# Seasonal Variation of Heavy Metals in Industrial Soils: Assessment Using Contamination Factor, Pollution Load Index and Geoaccumulation Index

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**Abstract**
Heavy metal contamination in industrial soils is a persistent environmental concern because metals are non-biodegradable, toxic, and capable of accumulating in soil systems over long periods. Seasonal processes such as rainfall, runoff, leaching, and atmospheric deposition may influence the distribution and pollution intensity of metals in soil. This study assessed seasonal variation of copper (Cu), lead (Pb), nickel (Ni), and zinc (Zn) in industrial soils of Jammu City during pre-monsoon and post-monsoon seasons. Soil samples were collected from six selected industrial sites and analyzed using Atomic Absorption Spectrophotometry. Contamination Factor (CF), Pollution Load Index (PLI), and Geoaccumulation Index (Igeo) were used to evaluate contamination status, while Wilcoxon signed-rank test, Spearman correlation, and Principal Component Analysis were applied for statistical interpretation. Zn showed the highest concentration in both seasons, followed by Cu, Pb, and Ni. CF values exceeded 6 for all metals, indicating very high contamination. PLI values were 9.00 and 8.84 during pre-monsoon and post-monsoon seasons, respectively, indicating progressive pollution. Mean Igeo values indicated moderate to heavy pollution. Although seasonal variations were observed, they were not statistically significant. The findings suggest persistent industrial soil contamination in Jammu City, mainly associated with anthropogenic activities, highlighting the need for regular monitoring and remediation.

**Keywords:** Heavy metals; Industrial soils; Seasonal variation; Pollution Load Index; Geoaccumulation Index

## 1. Introduction

Soil contaminated with substantial metals is a major ecological concern because heavy metal compounds are non-biodegradable, persistent in soil (may be accumulated in soil systems for long periods), toxic at high concentrations. The presence of potentially toxic metals as a result of industrialisation, urban development, vehicle use, mining, wastewater discharge and poor waste disposal has been enhanced in terrestrial environments. Heavy metals can modify the physicochemical characteristics of soils, impact soil microbial life, impair soil fertility, and enter into food chains via plant assimilation, dust inhalation, dermal contact and accidental ingestion. In Jammu district, soil contamination with heavy metals is already linked with potential risk to human health and is a problem that needs to be monitored regularly and assessed site-specifically for contaminated soil [1].

Soils in industrial areas can be especially susceptible to enrichment with heavy metals because they are constantly exposed to industrial emissions, metal-processing, combustion wastes, waste dumping, vehicle exhaust, lubricant leakage, and atmospheric deposition. The industrial and mining areas have been the subject of many studies, which revealed that high levels of metals like Cu, Pb, Ni, Zn, Cd and other trace elements can be found in the topsoil, posing ecological and human health concerns [2].

An important dimension of soil contamination studies is seasonal variation as the concentration of metals, their mobility and redistribution can vary with different climatic conditions. A combination of dryness, deposition of dust, evaporation and limited leaching during the pre-monsoon can contribute to the accumulation of metals in the shallow soils. In contrast, post-monsoon conditions can affect the behavior of metals through precipitation, runoff, precipitation-induced leaching, transport of particles suspended in the surface waters, erosion, dilution, and fresh deposition from industrial/urban sources. Sediments of coastal wetlands are reported to be seasonally contaminated with heavy metals, with rainfall and hydrological processes influencing the distribution and ecological risk of metals [3]. The same applies to the soils around the mining area, where temporal variation has been reported in the levels of trace and heavy metals, and thus needs to be accounted for when assessing contamination [4].

Because total metal concentration alone does not fully explain environmental risk, various pollution indices are used to interpret contamination levels relative to background concentrations. The pollution index is a more useful tool for interpreting pollution levels because it makes it easier to compare observed metal concentrations with background concentrations, The Pollution Load Index (PLI) provides the total pollution burden of the metals, while the Contamination Factor (CF) measures the degree of metal enrichment above the background concentration. A useful technique for determining the level of metal enrichment while also accounting for lithogenic variation in the natural environment is the Geoaccumulation Index (Igeo).The use of these indices in soil contamination studies is common, as they enable the

classification of pollution intensity, identification of possible anthropogenic enrichment, and support environmental management decisions. The presence of heavy metals in soils has been widely discussed and there has been a high level of interest in assessing their contamination by chemical methods, by the use of pollution indices and by interpretation according to risk [5].
Global anthropogenic activities, including the burning of fossil fuels, industrial operations, mining and smelting, and excess dumping, have been linked to the contamination of air, water, and soils by trace metals. The long-term storage of metals in environmental compartments caused by these inputs increases the necessity for local contamination assessments [6]. Heavy metal contamination in urban, agricultural, mining, and sedimentary contexts has been the subject of a few studies, however there is very little data on the seasonal variation of heavy metals in Jammu City's industrial soils using a combined pollution-index and statistical technique. Hence, the present study was aimed to investigate the seasonal variation in the concentration of Cu, Pb, Ni and Zn in pre-monsoon and post-monsoon seasons in the industrial soils of Jammu city. The specific objectives were to assess the contamination status of the soil by applying the CF, PLI and Igeo, analyze the correlation between the metals using Spearman correlation and identify possible source patterns using PCA and to provide scientific evidence for monitoring and remediation of industrial soil contamination in the study area.

