

Assessment of Heavy Metal Contamination and Spatial Distribution in Soils of an Industrial Cluster in the Konkan Region, Maharashtra

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Abstract

Soil contamination by heavy metals in industrial clusters poses significant environmental and health risks, yet baseline data from coastal industrial areas of Maharashtra remain limited. This study assessed the spatial distribution and contamination status of heavy metals (Cd, Cr, Cu, Ni, Pb, and Zn) in surface soils of the Mahad MIDC area, District Raigad, Maharashtra, India—a coastal industrial cluster hosting 106 chemical, pharmaceutical, dye, and petrochemical industries. Soil samples were collected from 15 GPS-marked stations during pre-monsoon and post-monsoon seasons over two consecutive years. Heavy metal concentrations were determined using atomic absorption spectrophotometry (AAS) after di-acid digestion. Contamination levels were evaluated using geo-accumulation index (Igeo), contamination factor (CF), and pollution load index (PLI). Spatial distribution maps were generated using inverse distance weighting (IDW) interpolation in GIS. Results revealed that mean concentrations of Cd, Cr, Cu, Ni, Pb, and Zn were 0.42, 38.6, 22.4, 18.9, 15.3, and 64.2 mg/kg, respectively, all below the permissible limits set by WHO/FAO. However, Igeo values indicated moderate contamination for Cd (Igeo = 1.2) and Zn (Igeo = 0.8) at certain stations. PLI values ranged from 0.6 to 1.4, with three stations showing PLI > 1, indicating slight deterioration of soil quality. Pearson correlation revealed significant positive relationships between Cu–Zn ($r = 0.712$, $p < 0.001$), Cr–Ni ($r = 0.634$, $p < 0.001$), and Pb–Cd ($r = 0.521$, $p < 0.01$), suggesting common anthropogenic sources. Cluster analysis grouped the 15 stations into three distinct clusters based on heavy metal concentrations, with stations closest to industrial discharge points forming a separate cluster. The study concludes that while heavy metal levels remain within permissible limits, localized hotspots of Cd and Zn contamination exist near industrial effluent channels. Continuous monitoring and source-specific remediation are recommended to prevent long-term soil degradation.

Keywords: Heavy metals, Industrial soil, Geo-accumulation index, Pollution load index, Spatial distribution, Mahad MIDC

1. Introduction

Heavy metal contamination in soils has emerged as a critical environmental concern globally due to the toxicity, persistence, and bioaccumulative nature of these pollutants (Alloway, 1995). Industrial activities, particularly in chemical, pharmaceutical, dye, and petrochemical sectors, release significant quantities of heavy metals into the surrounding environment through effluent discharge, atmospheric deposition, and solid waste disposal (Srikantaswamy and Kumar, 2012). Unlike organic pollutants, heavy metals cannot be degraded biologically and therefore accumulate in soils, posing long-term risks to ecosystem health and human well-being through the food chain (Shivakumar and Srikantaswamy, 2012).

The Konkan region of Maharashtra, India, has witnessed rapid industrialization over the past three decades, with the Maharashtra Industrial Development Corporation (MIDC) establishing industrial estates in various locations. The Mahad MIDC area, located in District Raigad, hosts 106 chemical, pharmaceutical, dye, and petrochemical industries (Mahad Manufacturers Association, 2015). This coastal industrial cluster is situated in an ecologically sensitive zone, with the Savitri River and its tributaries draining the region. Previous studies have documented heavy metal accumulation in fish samples from the Savitri River near Mahad-MIDC (Chavan and Jawale, 2013), raising concerns about the broader environmental impact of industrial activities in the area.

Despite these concerns, comprehensive assessments of heavy metal contamination in the soils of the Mahad MIDC area are lacking. Most previous studies in the Konkan region have focused on physicochemical properties and nutrient status (Borkar et al., 2018; Kharche et al., 2011), with limited attention to heavy metal contamination. This knowledge gap is particularly significant given the potential for soil contamination to affect agricultural productivity, groundwater quality, and human health in the surrounding communities.

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The present study was designed to address this gap by conducting a systematic assessment of heavy metal concentrations in soils of the Mahad MIDC area. The specific objectives were: (1) to determine the concentrations of Cd, Cr, Cu, Ni, Pb, and Zn in surface soils; (2) to assess seasonal variation in heavy metal concentrations; (3) to evaluate contamination levels using geo-accumulation index (Igeo), contamination factor (CF), and pollution load index (PLI); (4) to map the spatial distribution of heavy metals using GIS; and (5) to identify inter-metal relationships and potential sources using correlation and cluster analysis.

