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The impact of industrial activities on the distribution and geochemical accumulation of heavy metals in soil in the wards of Tan Khanh, Tan Uyen, and Tan Hiep, Ho Chi Minh City, Vietnam

Thi Anh Thu Tran[1*], Le Tan Dat Nguyen[1], Pham Phuong Thanh Bui[1]

[1] Institute of Green and Sustainable Technology, Thu Dau Mot University, Ho Chi Minh City, Vietnam
* Corresponding author's e-mail: thutta@tdmu.edu.vn

ABSTRACT

North of Ho Chi Minh City, Vietnam, which has the country's highest concentration of industrial zones, there is a risk of heavy metals (HMs) contamination in soil from industrial emissions. Certain wards, including Tan Hiep, Tan Khanh, and Tan Uyen, have industrial zones and manufacturing companies intermingled with urban areas. Therefore, it is necessary to conduct research in this region to assess the accumulation levels, distribution, and sources of HMs emissions. This study involved calculating geochemical indices (EF, I_{geo}, and PLI), mapping HMs distributions, identifying sources using statistical methods, and finally assessing ecological risk. The results showed that lead (Pb), zinc (Zn), and cadmium (Cd) originate from industrial activities. Lead is distributed in clusters, Zn exhibits locally high contents at specific points, and Cd is dispersed and may also be linked to agricultural activities. However, average content results indicate that levels have not exceeded the Vietnamese national technical regulation on soil quality (QCVN 03:2023/BTNMT) or the upper continental crust (UCC) background. The results suggest that HMs are accumulating locally, with some areas exceeding the UCC (Zn = 207.24 mg/kg, Pb = 19.91 mg/kg, and Cd = 0.18 mg/kg), though no widespread contamination has been observed. The potential ecological risk is also low (PERI = 22.48). However, attention should be paid to the variability in Cd contents, as, although the average content is relatively low, Cd accounts for 80% of the total risk. These results help local authorities prioritize monitoring of Pb, Zn, and Cd at hotspots, preventing the spread of contamination.

Keywords: geochemical accumulation, heavy metals, ecological risk, industrial zones.

INTRODUCTION

Ho Chi Minh City is the nation's economic hub, experiencing remarkable industrial growth. The northern part of the city is considered the industrial heartland, boasting the highest concentration of industrial zones and clusters in the country. However, in some districts, such as Tan Hiep, Tan Khanh, and Tan Uyen, industrial zones and clusters are located adjacent to or within urban areas and agricultural land. Examples include Song Than 3, Nam Tan Uyen, Vietnam–Singapore 3, and Dat Cuoc. This proximity can lead to soil contamination from various emission sources in the area (Hu et al., 2018; Huang et al., 2018). Industrial activities such as electroplating, tanning, metal smelting, and fertilizer production can release heavy metals (HMs) into the soil. These HMs then accumulate in the soil and can affect crops and threaten public health via the food chain (Alloway, 2013; Kabata-Pendias, 2010). It is currently estimated that approximately 14–17% of agricultural land worldwide is contaminated with HMs (Hou et al., 2025). Therefore, research into the accumulation, distribution, and sources of HM contamination, as well as the associated ecological risks, is essential.

In Vietnam, studies on HMs in soil have primarily focused on areas where severe pollution caused by industry and artisanal workshops has been identified, such as the study conducted at

the Dong Mai lead recycling workshop, Hung Yen Province (Chu, 2011). In addition, studies on identifying the sources of HMs and assessing ecological risks remain quite limited. A survey of agricultural soil in Nam Dinh Province revealed that chromium (Cr) has a natural origin, cadmium (Cd) and arsenic (As) have an anthropogenic origin, and lead (Pb) and zinc (Zn) have both natural and anthropogenic origins (Nguyen et al., 2020c). Another study on atmospheric HMs deposition in Ho Chi Minh City showed that the composition and intensity of deposition are influenced by the Northeast Monsoon and the Southwest Monsoon (Nguyen et al., 2026). In the same study, the results showed that Pb had a lower concentration than Zn but posed a higher potential ecological risk, accounting for 60% of the total risk index.