## 2. Literature Review

However, heavy metal pollution of soils has been known to be a serious environmental problem due to the persistence, non-biodegradability and bioaccumulation of trace metals in the air, water, soil, sediment and biological systems. Nriagu Pacyna provided one of the earlier global estimates of the contribution of anthropogenic activities by industrial emissions, mining, fossil fuel combustion, waste disposal and urbanisation to the global distribution of trace metals in the environmental media [6]. Their work paved the way for the recognition of the importance of assessing heavy metals as local pollutants as well as pollutants with environmental and ecological effects.
Metal content of sediments and soils was measured to evaluate the extent of accumulation, and the Geoaccumulation Index (Igeo) was introduced by Muller, who accounted for natural lithogenic variations, and compared the measured metal contents to geochemical background levels [7]. Igeo has since been recognized as a valuable indicator of pollution intensity and an indicator of the difference between anthropogenic enrichment and natural background pollution. In heavy metal studies it can be useful, because, the total concentration alone does not adequately explain the severity of contamination, or the extent of enrichment above background levels.
Identification of the sources is also becoming important in soil contamination studies. In fact, multivariate statistical and geospatial analysis methods were successfully used to trace sources of heavy metals in soil by Facchinelli et al. [8]. They found that spatial distribution patterns and statistical relationships between metals may be useful to distinguish between natural, industrial, traffic-related, and mixed sources of contamination. These techniques are especially useful for the soils in industrial and urban areas, where several anthropogenic processes can occur at the same time and can cause high metal levels.
Contamination in urban or traffic areas is reported in several studies. Lu et al. measured the content of Cu, Pb, Zn, Mn and Ni in street dust from the city of Baoji, located in the northwestern part of China and concluded that urban dust is an effective sink of heavy metals as well as a transport medium [9]. Li et al. also reported high concentrations of heavy metals in urban soils and street dusts from Hong Kong, with traffic emission, industry and high density urban development being the factors that affect the enrichment of heavy metals [10]. These studies suggest that urban-industrial areas are especially susceptible to metal buildup because of the continual deposition of metals from vehicles, industry and the atmosphere as particulates.
Wei and Yang summarized the levels of heavy metal contamination in urban soils, road dusts and agricultural soils in China, and concluded that rapid urbanization, industrial development, traffic emissions, and agricultural inputs are important factors that cause soil to be enriched with heavy metals [11]. They also highlighted the importance of frequent monitoring and risk assessment, particularly where human exposure can take place via inhalation, ingestion, dermal contact or food-chain transfer.
Contamination of soils is not the only area of concern for heavy metals; they can contaminate crops as well and pose a risk to food safety. Heavy metal accumulation in the vegetables cultivated in the wastewater-irrigated regions of Varanasi, India has been reported by Sharma et al. [12] which indicated that contaminated soils and wastewater sources are able to pass heavy metals to edible parts of vegetables. This emphasizes the importance of soil contamination studies in the wider context of ecology and public health. Combined, these studies give ample ground to assess the seasonal changes of heavy metals in industrial soils through contamination indexes, statistics and source identification techniques.

## 3. Materials and Methods

### 3.1 Study Area

In the existing study, Industrial soil sampling sites of Jammu City, Jammu and Kashmir were selected. Geographically, Jammu is in the north western part of India, and is the winter capital of Jammu and Kashmir Union Territory. Shivalik Himalayas in the North and the northern plains in the South form the boundaries of the region. In terms of climate, Jammu has a sub-humid-subtropical climate and has 4 distinct climatic seasons: There are four seasons, namely Summer/Pre-monsoon (April to June), monsoon (July to September), autumn or Post-monsoon (October to November) and winter (December to February).
The selected sampling sites are characterised by small and medium scale manufacturing industries, automobile workshops, steel and metal fabrication industries, paint-related industries, repair workshops, and high traffic routes.

Anthropogenic activities can lead to the deposition of heavy metals in surface soils by emissions from industry, vehicle exhaust, leakage of lubricants, surface runoff and inappropriate disposal of waste by human activity.

Six sampling sites were chosen for a seasonal evaluation of heavy metal contamination. Geographic coordinates of sampling sites were obtained and the map of the study area was prepared. The selected sites are located on the map (Figure 1) and the coordinates of these sites are shown in Table 1.