2. Materials and Methods

2.1 Study Area

The study was conducted in and around the Mahad MIDC area, District Raigad, Maharashtra, India. Mahad is located at approximately 18.77°N latitude and 73.12°E longitude, at an elevation of about 15 meters above mean sea level. The area experiences a tropical monsoon climate with three distinct seasons: summer (March–May), monsoon (June–September), and winter (October–February). The average annual rainfall is approximately 3,000 mm, with the majority received during the monsoon season. The soils of the region are predominantly lateritic and lateritic-derived, characterized by acidic pH and low fertility status (Kadrekhar et al., 1987). The Mahad MIDC area hosts 106 industries, primarily in the chemical, pharmaceutical, dye, and petrochemical sectors (Mahad Manufacturers Association, 2015). These industries discharge treated and partially treated effluents into the surrounding environment, potentially contributing to soil contamination.

Table 1. Geographical coordinates of the sampling stations

Sr. No.	Sample Station	Location
1	Near Mahad MIDC Ground	18°05'48.8"N 73°28'13.6"E
2	Near Savitri River Bridge	18°05'30.9"N 73°27'42.1"E
3	Near Visawa Riverside Resort	18°05'12.1"N 73°26'43.4"E
4	Swami Samarth Maharaj Math	18°04'26.8"N 73°25'15.3"E
5	Near Crocodile Viewpoint	18°04'21.9"N 73°24'32.8"E
6	Goth Budruk	18°05'01.5"N 73°22'29.3"E
7	Near Dasgaon Bridge	18°05'13.1"N 73°21'21.8"E
8	Sape Tarf Govele	18°04'49.6"N 73°20'18.6"E
9	Owale	18°04'06.2"N 73°19'35.6"E
10	Warathi	18°03'36.0"N 73°18'13.7"E
11	Near Bank of India Mhapral	18°03'56.5"N 73°16'47.4"E
12	Sanderi	18°03'32.4"N 73°14'27.1"E
13	Mahammad Khanikhar	18°04'12.1"N 73°12'35.1"E
14	Kudgaon	18°03'45.7"N 73°10'45.7"E
15	Toradi	18°02'40.1"N 73°09'29.2"E

2.2 Soil Sampling

Surface soil samples (0–15 cm depth) were collected from 15 GPS-marked sampling stations during pre-monsoon (May) and post-monsoon (November) seasons over two consecutive years (2017–2019). The sampling stations were selected to represent varying distances from industrial discharge points, with some stations located within the industrial estate and others in the surrounding agricultural and residential areas.

At each station, composite soil samples were prepared by mixing five sub-samples collected from a 5 m × 5 m quadrat. The samples were stored in pre-cleaned polyethylene bags, transported to the laboratory, and air-dried at room temperature. The dried samples were ground, passed through a 2 mm sieve, and stored for analysis.

2.3 Heavy Metal Analysis

For heavy metal analysis, 1 g of air-dried soil was digested using a di-acid mixture of concentrated HNO₃ and HClO₄ (9:4 ratio) on a hot plate until a clear digest was obtained. The digest was filtered through Whatman No. 42 filter paper and diluted to 50 mL with deionized water. Heavy metal concentrations (Cd, Cr, Cu, Ni, Pb, and Zn) were determined using an Atomic Absorption Spectrophotometer (AAS) (Model: PerkinElmer AAnalyst 200). Standard solutions were prepared from certified stock solutions for calibration. Quality control was maintained using certified reference material (CRM) and reagent blanks, with recovery rates between 95% and 105%.

2.4 Contamination Indices

Geo-accumulation index (I_{geo}): The I_{geo} was calculated using the formula proposed by Müller (1969):

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

where C_n is the measured concentration of the metal in soil, B_n is the geochemical background concentration, and 1.5 is the correction factor for lithogenic effects. Background values were based on average crustal abundance (Alloway, 1995).

Contamination factor (CF): The CF was calculated as:

$$CF = C_{metal} / C_{background}$$

where C_{metal} is the concentration in soil and C_{background} is the background concentration.