However, the above studies lack an integrated approach to pollution assessment that combines indices such as HMs content, geochemical analysis, and potential risk. Spatial analysis that combines geographic information systems (GIS) with meteorological data is also important for explaining the distribution of HMs when there is no correlation between decreasing HMs content and increasing distance. While Nguyen et al. (2026) have investigated the effect of wind direction on the deposition and distribution of HMs, their study did not consider its impact on adjacent agricultural land (Nguyen et al., 2026). This study, therefore, combines geochemical indices (EF, Ig,eo, and PLI) to evaluate accumulation levels; determine pollution sources through statistical methods such as correlation and principal component analysis; clarify transmission mechanisms; and finally evaluate potential ecological risk. This study, therefore, aims to achieve three specific objectives: (1) determining the content and extent of HMs contamination in the soil, (2) identifying the sources, pathways, and distribution patterns of HMs in the soil, and (3) assessing the potential ecological risk.

MATERIALS AND METHODS

Study area

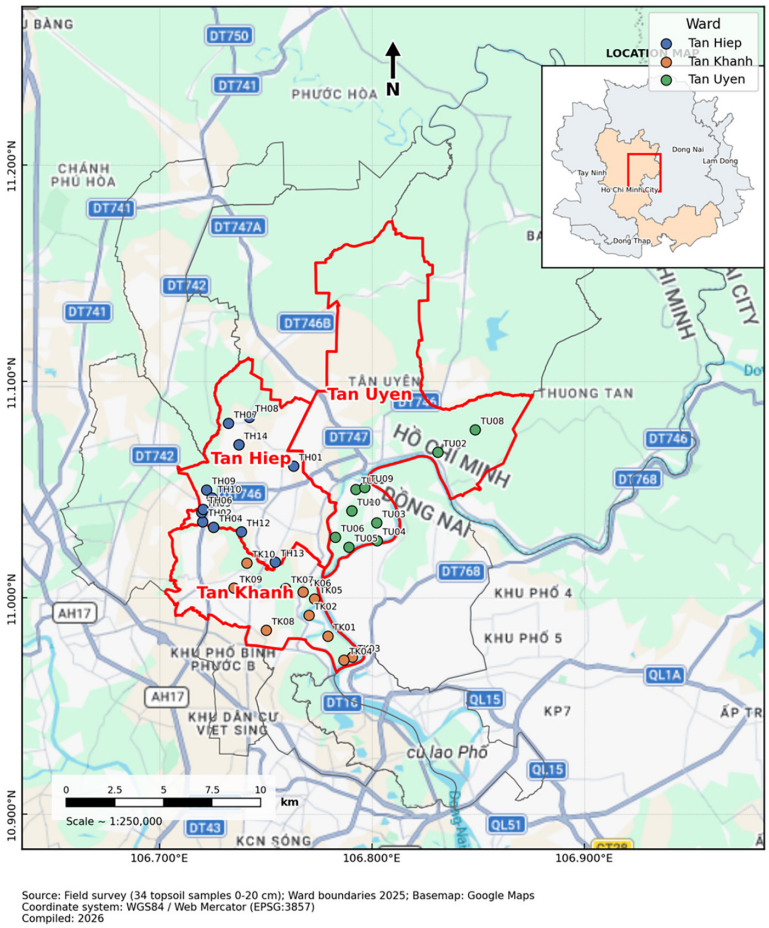
The study was conducted in the northeastern part of Ho Chi Minh City, Vietnam. This area consists of three wards: Tan Khanh, Tan Uyen, and Tan Hiep. The climate here is a hot and humid tropical monsoon climate, with an average temperature of 26.5–27 °C and annual rainfall of 1.800–2.000 mm; there are two rainy seasons and one dry season. The soil types include gray soil on ancient alluvial deposits, yellow-brown soil on ancient alluvial deposits, and glay alluvial soil. The region primarily cultivates specialty fruits such as pomelo; it also grows various vegetables, other fruit trees, and rice. Within these three districts are industrial zones such as Song Than 3, Nam Tan Uyen, Vietnam–Singapore 3, and Dat Cuoc, as well as smaller industrial clusters. The industries in these industrial zones primarily include wood processing, paint manufacturing, electronics, engineering plastics, components, and fertilizers. However, agricultural and urban areas are currently intermingled with, or located near, these industrial zones, which can easily lead to soil contamination by heavy metals such as As, Cd, Pb, Cu, Zn, and Cr.

