an increasing world's population, the demand for industrial products has also been increased leading to industrial expansion and production of industrial effluents. Industrial effluents contain hazardous material including toxic chemicals which can cause soil and water pollution when added to water bodies and soil without any treatment (Abdullahi et al., 2024). Industrial effluents when added into the soil change the physical and chemical properties of soil by increasing the concentration of hazardous material including heavy metals, radioactive material, hydrocarbons and other toxic chemicals. Accumulation of such toxins in the soil cause negative impacts on soil quality and cause harm to the natural environment (Singha & Chatterjee, 2022). It has been observed that the heavy metal pollution is maximum in the soils near industries because waste material from various industries leaches into the soil and contaminate it (Swain, 2024).

Developing countries like Pakistan are facing a challenge of heavy metal pollution due to industrial effluents because of lack of awareness and proper policies (Akhtar et al., 2023). Increasing rates of industrialization and urbanization in Pakistan has increased the production of industrial effluents which further increased the risk of soil pollution when these untreated effluents are added into the soil (Khan et al., 2022). Faisalabad is an industrial city of Pakistan but until now very little comprehensive research has been done on the assessment of the soil pollution of the agricultural soil of Faisalabad due to industrial effluents. The study focuses on assessment of soil pollution of Faisalabad due to industrial effluents and its impact on environment with the following objectives

- To determine the concentration of heavy metals such as iron, copper, zinc, and nickel in industrial effluent samples.
- To analyze the levels of heavy metals in soil samples collected from the study area.
- To assess the relationship between heavy metal concentrations in industrial effluent and soil using correlation analysis.
- To evaluate the variation in heavy metal concentrations using statistical analysis.
- To calculate various pollution indices

2. Materials and Methods

2.1. Study Area

The study was conducted in industrial area of Faisalabad which is one of the most important industrial cities of the Punjab province of Pakistan. Faisalabad is located between two main persistent rivers, Chenab and Ravi, at 73.08′ E, 31.25′ N and at an altitude of 214 m above sea level. The wastewater and soil samples from three industries viz., ghee, tannery (LHU), and textile (FU) were selected for soil and waste water quality assessment. The sites for sample collection were within city zone of Faisalabad, Pakistan. A map of Faisalabad and the sample collection area is shown in figure 2.1.

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Figure 2.1. Map of Faisalabad

2.2. Samples Collection and Preservation

Soil and water samples were collected near the industrial area. The soil sample was collected up to the depth of 5-60 cm from each site. Five to six soil samples were arbitrarily collected and shared to mix composite soil samples for every location. During sample collection, it was ensured that the sample is free of debris. Labelled plastic bags were used to store the samples. In the laboratory, the samples were subjected to air-drying, homogenized by passing it through a 2 mm sieve size and again stored in sterilized plastic bottles. Afterwards, these soil samples were subjected to different analysis (Ahmad et al., 2021). 100 ml of water samples were collected from all three sites. Samples collected in polypropylene bottles pre-treated with nitric acid (1%) were transported to Labs and maintained at 4 C until analyzed (Yang et al., 2020).

2.5. Digestion procedure

All water samples collected from industrial area were digested using the APHA technique (2005). With 10 ml of HNO3 water, samples were digested in their intense form at 80 C until the solution turned colourless. The solutions were subsequently filtered through filter paper (0.22 ml, Maidstone Whatman filters) and distilled water was added to bring the level up to 50 ml. Each dried soil samples were digested with H2SO4, HClO4, and HNO3, solution (15 ml) in a ratio of (1:1:5) at 80 C the solution becomes obvious liquid. After filtration amount of each digested sample was adjusted (50 ml) for further examination.

2.6. Analytical method to determine metal

After completing digestion, wet digestion samples were diluted and all specimens were subjected to metal investigation through an atomic absorption spectrophotometer (AAS).

2.7. Soil Pollution Indices

2.7.1. Pollution index

The pollution index (PI) was calculated using the modified formula

$$PI = \frac{C_n}{B_n}$$

Where Cn is the concentration of the examined element in the soil, Bn is the geochemical background value.

Table 2.2. Background Values of Heavy Metals in Soil

Metals	Background Value (mgkg-1)
Cu	8.39
Fe	56.9
Zn	44.19
Ni	9.06

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Fe (Akhtar et al., 2022), Zn (Nadeem et al., 2020), Cu, Ni (Singh et al., 2010)

Table 2.3. Classfication of different soil contamination assessment of pollution index (PI).