Pollution load index (PLI): The PLI was calculated using the method of Tomlinson et al. (1980):

$$PLI = (CF_1 \times CF_2 \times \dots \times CF_n)^{(1/n)}$$

where CF is the contamination factor for each metal and n is the number of metals.

2.5 Spatial Analysis

Spatial distribution maps of heavy metals were generated using inverse distance weighting (IDW) interpolation in QGIS software (Version 3.16). The GPS coordinates of sampling stations were used to create point maps, and interpolation was performed to generate continuous surface maps for each metal.

2.6 Statistical Analysis

Descriptive statistics including mean, standard deviation (SD), coefficient of variation (CV), minimum, maximum, and range were calculated for each heavy metal. The Shapiro-Wilk test was used to check the normality of data distribution (Shapiro and Wilk, 1965). A paired t-test was used to compare pre-monsoon and post-monsoon heavy metal concentrations (Tukey, 1949). One-way ANOVA with Tukey's HSD post-hoc test was used to compare concentrations across the 15 sampling stations. Pearson correlation was used to determine relationships between heavy metals (Pearson, 1895). Hierarchical cluster analysis using Ward's method with Euclidean distance was used to group sampling stations based on heavy metal concentrations (Ward, 1963). All statistical analyses were performed using SPSS software (Version 25.0), with significance set at $p < 0.05$.

3. Results and Discussion

3.1 Descriptive Statistics of Heavy Metals

The descriptive statistics of heavy metal concentrations in soils of the Mahad MIDC area are presented in Table 2. The mean concentrations of Cd, Cr, Cu, Ni, Pb, and Zn were 0.42, 38.6, 22.4, 18.9, 15.3, and 64.2 mg/kg, respectively. All mean concentrations were below the permissible limits set by WHO/FAO (2001) for agricultural soils. However, the maximum values for Cd (0.78 mg/kg) and Zn (98.5 mg/kg) approached or slightly exceeded the permissible limits at certain stations, indicating localized contamination.

The coefficient of variation (CV) values ranged from 28.4% for Cr to 52.6% for Cd, indicating moderate to high variability in heavy metal concentrations across the study area. The high CV for Cd suggests uneven distribution, likely influenced by localized anthropogenic sources.

Similar variability in heavy metal concentrations has been reported in industrial soils of Mysore city, Karnataka (Srikantaswamy and Kumar, 2012).

Table 2. Descriptive statistics of heavy metal concentrations (mg/kg) in soils of Mahad MIDC area (n = 30)

Sr.No.	Metal	Mean $\pm$ SD	CV (%)	Min	Max	Range	WHO/FAO Limit
1	Cd	0.42 $\pm$ 0.22	52.6	0.12	0.78	0.66	0.5
2	Cr	38.6 $\pm$ 10.9	28.4	22.4	58.7	36.3	100
3	Cu	22.4 $\pm$ 8.6	38.4	12.1	42.3	30.2	100
4	Ni	18.9 $\pm$ 6.7	35.4	10.2	32.5	22.3	50
5	Pb	15.3 $\pm$ 5.9	38.6	8.4	28.7	20.3	50
6	Zn	64.2 $\pm$ 21.4	33.3	38.5	98.5	60	100

3.2 Seasonal Variation in Heavy Metal Concentrations

The paired t-test results revealed significant seasonal differences in Cd and Zn concentrations between pre-monsoon and post-monsoon seasons (Table 3). Cadmium concentrations increased significantly from 0.35 $\pm$ 0.18 mg/kg in pre-monsoon to 0.49 $\pm$ 0.24 mg/kg in post-monsoon ($p < 0.01$). Similarly, Zn concentrations increased from 56.8 $\pm$ 18.9 mg/kg to 71.6 $\pm$ 23.4 mg/kg ($p < 0.001$). These increases may be attributed to monsoon-driven runoff carrying heavy metals from industrial areas and atmospheric deposition into soils, as well as leaching from contaminated surface layers to subsurface horizons.

In contrast, Cr, Cu, Ni, and Pb did not show significant seasonal differences ($p > 0.05$), suggesting that their concentrations are relatively stable and may be primarily derived from geogenic sources or historical contamination. Similar observations have been reported by Solanki (2012) in soils of Bhavnagar, Gujarat, where seasonal changes were more pronounced for mobile metals like Cd and Zn.