Sampling and sample analysis

The study collected 34 soil samples from the three wards of Tan Hiep, Tan Khanh, and Tan Uyen (Figure 1). The samples were collected during the dry season (January 2026). The coordinates of the sampling points were determined using GPS. Samples were collected across three zones based on distance from the industrial park: the near zone (1.31–3.63 km) yielded 11 samples; the transitional zone (3.63–4.65 km) yielded 12 samples; and the far zone (4.65–9.44 km) yielded 11 samples. Soil samples were collected at a depth of 0–20 cm. Sampling was conducted as follows: five points were selected within a 100 m² area and combined to form a single sample. Samples were placed in sealed plastic bags and stored on ice. Subsequently, the soil samples were air-dried at room temperature and sieved through a 2-mm sieve for analysis of As, Cd, Cr, Cu, Pb, Zn, Fe, and Mn.

Place 0.5 g of each sample into a 100-mL glass tube. Then, add 10 mL of a 3:1 (v/v) HNO_3–H_2O_2 mixture to the tube and let it stand overnight at room temperature. Next, heat the sample at 180 °C until the solution becomes clear. After decomposition, the sample solutions were cooled and diluted with deionized water. The contents of the HMs As, Cd, Cr, Cu, Pb, Zn, Fe, and Mn were determined using an atomic absorption spectrometer (AAS AA-7000, Shimadzu Corporation, Kyoto, Japan).

Quality Control and Quality Assurance (QA/QC): Metal recovery rates ranged from 90% to 110%. The relative standard deviation (RSD) for duplicate samples was less than 8%. All values below the limit of detection (LOD) were recorded



Source: Field survey (34 topsoil samples 0-20 cm); Ward boundaries 2025; Basemap: Google Maps
Coordinate system: WGS84 / Web Mercator (EPSG:3857)
Compiled: 2026

Figure 1. Study area and 34 soil samples

as not detected (ND) and treated as ½ LOD in statistical calculations.

Calculation of geochemical indices

Enrichment factor (EF):

$$EF = \frac{(C_M/C_{Ref})_{sample}}{(C_M/C_{Ref})_{background}} \quad (1)$$

where: C_M is the content of As, Cd, Cu, Pb, Zn, and Cr; C_{Ref} is the content of Fe (Fe is used as the reference element); *sample* values are analytical values, and *background* values are the average composition of the upper continental crust (UCC) (Taylor and McLennan, 1985).

EF values are classified as follows: $EF < 1.5$: naturally occurring HMs; $1.5 \leq EF < 5$: moderate levels of anthropogenic HMs contamination; $5 \leq EF < 20$: significant levels of anthropogenic HMs contamination; $EF \geq 20$: very high levels of anthropogenic HMs contamination.

Geological accumulation index (Igeo) (Muller, G., 1969):

$$I_{geo} = log_2\left(\frac{C_n}{1.5 \times B_n}\right) \quad (2)$$

where: C_n is the content of HM n; B_n is the geochemical background value of HM n.