Classification index	PI value	Description of class
1	PI<1	Uncontaminated
2	1≤PI<2	Slightly polluted
3	2≤PI<3	Moderately polluted
4	3<PI	Highly polluted

2.7.2. Pollution load index (PLI)

The PLI was used to calculate the overall pollution level in the soil. The PLI was examined using the following formula (Swetha et al., 2025).

$$PLI = (PI_1 \times PI_2 \times PI_3 \times \dots \dots PI_n)^{\frac{1}{n}}$$

where PI_n is the Polllution index of different elements.

- PLI < 0: Unpolluted;
- 0 < PLI ≤ 1: Baseline levels of pollutant present;
- 1 < PLI ≤ 10: Polluted;
- 10 < PLI ≤ 100: Highly polluted;
- PLI > 100: Progressive deterioration of environment.

2.7.3. Potential ecological risk (ER)

The assessment of soil contamination degree was primarily conducted by the ecological risk model that has been introduced, wherein due regard is given to the hazardous of noxious metallic constituents and their consequential impacts on the ecosystem. The chief aim of this paradigm is to categorize elements based on their hazardous levels (Cao et al., 2023).

$$Potential\ Ecological\ Risk = Tri \times PI$$

Eri = monomial ecological risk value, CF = contamination factor, and Tri = toxic or lethal response values given by Zhang et al., (2023). The Tri values of Zn, Cu, Ni, and Fe are1,5,3-5, and 1 respectively. The categorization of Eri is elaborated as follows: Eri falls under the category of minimal environmental hazard when it is less than 95, represents an intermediate environmental hazard when it ranges between 95 and 190, indicates a significant environmental hazard when it lies between 190 and 380, and signifies an extremely elevated environmental hazard when it exceeds 380.

3. Results and Discussion

3.1. Assessment of heavy metals in soil

Table 1 presents the concentrations of heavy metals in soils collected from industrial complexes in Faisalabad. The results show variations in the levels of Fe, Cu, Zn, and Ni among the three sampling sites (S1–S3). Iron (Fe) exhibited the highest concentration at site S2 (151.59±1.21) and lowest concentration at S3 (103.48±1.51). The highest obtained result was in accordance with the value (166 mg/kg) observed by Din et al., (2023).The result for the lowest value of Iron obtained in the soil was supported by the value (104 mg/kg) calculated by Salem et al., (2020). Similarly, copper (Cu) showed the highest value at S2 (125.10±0.50), while lower concentrations were observed at S3 (101.78±0.45). The obtained results were higher than the results (30.0 mg/kg and 62.0 mg/kg) previously reported by Batjargal et al., (2010). The slight difference between previous documented values and studied values may be due effect of environmental factors and soil pH which can increase or decrease the availability of metals (Kicińska et al., 2022). Zinc (Zn) concentrations ranged from 33.18±0.77 to 61.48±0.96, with the maximum value also recorded at S2. The values obtained for the concentration of Zinc in soil was close to slightly higher value (72.5 mg/kg) reported by Brito et al., (2020). Nickel (Ni) showed comparatively lower concentrations at all sites, ranging from 0.69±0.07 to 1.08±0.05. The obtained values were in accordance with the slightly higher value (4.6 mg/kg) obtained by Latosińska et al., (2021). Overall, site S2 exhibited relatively higher concentrations of most metals, indicating a greater influence of industrial activities at this location. Among the obtained values ,the values of Zinc and Copper were more than the permissible limit (Osobamiro et al., 2019). Toxic concentrations

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of metals beyond permissible limit cause soil pollution and it affects the human health through food chain (Hlihor et al., 2022).

Table 3.1. Concentration of heavy metals in soils of industrial complexes in Faisalabad

SITE	Fe	Cu	Zn	Ni
S1	121.54±1.28	114.39±0.98	51.24±0.59	0.69±0.07
S2	151.59±1.21	125.10±0.50	61.48±0.96	1.08±0.05
S3	103.48±1.51	101.78±0.45	33.18±0.77	0.98±0.07

Table 3.2 shows the analysis of variance results depicting the significant differences in the concentrations of heavy metals in soil samples across the studied groups. Iron, copper, and zinc exhibit very high F values of 653.14, 567.13, and 651.43, respectively, with p-values less than 0.001, indicating highly significant variation among groups. Nickel also shows a statistically significant difference with an F value of 17.28 and a p-value of 0.0032. The between-group sum of squares for iron, copper, and zinc is much higher than the within-group variation, suggesting strong differences in metal concentrations among sampling locations. Overall, the results indicate that soil metal concentrations vary significantly across the studied sites, reflecting spatial differences in heavy metal contamination.

Table 3.2 Analysis of variance showing significant differences in iron, copper, zinc, and nickel concentrations in soil samples across the studied groups.