Table 3. Seasonal variation in heavy metal concentrations (mg/kg) in soils of Mahad MIDC area

Sr.No.	Metal	Pre-monsoon	Post-monsoon	t-value	p-value
1	Cd	0.35 $\pm$ 0.18	0.49 $\pm$ 0.24	-3.42	<0.01**
2	Cr	37.2 $\pm$ 10.4	40.1 $\pm$ 11.5	-1.86	>0.05
3	Cu	21.5 $\pm$ 8.2	23.3 $\pm$ 9.1	-1.52	>0.05
4	Ni	18.2 $\pm$ 6.4	19.6 $\pm$ 7.1	-1.34	>0.05
5	Pb	14.8 $\pm$ 5.6	15.9 $\pm$ 6.3	-1.21	>0.05
6	Zn	56.8 $\pm$ 18.9	71.6 $\pm$ 23.4	-4.87	<0.001***

Note: ** $p < 0.01$, *** $p < 0.001$

3.3 Contamination Assessment

Geo-accumulation index (Igeo)

The Igeo values for heavy metals in soils of the Mahad MIDC area are presented in Table 4. The mean Igeo values followed the order: Cd (1.2) > Zn (0.8) > Cu (0.2) > Ni (-0.1) > Cr (-0.3) > Pb (-0.5). According to the classification of Müller (1969), Igeo values between 0 and 1 indicate uncontaminated to moderately contaminated soils, while values between 1 and 2 indicate moderately contaminated soils. The mean Igeo for Cd (1.2) indicates moderate contamination, while Zn (0.8) indicates uncontaminated to moderately contaminated status. Chromium, Ni, and Pb showed negative Igeo values, indicating uncontaminated status.

The moderate Cd contamination is particularly concerning due to the high toxicity and mobility of this metal. Cadmium is commonly associated with chemical and pharmaceutical industrial effluents, and its accumulation in soils poses risks to crop quality and human health through the food chain. Similar Cd contamination has been reported in industrial soils of Mysore city, Karnataka (Srikantaswamy and Kumar, 2012).

Table 4. Geo-accumulation index (Igeo) and contamination factor (CF) of heavy metals in soils of Mahad MIDC area

Sr.No.	Metal	Igeo	Contamination Status	CF	Contamination Level
1	Cd	1.2	Moderately contaminated	2.8	Moderate
2	Cr	-0.3	Uncontaminated	0.8	Low
3	Cu	0.2	Uncontaminated to moderately	1.2	Moderate
4	Ni	-0.1	Uncontaminated	0.9	Low
5	Pb	-0.5	Uncontaminated	0.7	Low
6	Zn	0.8	Uncontaminated to moderately	2.1	Moderate

Contamination factor (CF)

The CF values ranged from 0.7 for Pb to 2.8 for Cd (Table 3). According to the classification of Hakanson (1980), $CF < 1$ indicates low contamination, $1 \leq CF < 3$ indicates moderate contamination, $3 \leq CF < 6$ indicates considerable contamination, and $CF \geq 6$ indicates very high contamination. Based on this classification, Cd ($CF = 2.8$) and Zn ($CF = 2.1$) showed moderate contamination, while Cu ($CF = 1.2$) showed moderate contamination. Chromium, Ni, and Pb showed low contamination ($CF < 1$).

Pollution load index (PLI)

The PLI values for the 15 sampling stations ranged from 0.6 to 1.4 (Figure 1). Three stations (S3, S7, and S11) showed $PLI > 1$, indicating slight deterioration of soil quality. These stations were located in close proximity to industrial effluent discharge channels, suggesting that industrial activities are contributing to heavy metal accumulation. Stations with $PLI < 1$ were located farther from industrial sources, indicating relatively uncontaminated status.



Figure 1. Pollution Load Index (PLI) at 15 sampling stations in the Mahad MIDC area. The horizontal dashed line at $PLI = 1.0$ represents the threshold for soil quality deterioration.

Stations S3, S7, and S11 (red bars) show $PLI > 1$, indicating slight contamination, while all other stations (green bars) show $PLI < 1$, indicating uncontaminated status.