I_{geo} values are classified as follows: $I_{geo} < 0$: no contamination; $0 < I_{geo} \leq 1$: no contamination – moderate contamination; $1 < I_{geo} \leq 2$: moderate to severe contamination; $2 < I_{geo} \leq 3$: severe contamination; $3 < I_{geo} \leq 4$: severe to extremely severe contamination; $4 < I_{geo} \leq 5$: extremely severe contamination; $I_{geo} > 5$: very extremely severe contamination.

Pollution load index (PLI):

$$PLI = (CF_1 \times CF_2 \times \cdots \times CF_n)^{1/n} \quad (3)$$

where: $CF_i = C_n/B_n$ is the pollution coefficient for each HM, and n is the number of HMs. $PLI > 1$ indicates an overall level of pollution.

Construction of spatial distribution maps

Studying plotting and processing sample points, industrial zone locations, and infrastructure data on maps using the Python programming language. The spatial distribution of HMs and the ecological risk index were determined using the IDW interpolation method. Transportation infrastructure data (railways, gas stations, traffic lights, roads, major thoroughfares, and road density within a 500-meter radius) was sourced from OpenStreetMap.

Ecological risk assessment

The potential ecological risk index (PERI) is used to assess the extent of the impact of HMs or HM toxins on ecosystems and the environment (Hakanson, 1980; Liang et al., 2023).

The pollution factor (C_f^i) for HM i:

$$C_f^i = \frac{C^i}{C_n^i} \quad (4)$$

where: C^i is the content of HM i, and C_n^i is the soil background value for HM i.

The ecological risk of each HM (E_r^i):

$$E_r^i = T_r^i \times C_f^i \quad (5)$$

where: T_r^i is the biological toxicity response factor for HM i (As = 10, Cd = 30, Cr = 2, Cu = 5, Hg = 40, Ni = 3, Pb = 5, Zn = 1).

The potential ecological risk index (PERI) is calculated as the sum of the risks for all HMs:

$$PERI = \sum E_r^i \quad (6)$$

Classification criteria: PERI < 150: low risk; 150 ≤ PERI < 300: moderate risk; 300 ≤ PERI < 600: significant risk; 600 ≤ PERI < 1200: high risk; PERI ≥ 1200: very high risk.

RESULTS

Heavy metal content in soil

The results of the HMs' content analysis are presented in Figure 2. The study area has not been widely contaminated; however, localized accumulation was observed, particularly near emission sources. The average contents of the HMs ranged from the highest, Zn (20.56 mg/kg), to the lowest, Cd (0.05 mg/kg); all were below the UCC background values and did not exceed the Vietnamese national technical regulation on soil quality (QCVN 03:2023/BTNMT) thresholds. Some localized accumulation sites had maximum HM contents exceeding the UCC background values by 17% to 200%, including Zn (207.24 mg/kg), Pb (19.91 mg/kg), Cd (0.18 mg/kg), and As (7.93 mg/kg). Fe and Mn have very high average contents of 12,170.86 mg/kg and 78.94 mg/kg, respectively, which may be attributable to the soil's natural geochemistry.

The maximum Zn content was 3 times the UCC background value (207.24 mg/kg) at sampling point TH03. In addition, several other sampling points showed values close to the UCC background value, such as TH05, TH06, TK07, TU02, TU05, and TU10, with values of 54.43 mg/kg, 45.01 mg/kg, 44.02 mg/kg, 41.52 mg/kg,