**Table 1.** Geographic coordinates of selected soil sampling sites

| Site no. | Latitude (N) | Longitude (E) |
|---|---|---|
| 1 | 32.674991 | 74.871340 |
| 2 | 32.678957 | 74.879664 |
| 3 | 32.677136 | 74.872656 |
| 4 | 32.679192 | 74.879500 |
| 5 | 32.685280 | 74.854555 |
| 6 | 32.673240 | 74.867785 |


**Figure 1.** Location map of the six selected industrial soil sampling sites in Jammu City

**3.2 Soil Sampling and Sample Preparation**

Soil samples were taken at the six selected industrial sites in two seasons namely pre-monsoon and post-monsoon. When taking samples, there were minimal effects from surface runoff or water logging, and that is why the samples were taken under dry meteorological conditions. Surficial soil was obtained at each site from an average depth of 10-15 cm using a clean shovel. A 1–2 kg sample of soil was taken at each location and put into clean, labelled zippered plastic bags. To compare the heavy metal concentrations and the pollution indices of both seasons, the same sampling locations were used. The samples were then collected and sent to the lab for processing. Manual removal of visible extraneous materials like stones, concrete fragments, plant residues, leaf litter, wood pieces and other debris was done. The soil samples were dried in the oven at 40°C for 48 h and then passed through a 2 mm mesh to get rid of the coarse particles. The dried and sieved samples were homogenized by coning and quartering. An aliquot of each homogenized sample was then ground to -200 mesh size (<63 µm) with an agate mortar and pestle and preserved in plastic vials which were pre-labelled for chemical digestion and instrumental analysis.

**3.3 Acid Digestion and Instrumental Analysis**

The soil samples were finely ground and 0.20 g of each sample was taken, accurately weighed and transferred to Teflon/PTFE microwave digestion vessels for the determination of the heavy metals. Mixed acid solution of nitric acid, hydrofluoric acid and hydrochloric acid were used for digestion. The acid mixture contained 6 mL $HNO_3$ (65%), 2 mL HF (40%), and 1 mL HCl (37%). The digestion vessels were tightly sealed and samples were digested using a closed-vessel microwave digestion system.

Once digested, the vessels were set at room temperature to cool. The solutions were then filtered, diluted to a final volume of 50 ml with deionized water. Atomic Absorption Spectrophotometry (AAS), PerkinElmer Analyst 400, was used to determine the concentrations of Cu, Pb, Ni and Zn. The concentrations of metals were reported as mg/kg (dry weight of soil).

**Table 2.** Soil sample digestion and heavy metal analysis

| Step no. | Procedure | Details |
|---|---|---|
| 1 | Sample weighing | Approximately 0.20 g of homogenized soil sample was accurately weighed. |
| 2 | Transfer to vessel | The sample was transferred into Teflon/PTFE microwave digestion vessels. |
| 3 | Acid addition | $HNO_3$, HF, and HCl were added in the ratio 6 mL:2 mL:1 mL. |
| 4 | Digestion | Samples were digested using a closed-vessel microwave digestion system. |
| 5 | Filtration and dilution | Digested samples were filtered and diluted using deionized water. |
| 6 | Instrumental analysis | Cu, Pb, Ni, and Zn were analyzed using AAS. |
| 7 | Instrument details | PerkinElmer Analyst 400 Atomic Absorption Spectrophotometer. |
| 8 | Unit of expression | Metal concentrations were reported as mg/kg dry weight. |

### 3.4 Quality Assurance and Quality Control

The reliability and repeatability of the results were ensured by implementing quality assurance and quality control processes in analytical results. All reagents used in sample digestion and dilution were analytical grade and deionized water was used. Reagent blanks were run throughout digestion to check for chemical and laboratory handling and vessel contamination. AAS analysis of the calibration standards for Cu, Pb, Ni, and Zn was done before calibration and only if good linearity was achieved were the calibration curves accepted.

The pre and post-monsoon soil samples were processed using the same digestion procedure and instrumental conditions to ensure consistency. Cross-contamination was minimized in the preparation of the glassware, digestion vessels and sampling equipment. The analytical results were expressed in terms of mg/kg of dry soil.

### 3.5 Pollution Assessment Indices

Three contamination indices Contamination Factor (CF), Pollution Load Index (PLI) and Geoaccumulation index (Igeo) were employed for the evaluation of heavy metals pollution in soil. The levels of these elements were measured and their geochemical background values used to calculate these indices.

Background concentrations used were based on averaged values for shale reported by Taylor and McLennan (1985) [13] for the present study. The background values used were Cu = 25 mg/kg, Pb = 20 mg/kg, Ni = 20 mg/kg, and Zn = 95 mg/kg. The background values used were the same for both CF and Igeo calculations.

#### 3.5.1 Contamination Factor

The relative enrichments of the different heavy metals in the soil compared to the background concentration were determined using contamination factor (CF). It was estimated from the following equation:

$$CF = \text{Cmetal/Cbackground}$$

where ($C_{metal}$) is the measured concentration of a particular metal in the soil sample and ($C_{background}$) is the background concentration of the same metal. The classification of CF values as given by Hakanson (1980) [14] is as follows:

| CF value | Contamination category |
|---|---|
| CF < 1 | Low contamination |
| 1 ≤ CF < 3 | Moderate contamination |
| 3 ≤ CF < 6 | Considerable contamination |
| CF ≥ 6 | Very high contamination |

CF values were calculated separately for Cu, Pb, Ni, and Zn during pre-monsoon and post-monsoon seasons.