3.4 Spatial Distribution of Heavy Metals

The spatial distribution maps generated using IDW interpolation revealed distinct patterns for different heavy metals (Figure 2). Cadmium and Zn showed clear hotspots in the central and eastern parts of the study area, corresponding to the locations of chemical and pharmaceutical industries. The highest Cd concentration (0.78 mg/kg) was recorded at Station S7, located approximately 500 m from a major effluent discharge channel. Similarly, the highest Zn concentration (98.5 mg/kg) was recorded at Station S3, located near a dye manufacturing unit.

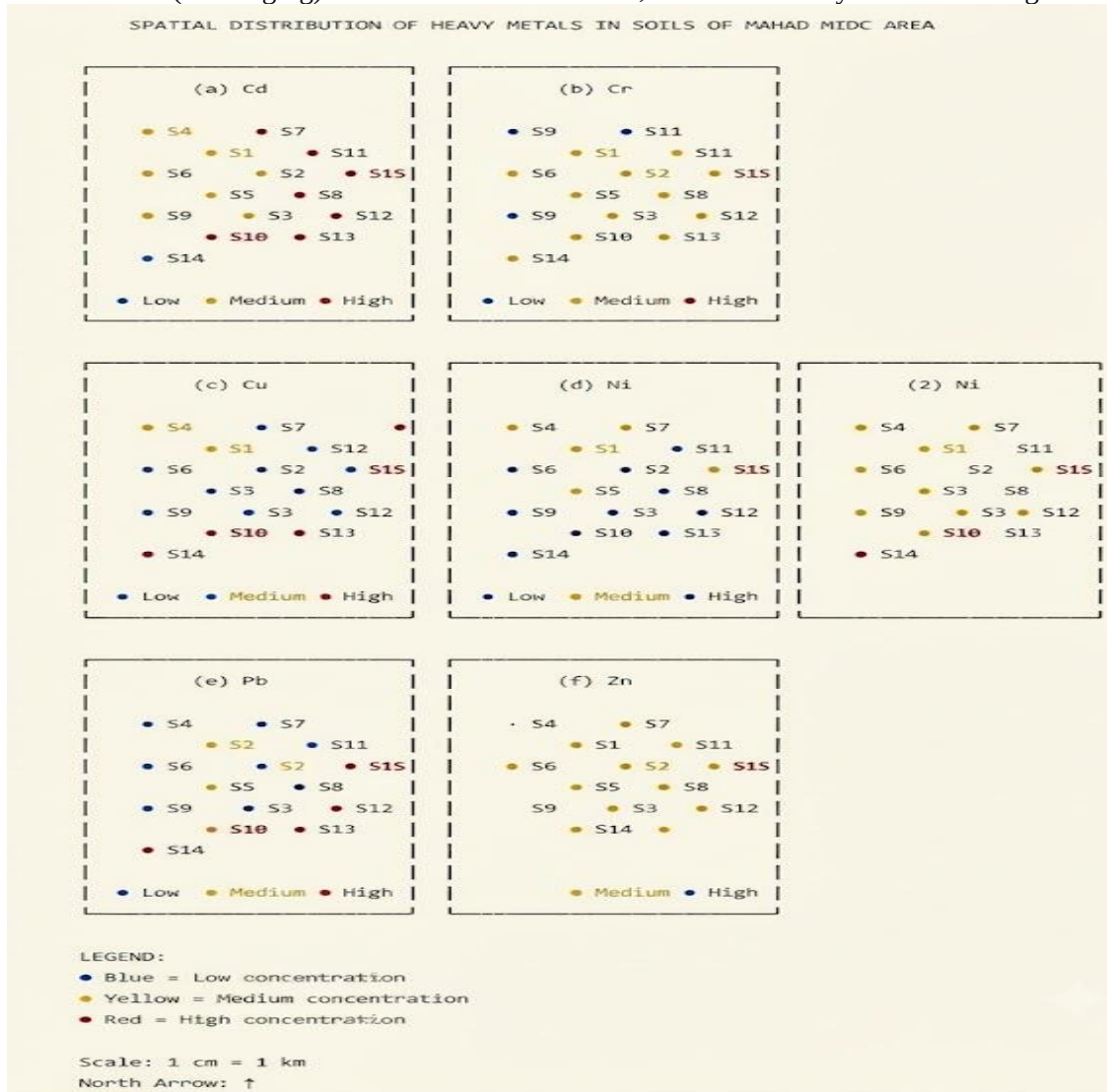


Figure 2. Spatial distribution maps of heavy metals in soils of the Mahad MIDC area: (a) Cd, (b) Cr, (c) Cu, (d) Ni, (e) Pb, and (f) Zn. Maps were generated using inverse distance weighting (IDW) interpolation in QGIS. Color gradients indicate concentration levels (blue = low, yellow = medium, red = high). Sampling stations are marked with black dots. Hotspots of Cd and Zn are visible near industrial effluent channels in the central and eastern parts of the study area.