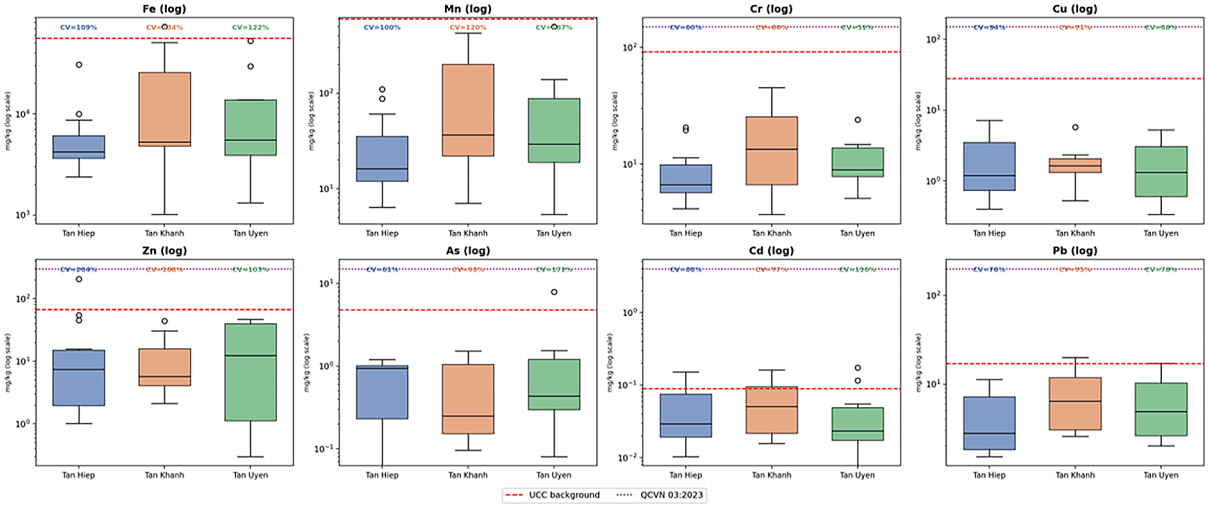


Figure 2. Content of heavy metals in soil by ward

46.96 mg/kg, and 41.08 mg/kg, respectively. Of these, the three points TH03, TH05, and TH06 are located approximately 3 km from the Song Than 3 industrial park. These results indicate a correlation between localized accumulation and industrial production activities. The highest average Zn content was observed in Tan Hiep ward (26.69 mg/kg) (Figure 2). The maximum Cr content was approximately equal to the UCC background value (45.33 mg/kg) at sampling point TK05. In addition, several other points showed significantly higher contents than the remaining points, including TK01, TK04, TU09, and TH08, with contents of 31.04 mg/kg, 28.93 mg/kg, 24.10 mg/kg, and 20.57 mg/kg, respectively. These results indicate that Cr accumulation remains at an average level. Site TK05 is located approximately 6 km from the Nam Tan Uyen industrial park; however, sites TK01 and TK04 are 8 and 9.4 km away, respectively. Therefore, determining the source of Cr emissions from industrial activities requires a more careful assessment. The highest average Cr content was observed in Tan Khanh ward (17.14 mg/kg) (Figure 2). The maximum Cd content exceeded the UCC background value by more than double (0.18 mg/kg) at sampling point TU09. Additionally, several other points showed contents far exceeding the UCC background value, including TH05 and TK04, at 0.15 mg/kg and 0.16 mg/kg, respectively. Point TU09 is located approximately 4.3 km from the Nam Tan Uyen industrial park. The highest average Cd content was observed in Tan Khanh ward (0.06 mg/kg) (Figure 2). The maximum Pb content exceeded the UCC background value (19.91 mg/kg) at site TK05. In addition, several other points also showed significantly higher content than the remaining sites, such as TU02, TK04, TK01, TU09, and TU05, with values of 17.20 mg/kg, 15.21 mg/kg, 13.16 mg/kg, 12.29 mg/kg, and 11.75 mg/kg, respectively. The TK05 point is located approximately 6 km from the Nam Tan Uyen industrial park. The highest average Pb content was observed in Tan Khanh ward (8.1 mg/kg).

The coefficient of variation (CV) analysis results indicate that the area does not exhibit widespread HM contamination; rather, contamination is primarily localized due to uneven spatial distribution (Figure 2). Zn, As, Mn, and Fe show localized contamination with high CVs. The CV for Zn reached 204.3% in Tan Hiep Ward, the CV for As reached 172.5% in Tan Uyen Ward, and the CV for Fe reached 133.9% in Tan Khanh ward (Figure 2). Meanwhile, Cr, Cu, and Pb are relatively more stable due to moderate variations in content levels across the area. The CVs for Cr, Cu, and Pb ranged from 50.8% to 80.0%, 71% to 93.6%, and 71% to 93.6%, respectively.