#### 3.5.2 Pollution Load Index

The total heavy metal pollution of the sampling sites was evaluated using pollution load index. The geometric mean of the contamination factors for the metals studied was used to calculate PLI. The general formula developed by Tomlinson et al. (1980) [15] is:

$$\text{PLI} = (\text{CF}_1 \times \text{CF}_2 \times \text{CF}_3 \times \dots\dots\dots\dots\dots\dots \times \text{CF}_n)\text{^}(1/n)$$

where (CF) represents the contamination factor of each metal and (n) is the number of metals analyzed. In the present study, four metals were analyzed: Cu, Pb, Ni, and Zn. Therefore, PLI equation was applied as:

$$\text{PLI} = \left(\text{CF}_{\text{Cu}} \times \text{CF}_{\text{pb}} \times \text{CF}_{\text{Ni}} \times \text{CF}_{\text{Zn}}\right)^{\wedge}(1/4)$$

PLI values were interpreted as follows:

| **PLI value** | **Pollution status** | **Environmental inference** |
|---|---|---|
| PLI < 1 | Baseline level | No significant pollution |
| PLI = 1 | Baseline deterioration | Beginning of pollution |
| PLI > 1 | Progressive pollution | Deterioration of site quality |

#### 3.5.3 Geoaccumulation Index

The Geoaccumulation Index (Igeo)) was used to determine the extent of the metal enrichment in soil, relative to the background concentrations. Igeo value was calculated in the following way as proposed by Muller (1969) [7]:

$$\text{Igeo} = \log_2 (\text{C}_\text{n}/1.5\text{B}_\text{n})$$

where ($C_n$) is the measured concentration of the metal in soil, ($B_n$) is the geochemical background value of the corresponding metal, and 1.5 is the correction factor used to account for natural lithogenic variation in background

concentrations. Igeo was calculated separately for Cu, Pb, Ni, and Zn. A mean Igeo value was used to summarize the overall geoaccumulation status of the studied metals for each season.
The Igeo classification was interpreted as follows:

| Igeo class | Igeo range | Pollution intensity |
|---|---|---|
| Class 0 | Igeo < 0 | Not polluted |
| Class 1 | 0 ≤ Igeo < 1 | Uncontaminated to moderately polluted |
| Class 2 | 1 ≤ Igeo < 2 | Moderately polluted |
| Class 3 | 2 ≤ Igeo < 3 | Moderately to heavily polluted |
| Class 4 | 3 ≤ Igeo < 4 | Heavily polluted |
| Class 5 | 4 ≤ Igeo < 5 | Heavily to extremely polluted |
| Class 6 | Igeo ≥ 5 | Extremely polluted |

### 3.6 Statistical Analysis

The seasonal variations and relation between the heavy metals were evaluated using statistical analysis. Cu, Pb, Ni, and Zn concentrations have been determined for descriptive statistics in the pre-monsoon and post-monsoon seasons. Due to the small sample size, the seasons were paired, and pre-monsoon and post-monsoon data were compared using the Wilcoxon signed-rank test. Statistical significance was assessed using a significance level of $p < 0.05$.
The relationships between the metals studied were evaluated using Spearman's rank correlation analysis. The choice of this non-parametric method of correlation was made due to the limited numbers of sampling sites and possible non-normal distribution of environmental data. The results of the correlation were presented as Spearman's rho (ρ) along with the p-values.
Principal Component Analysis (PCA) was also used as an exploratory multivariate technique to determine possible sources and relationships between Cu, Pb, Ni and Zn. Standardized concentration data of metals and correlation matrix were used to perform PCA. The Kaiser criterion was used for retaining the components with eigenvalues > 1. The results of the PCA were interpreted with caution because the number of sampling sites was only 6. Seasonal comparison, source interpretation and pollution assessment in the study area was carried out based on the results of statistical analysis.

## 4. Results

### 4.1 Seasonal variation in heavy metal concentrations

The concentration of Cu, Pb, Ni and Zn was determined in pre and post monsoon season to explore a variation in industrial soils of Jammu City. In both seasons, the mean concentration of Zn was the highest followed by Cu, Pb, Ni. The concentration sequence (Zn>Cu>Pb>Ni) found during pre monsoon season and the same sequence was found during post monsoon season.
There was a decrease in Cu content from 364.16 mg/kg during pre-monsoon to 342.92 mg/kg during post-monsoon which suggested 5.83% decrease. There was also a 10.80% decline in Ni from 159.62 mg/kg to 142.38 mg/kg. In contrast, Pb slightly increased from 181.53 mg/kg to 184.42 mg/kg, while Zn increased from 717.58 mg/kg to 786.40 mg/kg. The maximum seasonal change was recorded for Zn (9.59%) during the post-monsoon season. The Wilcoxon signed rank test, however, revealed no differences that were statistically significant in metal concentrations between the seasons ($p > 0.05$) and hence, levels of heavy metal contamination did not vary significantly among the seasons (Table 3 and Figure 2). The maximum seasonal increment was seen in the case of Zn, i.e., post-monsoon (9.59%). The Wilcoxon signed-rank test, however, showed that the seasonal differences in the concentration of metals were not statistically significant.