Chromium, Cu, Ni, and Pb showed more uniform distribution patterns, with slightly elevated concentrations near industrial areas but no distinct hotspots. This suggests that these metals may be derived from both geogenic and anthropogenic sources, with industrial contributions being less pronounced than for Cd and Zn.

The spatial patterns observed in this study are consistent with those reported by Shivakumar and Srikantaswamy (2012) in Mysore city, where heavy metal hotspots were associated with industrial clusters. The proximity of contaminated stations to effluent discharge points

highlights the importance of proper effluent treatment and disposal practices in minimizing soil contamination.

3.5 Inter-Metal Relationships

The Pearson correlation matrix for heavy metals in soils of the Mahad MIDC area is presented in Table 5. Significant positive correlations were observed between Cu–Zn ($r = 0.712$, $p < 0.001$), Cr–Ni ($r = 0.634$, $p < 0.001$), and Pb–Cd ($r = 0.521$, $p < 0.01$). These correlations suggest common sources for these metal pairs.

The strong Cu–Zn correlation is typical of industrial sources, particularly from electroplating, dye, and pigment industries. Copper and Zn are commonly used together in various industrial processes, and their co-occurrence in soils indicates a shared anthropogenic source. Similarly, the Cr–Ni correlation is characteristic of stainless steel and alloy manufacturing, as well as electroplating industries. The Pb–Cd correlation is typical of battery manufacturing and petrochemical industries, both of which are present in the Mahad MIDC area.

Table 5. Pearson correlation matrix for heavy metals in soils of Mahad MIDC area

Sr.No.	Metal	Cd	Cr	Cu	Ni	Pb	Zn
1	Cd	1					
2	Cr	0.234	1				
3	Cu	0.312	0.289	1			
4	Ni	0.198	0.634**	0.245	1		
5	Pb	0.521*	0.178	0.234	0.156	1	
6	Zn	0.345	0.267	0.712**	0.289	0.312	1

Note: * $p < 0.01$, ** $p < 0.001$

3.6 Cluster Analysis

Hierarchical cluster analysis using Ward's method with Euclidean distance grouped the 15 sampling stations into three distinct clusters based on heavy metal concentrations (Figure 1).

Figure 1. Dendrogram Showing Hierarchical Clustering of 15 Sampling Stations
Based on Heavy Metal Concentrations (Cd, Cr, Cu, Ni, Pb, Zn) in Soils of the Mahad MIDC Area