Assessment of heavy metal pollution levels

The results of the calculations for geochemical indices EF, I_{geo}, and PLI are presented in Figure 3. The average PLI value for the entire study area was only 0.16 ± 0.10; the average EF values for most HMs were < 2; and the average I_{geo} values were < 0, indicating that the study area is not contaminated by HMs. However, the EF values for Cd, Zn, and Pb show some points with values > 20, indicating a very high level of contamination, such as TK02, TH06, and TH12; some points with values ranging from 5 to 20 indicate a significant level of contamination, such as TH05, TH03, TK03, TK10, TU10, and TU01. These points are mostly concentrated near the Song Than 3, Nam Tan Uyen, and Dat Cuoc industrial zones, as well as the road No. 5 industrial cluster, indicating localized enrichment from industrial activities. For Cr, Cu, and As, the EF values are all below 1.5, indicating that they are of natural origin.

In Tan Hiep ward, sampling points TH12 and TH06 had Cd EF values of 28.28 and 24.95,

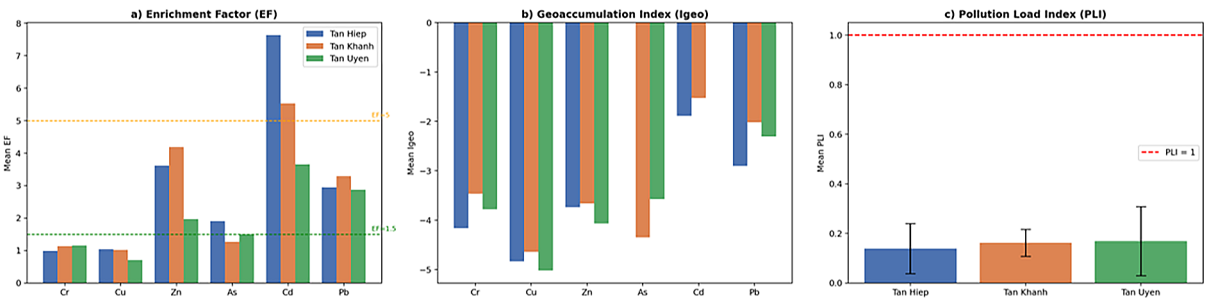


Figure 3. Geochemical indices by ward

respectively, indicating very high pollution; sampling point TH05 had a Cd EF value of 17.63, indicating significant pollution. For Zn, points TH03 and TH06 have EF values of 17.36 and 12.78, respectively, indicating significant contamination. These points are located approximately 3 km from the Song Than 3 industrial park, suggesting that the accumulation of Cd and Zn may be due to industrial activities. The I_{geo} value for Zn at sampling point TH03 is 1.04, indicating moderate contamination; the I_{geo} value for Cd at sampling point TH05 is also greater than 0 (0.17). The PLI index for sampling point TH03 is also the highest in the ward (0.37). In Tan Khanh ward, site TK02 has a Zn EF of 25.58, indicating very high contamination. For Cd, sites TK02, TK03, and TK10 have EF values of 17.65, 10.32, and 10.66, respectively, indicating significant contamination. For Pb, sampling points TK02 and TK10 have EF values of 8.45 and 6.67, respectively, indicating significant contamination. The I_{geo} value for Cd at sampling point TK04 is 0.25, indicating a mild level of contamination. The PLI indices for sampling points TK05 and TK04 are 0.29 and 0.20, respectively, the highest in the ward. In Tan Uyen ward, the TU10 point has EF values of 16.86 and 8.03 for Cd and Zn, respectively, indicating significant pollution. For Pb, the TU01 point has an EF of 7.94, indicating significant pollution. The I_{geo} value for Cd at monitoring point TU09 is 0.38, indicating a moderate level of pollution. The PLI index for monitoring point TU02 is also the highest among all 34 samples (0.44).