**Table 3.** Comparative analysis of heavy metal concentrations in soil during pre-monsoon and post-monsoon seasons

| **Metal** | **Background value** | **Pre-monsoon concentration** | **Post-monsoon concentration** | **Difference** | **% Change** | **Pre-monsoon CF** | **Post-monsoon CF** | **W** | **p-value** |
|---|---|---|---|---|---|---|---|---|---|
| Cu | 25 | 364.16 | 342.92 | -21.24 | -5.83% | 14.57 | 13.72 | 9.0 | 0.844 |
| Pb | 20 | 181.53 | 184.42 | +2.89 | +1.59% | 9.08 | 9.22 | 8.0 | 0.688 |
| Ni | 20 | 159.62 | 142.38 | -17.24 | -10.80% | 7.98 | 7.12 | 5.0 | 0.313 |
| Zn | 95 | 717.58 | 786.40 | +68.82 | +9.59% | 7.55 | 8.28 | 9.0 | 0.844 |

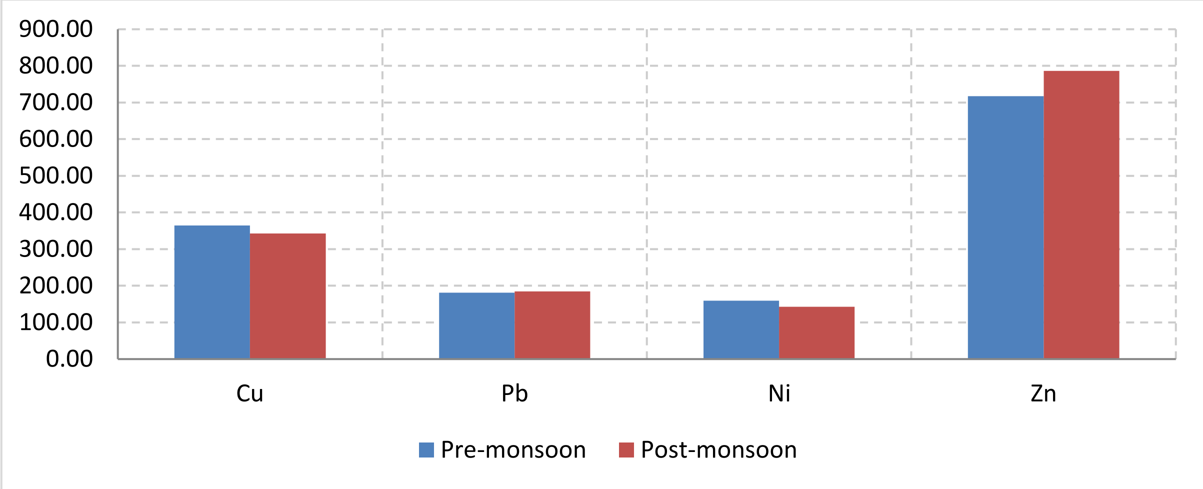


**Figure 2.** Seasonal comparison of mean heavy metal concentrations of Cu, Pb, Ni, and Zn in industrial soils during pre-monsoon and post-monsoon seasons

### 4.2 Contamination Factor assessment

The Contamination Factor (CF) values were calculated using background values for Cu, Pb, Ni, and Zn. In both seasons, all metal contamination was extremely high (CF > 6). During the pre-monsoon season, Cu was found to be the most prevalent metal, followed by Pb, Ni, and Zn. Cu had the largest CF during the post-monsoon season, followed by Pb, Zn, and Ni.

The pre-monsoon CF values were found to be from 7.55 (Zn) to 14.57 (Cu) and the post-monsoon CF values were found to be between 7.12 (Ni) to 13.72 (Cu). The slight decrease in CF for all elements after the monsoon was observed, while a slight increase was observed for Pb and Zn. The Wilcoxon signed-rank test results, however, revealed that the difference of the CF values between the seasons did not significantly differ for any metal ($p>0.05$). These results show that contamination was present at a fairly high concentration throughout the seasons (Table 4).