Metal	df	SS (Between)	MS (Between)	SS (Within)	MS (Within)	F	p-value
Fe	2	3544.1794	1772.0897	16.2792	2.7132	653.1364	0.0000
Cu	2	817.7529	408.8764	4.3257	0.7210	567.1313	0.0000
Zn	2	1232.1682	616.0841	5.6745	0.9457	651.4276	0.0000
Ni	2	0.2393	0.1196	0.0415	0.0069	17.2825	0.0032

3.2. Concentration of metals in water

Table 3.3 shows the concentrations (mg/L) of heavy metals in industrial effluents from Faisalabad industrial complexes. Iron (Fe) concentrations were highest at site S2 (22.33±0.74) and lowest at S3 (15.92±0.72). Copper (Cu) levels ranged from 1.15±0.14 at S3 to 3.39±0.12 at S2, indicating moderate variation across sites. The values of Fe and Cu were in accordance with the Sankpal & Naikwade, (2012). Zinc (Zn) concentrations were comparatively low, with values between 0.61±0.04 and 1.67±0.06. The lowest observed concentration of zinc in water samples collected from all sites was almost than the value (0.08 mg/L) reported by Rizani & Laze, (2017) and the highest observed value was almost equal to the value (1.06 mg/L) calculated by Mandal et al., (2019). Nickel (Ni) was detected in lower concentration ranging from 0.03±0.004 to 0.1±0.008 mg/L. Overall, site S2 showed relatively higher levels of Fe, Cu, and Zn, suggesting a greater contribution of industrial discharges at this location. The samples from various sites contain metals above permissible limits of WHO. The presence of heavy metals in water in excessive concentration leads to the accumulation of toxic level of heavy metals in food chain as reported by Laoye et al., (2025).

Table 3.3. Concentration of heavy metals in industrial effluents (mg/L) industrial complexes in Faisalabad

SITE	Fe	Cu	Zn	Ni
S1	17.28±0.45	2.45±0.111	1.03±0.03	0.03±0.004
S2	22.33±0.74	3.39±0.12	1.67±0.06	0.1±0.008
S3	15.92±0.72	1.15±0.14	0.61±0.04	0.07±0.008

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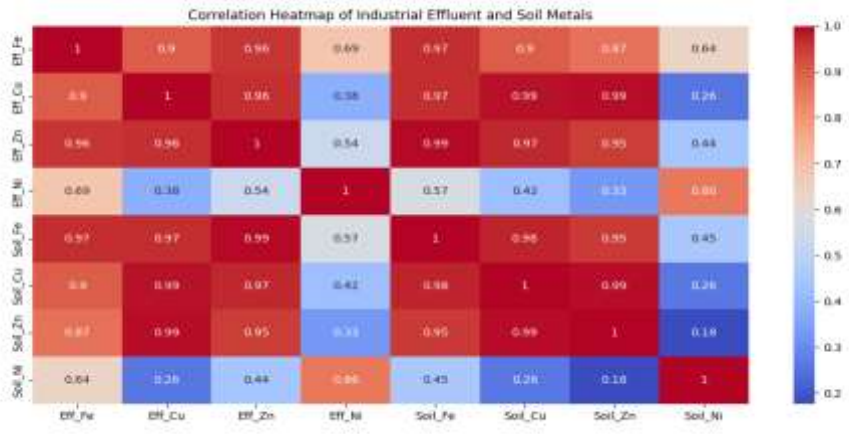
Table 3.4 shows the analysis of variance results indicating the significant differences in heavy metal concentrations in industrial effluent across the studied groups. Iron, copper, and zinc show very high F values of 53.33, 232.86, and 204.70, respectively, with p-values less than 0.001, indicating highly significant variation. Nickel also shows a statistically significant difference with an F value of 38.71 and a p-value of 0.0004. The between-group variation is much higher than the within-group variation for all metals, suggesting clear differences in effluent metal concentrations among the sampling locations.

Table 3.4 Analysis of variance results showing significant differences in iron, copper, zinc, and nickel concentrations in industrial effluent across the studied groups

Metal	df	SS (Between)	SS (Within)	MS (Between)	MS (Within)	F	p-value
Fe	2	68.4402	3.8498	34.2201	0.6416	53.3328	0.0002
Cu	2	7.6173	0.0981	3.8086	0.0164	232.8648	0.0000
Zn	2	1.7013	0.0249	0.8506	0.0042	204.6979	0.0000
Ni	2	0.0060	0.0005	0.0030	0.0001	38.7143	0.0004

Fig 3.1 shows the relationships between heavy metals in industrial effluent and soil samples. Iron, copper, and zinc in industrial effluent show strong positive correlations with each other, ranging from 0.90 to 0.96, indicating a similar source or discharge pattern. Soil metals also exhibit very strong correlations, particularly between copper and zinc (0.99) and iron and copper (0.98), suggesting co-accumulation in soil. Strong positive correlations are also observed between effluent metals and soil metals, such as zinc in effluent with iron in soil (0.99), indicating the influence of industrial discharge on soil contamination. In contrast, nickel in soil shows weaker correlations with other metals, ranging from 0.18 to 0.64. This suggests that nickel may originate from different sources or follow different environmental behaviour. Overall, the heat map highlights a strong association between industrial effluent and soil metal pollution.