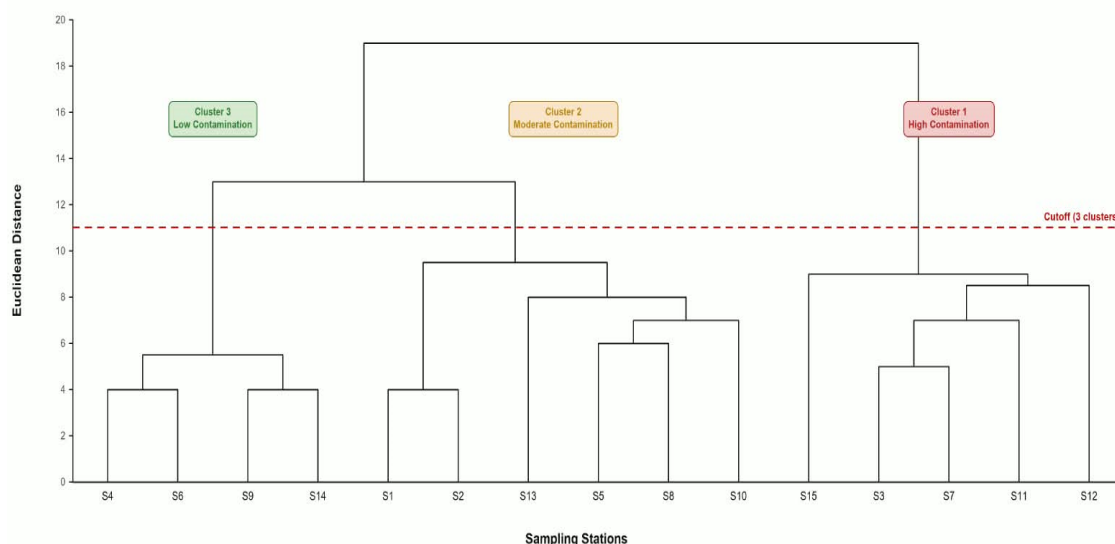


Figure 4. Dendrogram showing hierarchical clustering of 15 sampling stations based on heavy metal concentrations (Cd, Cr, Cu, Ni, Pb, Zn) in soils of the Mahad MIDC area. Ward's method with Euclidean distance was used. Three distinct clusters are highlighted: Cluster 1 (high contamination), Cluster 2 (moderate contamination), and Cluster 3 (low contamination).

Cluster 1 comprised five stations (S3, S7, S11, S12, and S15) with the highest heavy metal concentrations. These stations were located in close proximity to industrial effluent discharge channels, particularly from chemical, pharmaceutical, and dye industries. Cluster 2 comprised

six stations (S1, S2, S5, S8, S10, and S13) with moderate heavy metal concentrations, located at intermediate distances from industrial sources. Cluster 3 comprised four stations (S4, S6, S9, and S14) with the lowest heavy metal concentrations, located in relatively uncontaminated areas away from industrial activities.

The cluster analysis results are consistent with the spatial distribution patterns and contamination indices, confirming that proximity to industrial sources is a key determinant of heavy metal accumulation in soils. Similar clustering of sampling stations based on heavy metal concentrations has been reported by Srikantaswamy and Kumar (2012) in Mysore city and by Shivakumar and Srikantaswamy (2012) in industrial areas of Karnataka.

3.7 Source Identification

The correlation and cluster analysis results, combined with the spatial distribution patterns, suggest that heavy metals in soils of the Mahad MIDC area are derived from both anthropogenic and geogenic sources. Cadmium, Zn, Cu, and Pb appear to be primarily derived from anthropogenic sources, particularly industrial effluents from chemical, pharmaceutical, dye, and petrochemical industries. Chromium and Ni may have mixed sources, with contributions from both industrial activities (electroplating, alloy manufacturing) and natural weathering of parent rocks.

The moderate contamination of Cd and Zn at certain stations indicates that industrial activities are contributing to heavy metal accumulation, although the overall contamination levels remain within permissible limits. This is consistent with the findings of Chavan and Jawale (2013), who reported heavy metal accumulation in fish samples from the Savitri River near Mahad-MIDC, suggesting that industrial effluents are entering the aquatic ecosystem.

4. Conclusion

This study assessed heavy metal contamination in soils of the Mahad MIDC area, a coastal industrial cluster in the Konkan region of Maharashtra. It is observed that the mean concentrations of Cd, Cr, Cu, Ni, Pb, and Zn were below the permissible limits set by WHO/FAO, indicating that overall soil quality is not severely degraded. Significant seasonal variations were observed for Cd and Zn, with higher concentrations in post-monsoon season, likely due to monsoon-driven runoff and atmospheric deposition. Geo-accumulation index and contamination factor values indicated moderate contamination for Cd and Zn, while Cr, Ni, and Pb showed low contamination. Pollution load index values > 1 at three stations (S3, S7, and S11) indicate slight deterioration of soil quality near industrial effluent discharge channels. Spatial distribution maps revealed distinct hotspots of Cd and Zn contamination in the central and eastern parts of the study area, corresponding to industrial locations. Significant positive correlations between Cu–Zn, Cr–Ni, and Pb–Cd suggest common anthropogenic sources for these metal pairs. Cluster analysis grouped the 15 stations into three clusters based on heavy metal concentrations, with stations closest to industrial sources forming a separate cluster. Continuous monitoring and source-specific remediation are recommended to prevent long-term soil degradation and protect ecosystem health.

Future studies should include speciation analysis and bioavailability assessment to better understand the potential risks associated with heavy metal contamination in the Mahad MIDC area. Additionally, groundwater quality monitoring is recommended to assess the potential for heavy metal migration to water resources.

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