**Table 4.** Comparative analysis of heavy metal Contamination Factor (CF) in soil during pre-monsoon and post-monsoon seasons

| Metal | Pre-monsoon CF | Post-monsoon CF | W | p-value |
|---|---|---|---|---|
| Cu | 14.57 | 13.72 | 9.0 | 0.844 |
| Pb | 9.08 | 9.22 | 8.0 | 0.688 |
| Ni | 7.98 | 7.12 | 5.0 | 0.313 |
| Zn | 7.55 | 8.28 | 9.0 | 0.844 |

### 4.3 Pollution Load Index and Geoaccumulation Index

Pollution Load Index (PLI) was used to determine the degree of pollution caused by Cu, Pb, Ni and Zn. PLI value for pre-monsoon (season) was 9.00 and post-monsoon (season) was 8.84. Both of them were more than 1 and therefore in both seasons the soil is progressive polluted. Overall, there was a slight decrease in pollution load from pre-monsoon to post-monsoon period as inferred from the reduction in PLI, which was not however statistically significant ($p > 0.05$).

In pre-monsoon season, the Mean Igeo value was 2.56, whereas, in post-monsoon season it was 2.53. The values suggest moderate to heavy pollution. There was a small decrease in Mean Igeo for post-monsoon season, which indicates some seasonal variation but Wilcoxon test did not show any statistical significance. Hence, the results of PLI and Mean Igeo showed high level of contamination of the industrial soils under the study for both the seasons (Table 5, Figure 3).

**Table 5.** Comparative analysis of Pollution Load Index (PLI) and Mean Igeo in soil

| Variable | Pre-monsoon value | Post-monsoon value | Difference | % Change | W | p-value | Interpretation |
|---|---|---|---|---|---|---|---|
| PLI | 9.00 | 8.84 | -0.16 | -1.78% | 10 | 1.000 | Progressive pollution in both seasons |
| Mean Igeo | 2.56 | 2.53 | -0.03 | -1.17% | 10 | 1.000 | Moderate to heavy pollution |

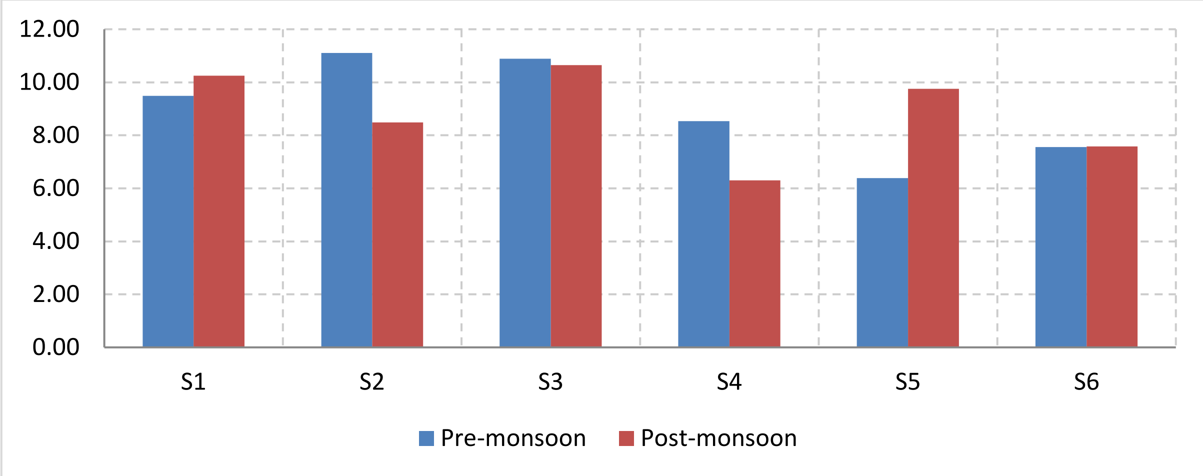


**Figure 3.** Site-wise comparison of Pollution Load Index (PLI) values during pre-monsoon and post-monsoon seasons across the six selected industrial soil sampling sites.

**4.4 Spearman correlation analysis**

To determine the association between Cu, Pb, Ni, and Zn during pre and post-monsoon season, Spearman correlation was used. The pre-monsoon season showed the strongest positive connection (0.60) between Pb and Zn levels, suggesting a similar depositional process or a same source. There were comparatively high positive associations between Cu and Pb ($\rho = 0.43$) and between Cu and Zn ($\rho = 0.37$). A weak negative correlation was observed between Cu and Ni ($\rho = -0.14$) that might suggest different behaviour or even source change.

The correlation pattern weakened and increased in variability during post-monsoon season. There were weak positive correlations between Pb and Ni ($\rho = 0.31$) as well as between Pb and Zn ($\rho = 0.26$). During post-monsoon, weak or negative correlation was observed between Cu and the other metals viz. Pb, Ni and Zn. A negative correlation between Cu and Ni ($\rho = -0.49$) could be due to a seasonal redistribution, dilution or differences in geochemical behaviour. All correlations however were statistically non-significant ($p>0.05$) and may be attributed to the small number of sampling sites and the natural different soil composition (Table 6).