Fig 3.1 Correlation heat map showing the relationships between heavy metals in industrial effluent and soil samples, including Iron, Copper, Zinc, and Nickel.



3.3. Soil Pollution indices

2.7.1. Pollution index and Pollution load index (PLI)

Table 3.5 presents the pollution index (PI) values for Fe, Cu, Zn, and Ni in soils collected near industrial areas of Faisalabad, along with the overall Pollution Load Index (PLI) for each site. Among all the metals, average pollution index ranged from 0.08 at S1 to 14.91 at S2. The values of PI suggested that all the sites were polluted because PI was above 1 (Suwanmanon & Kim, 2020). The calculated PLI values

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ranged from 1.16 at S3 to 1.60 at S2, indicating varying degrees of soil contamination. Site S2 recorded the highest PLI, suggesting greater overall pollution likely due to intense industrial activities. In contrast, S3 exhibited the lowest PLI, reflecting relatively lower contamination levels. The obtained PLI for all the sites was $1 \leq PI < 2$ indicating that the area was slightly polluted (Jorfi et al., 2017). Overall, the data indicate that Cu contributes most significantly to the soil pollution in the study area.

Table 3.5. Pollution index (PI) and Pollution Load Index (PLI) for studied soils near the industrial areas of Faisalabad in Pakistan

SITE	Fe	Cu	Zn	Ni	PLI
S1	2.13	13.64	1.16	0.08	1.28
S2	2.66	14.91	1.39	0.12	1.60
S3	1.81	12.13	0.75	0.11	1.16

2.7.4. Potential ecological risk (ER)

Table 3.6 shows the potential ecological risk (Eri) values of Fe, Cu, Zn, and Ni in soils from industrial areas of Faisalabad. Copper (Cu) exhibited the highest ecological risk at all sites, with values ranging from 60.65 at S3 to 74.55 at S2. Iron (Fe) and zinc (Zn) displayed low ecological risk values across all sites. Nickel (Ni) showed minimal risk, with values below 1 at each location. Overall, site S2 recorded the highest ecological risk due to elevated Cu levels, while S3 had the lowest overall risk. These results indicate that Cu is the major contributor to the potential ecological risk in the studied soils. Potential Ecological Risk Factor of Zinc, Iron and Nickel for soil of all the plants were recorded as $ER < 40$ which indicated the low ecological risk. Ecological risk factor of Copper (Cu) was observed as $40 < ER \leq 80$ which indicated moderate ecological risk (Copaja & Muñoz, 2022). High Potential Ecological Risk Factor of soils from which edible crops have been harvested affects the quality of crops, posing serious threat to human health (Wang & Hu, 2023).

Table 3.6. Potential ecological risk (ER) for studied soils near the industrial areas of Faisalabad in Pakistan

SITE	Fe	Cu	Zn	Ni
S1	2.13	68.20	1.16	0.40
S2	2.66	74.55	1.39	0.60
S3	1.81	60.65	0.75	0.55

Conclusion

The present study evaluated the concentration and ecological risks of selected heavy metals (Fe, Cu, Zn, and Ni) in soils and industrial effluents collected from three industrial sites in Faisalabad, Pakistan. The results revealed noticeable variations in metal concentrations among the sampling sites, with site S2 showing the highest levels of most metals in both soil and wastewater samples, indicating stronger influence of industrial activities. Copper and zinc concentrations in soil exceeded permissible limits, suggesting potential contamination of the surrounding environment. Analysis of industrial effluents also showed elevated levels of Fe, Cu, and Zn in some locations, while nickel was not detected in the water samples. The calculated pollution index (PI) values indicated that the soils at all sites were contaminated, particularly due to high copper levels. The Pollution Load Index (PLI) values ranged from 1.16 to 1.60, demonstrating that the studied area is slightly polluted overall. Ecological risk assessment further showed that copper posed a moderate ecological risk, whereas iron, zinc, and nickel presented low ecological risks across all sampling sites. Overall, the findings suggest that industrial

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discharges contribute significantly to heavy metal accumulation in soils and effluents in Faisalabad's industrial areas. Continuous monitoring of heavy metal levels, proper treatment of industrial wastewater, and implementation of strict environmental management practices are necessary to reduce metal contamination and protect soil quality, ecosystem stability, and human health.

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