**Table 6.** Spearman correlation coefficients and p-values for heavy metals during pre-monsoon and post-monsoon seasons

| Pair | Pre-monsoon ρ (rho) | Pre-monsoon p-value | Post-monsoon ρ (rho) | Post-monsoon p-value |
|---|---|---|---|---|
| Cu–Pb | 0.43 | 0.40 | 0.09 | 0.87 |
| Cu–Ni | -0.14 | 0.79 | -0.49 | 0.33 |
| Cu–Zn | 0.37 | 0.47 | -0.03 | 0.96 |
| Pb–Ni | 0.26 | 0.62 | 0.31 | 0.55 |
| Pb–Zn | 0.60 | 0.21 | 0.26 | 0.62 |
| Ni–Zn | 0.09 | 0.87 | 0.14 | 0.79 |

**4.5 Principal Component Analysis**

The correlation matrix of the standardized metal concentration data was used for Principal Component Analysis (PCA). The components with eigen values greater than one were chosen using the Kaiser criterion. Two significant factors that accounted for 79.3% of the variance were kept for the pre-monsoon season.The eigen value for PC1 was 2.05 with a variance of 51.3% and for PC2, 1.12 with a variance of 28.0%. PC1 has a strong positive loading for Cu, Pb and Zn, indicating potential common anthropogenic sources, such as metal processing, wastes and vehicles. The Ni exhibited relatively high contribution to PC2, implying that it may reflect a rather unique behavior and geogenic source.

Two significant components were also identified during the post-monsoon season; they explained 78.2% of the overall variance. 47.0% of the variance was explained by PC1 and 31.2% by PC2. Compared to the pre-monsoon loading pattern, the loading pattern during the post-monsoon season was far more intricate. The loading of PC1 was positive for Pb, Ni, and negative for Cu. The Cu, Pb and Zn had positive loadings and Ni had a negative loading on PC2. This suggests that post-monsoon rainfall and runoff can potentially affect redistribution and source mixing of the metals in the soil environment.

Based on the PCA results, the association of Cu, Pb and Zn with anthropogenic activities is more probable than those of Ni, while Ni could have a mixed geogenic-anthropogenic association. The study results were based on only 6 sampling sites and the PCA must be considered to be an exploratory source-identification tool instead of a definitive source-apportionment tool (Table 7).

**Table 7.** Principal Component Analysis of heavy metals during pre-monsoon and post-monsoon seasons

| Pair | Pre-monsoon | Post-monsoon |
|---|---|---|

| | Eigenvalue | Variance (%) | Eigenvalue | Variance (%) |
|---|---|---|---|---|
| PC1 | 2.05 | **51.3%** | 1.88 | **47.0%** |
| PC2 | 1.12 | **28.0%** | 1.25 | **31.2%** |
| PC3 | 0.53 | 13.2% | 0.57 | 14.3% |
| PC4 | 0.30 | 7.5% | 0.30 | 7.5% |
| **Factor Loadings** | **PC1** | **PC2** | **PC1** | **PC2** |
| Cu | 0.62 | -0.41 | -0.51 | 0.62 |
| Pb | 0.81 | 0.22 | 0.66 | 0.48 |
| Ni | 0.28 | 0.87 | 0.71 | -0.52 |
| Zn | 0.74 | 0.31 | 0.44 | 0.59 |

Standardization of metal concentration data was followed by PCA using the correlation matrix, where components having Eigen values > one were kept as per Kaiser's criterion.

## 5. Discussion

The concentration of the selected heavy metals, Contamination Factor (CF), Pollution Load Index (PLI), Geoaccumulation Index (Igeo)), Spearman correlation (r), and Principal Component Analysis (PCA) were all used in the current study to assess the levels of Cu, Pb, Ni, and Zn in Jammu City's industrial soils. All of the examined industrial soil samples were found to be contaminated throughout both the pre-monsoon and post-monsoon seasons, indicating the existence of long-term metal enrichment in the selected industrial sites. The highest concentration was for Zn, followed by Cu, Pb and Ni in both seasons. The predominance of Zn may be associated with industrial emissions, vehicular traffic, tyre wear, galvanisation processes, leakage of lubricants, metal work, and air fallout. The discharge of wastewater and poorly managed waste flows can also impact soil and environmental quality because contaminants associated with untreated discharges can impact land-use areas adjacent to agricultural operations [13].

The values of the CF for all the metals showed very high levels of contamination, with values being higher than 6 in both seasons. The PLI values were also higher than 1, indicating that the soil quality is degrading progressively. The results are in line with the studies conducted across India on heavy metal contamination in soils as a result of industrial activities, road traffic, mining, and urbanisation and are regarded as a source of soil pollution and ecological risk [14]. Similar multi-index and multivariate assessments have also shown that combined contamination indices provide a more reliable interpretation of metal pollution and ecological risk than individual concentration data alone [15]. The environmental importance of the persistence of metals in soil is the fact that heavy metals are not degradable, and can persist in the soil system for long time. They can impact soil fertility, soil microbial activity, crop productivity and can be a part of the food chain through plants, fodder, livestock and associated food products [16].

Seasonal comparison revealed that concentration of Cu and Ni decreased after monsoon season while that of Pb and Zn slightly increased during post-monsoon period. But Wilcoxon signed-rank test presented that the variances are not statistically significant. The results indicated that rainfall, leaching and runoff, dilution, and sediment redistribution may affect the behavior of metals, but the contamination in the study area appears to be fairly consistent throughout the seasons. Recent work on drainage-channel sediments from urban and agricultural areas also indicates that hydrological movement and land-use conditions can influence heavy metal distribution and ecological risk [17]. The occurrence of similar spatial variations has been reported in urban soils where land use, anthropogenic activity and point pollution sources play a significant role in the distribution of heavy metals [18]. Industrial soil investigations also have reported high metals concentrations close to industrial areas, which is consistent with the idea that long-term industrial activity may significantly contaminate surface soils with metals [19].

At the overall mean level, the Mean Igeo values showed moderate to heavy pollution. This indicates that the metals studied are present in concentrations higher than their natural background levels. The PLI and Igeo findings show that contamination is not only linked to the natural soil composition, but can also be related to anthropogenic activities. Similar index-based interpretations have been applied in polluted sediment environments, where multiple contaminants and depositional processes affect contamination status [20]. These issues have also been discussed in urban aquatic environments with long-term exposure to pollutants that are associated with ecosystem and human health problems [21].

Additional information on potential metal sources was gained from correlation and PCA results. The strong relationships between the metals were confirmed by Spearman correlation, and the highest pre-monsoon correlation was found between Pb and Zn. The association of these elements (Pb and Zn) was not significant, but they may share anthropogenic inputs. Source-identification studies have similarly used multivariate approaches to distinguish natural and anthropogenic contributions of metals such as Ni, Cd, Cr and Pb in contaminated wetland ecosystems [22]. The associations of the elements with anthropogenic sources, such as industrial emissions, traffic activity, workshops and waste disposal, were higher for Cu, Pb, and Zn, whereas Ni exhibited a relatively distinct association, suggesting a possible mixed geogenic-anthropogenic association. Multi-index risk evaluation of trace and rare earth elements in highly industrialized estuarine environments further supports the role of industrial inputs in metal enrichment patterns [23]. The interpretation of heavy metal contamination in sedimentary environments has been achieved using similar approaches based on the spatial distribution, abundance and risk assessment [24]. Recent source-apportionment studies also emphasize that anthropogenic drivers, urbanization and multi-media transport can strongly influence the occurrence and distribution of potentially toxic elements [25].

The CF and PLI values remain high in all the industrial soil samples, which suggest that these soils are experiencing a steady pollution state. Patterns of contamination in the vicinity of waste dumps and mechanic workshops add to the requirement to consider rainfall, waste handling and local industrial activity when interpreting the distribution of metals in contaminated environments [26]. Landfill leachate and poorly controlled waste-disposal systems are also recognized as important sources of hazardous pollutants, reinforcing the need for proper waste management and treatment strategies in industrial regions [27].

## 6. Implications

The conclusions of the existing study indicate that the soils of the industrial areas in Jammu City are experiencing heavy metal pollution pressure which can deteriorate the soil and result in ecological and health risk. The metals like Cu, Pb, Ni and Zn present in the soil for both seasons indicates that it is important to have soil monitoring in the industrial area on a regular basis. If not managed properly, poor industrial discharge, vehicle emissions, surface runoff and waste disposal can contribute further to contamination. Hence, regular soil quality evaluation, proper waste management, emission control and development of green-belts should be made priorities. Phytoremediation, biochar application and appropriate use of soil amendments could contribute to sustainable management of contaminated industrial soils by reducing the mobility of metals.

## 7. Conclusion

The current study used statistical techniques and the Contamination Factor (CF), Pollution Load Index (PLI), and Geoaccumulation Index (GAI) to assess the seasonal fluctuation in the amounts of Cu, Pb, Ni, and Zn in Jammu City's industrial soils. The findings indicated a significant level of pollution in the selected industrial locations since the heavy metal concentrations were likewise high before and after the monsoon. Zn had the highest concentration of the elements under study in both seasons, followed by Cu, Pb, and Ni. For all the metals under study, CF values exceeded 6, which indicated very high contamination. PLI values over 1 similarly showed progressive deterioration in soil quality while the Mean Igeo values showed moderate to heavy soil pollution. Seasonal variations were noted, but these were not seen to be statistically significant (Wilcoxon signed-rank test), which indicates that the levels of contamination are relatively stable in time. The outcomes of the correlation and PCA showed that Cu, Pb, and Zn were primarily related to anthropogenic sources (industrial emissions, traffic and metal processing, waste disposal), while Ni was more closely linked to a mixture of the geogenic and anthropogenic sources. In conclusion, the results emphasize the importance of ongoing surveillance, rigorous control of industrial wastes, emissions, and appropriate remediation measures to mitigate ecological risks and promote sustainable soil management in Jammu City.

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