Spatial distribution and transport mechanisms

The spatial distribution of HMs in the soil is shown in Figure 4 and Figure 5. The Zn distribution map reveals a cluster of three points at Tan Hiep and an anomalous point at TK02. The cluster of three points comprises TH03 (207.24 mg/kg), TH05 (54.43 mg/kg), and TH06 (45.01 mg/kg); notably, point TH03 has a Zn content that is three times the UCC background value. This cluster is located approximately 3 km from the Song Than 3 industrial park. The anomalous point TK02 (EF = 25.58) is isolated from the above cluster, possibly due to an independent source of contamination. Correlation analysis shows no correlation between Zn contents and distance to the industrial zone ($p > 0.05$). These results indicate that Zn is not uniformly distributed with distance but is concentrated in certain areas. The Pb distribution map shows two distinct clusters emerging in the southern part of Tan Khanh ward and the eastern part of Tan Uyen ward. The Tan Khanh cluster includes four points: TK05, TK02, TK04, and TK01; among these, point TK05 has the highest concentration in the area (19.91 mg/kg). The Tan Uyen cluster at point TU02 has a content of 17.20 mg/kg. Correlation analysis reveals a positive correlation between Pb content and distance to the industrial zone ($p = 0.028$). These results indicate that Pb distribution deviates from the expected pattern: contents do not increase with proximity to the industrial zone.

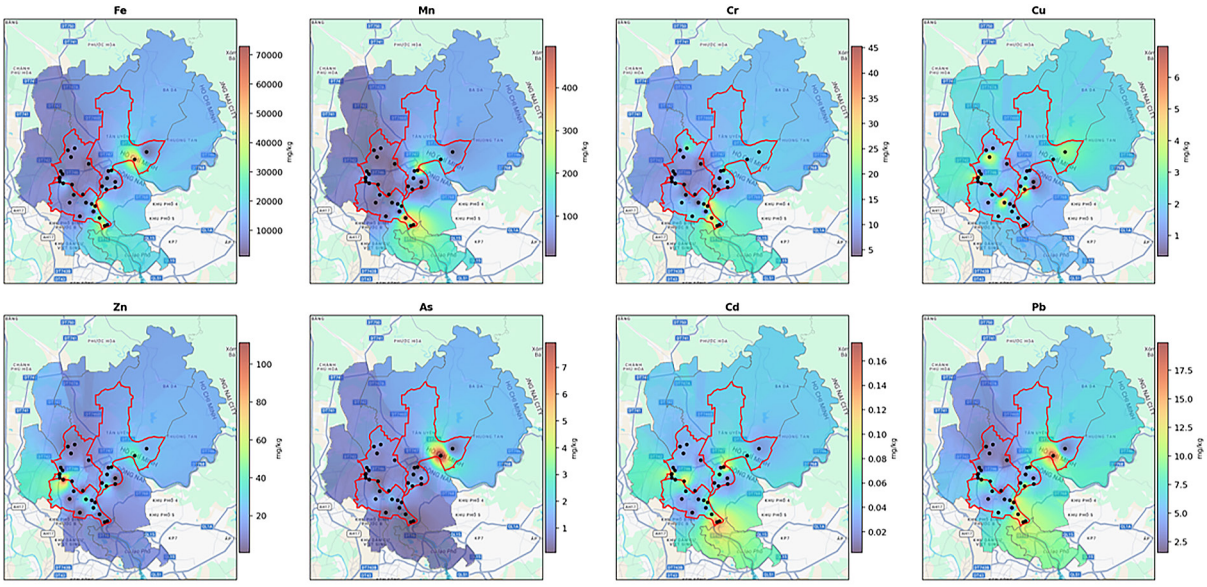


Figure 4. The spatial distribution of heavy metals in the soil

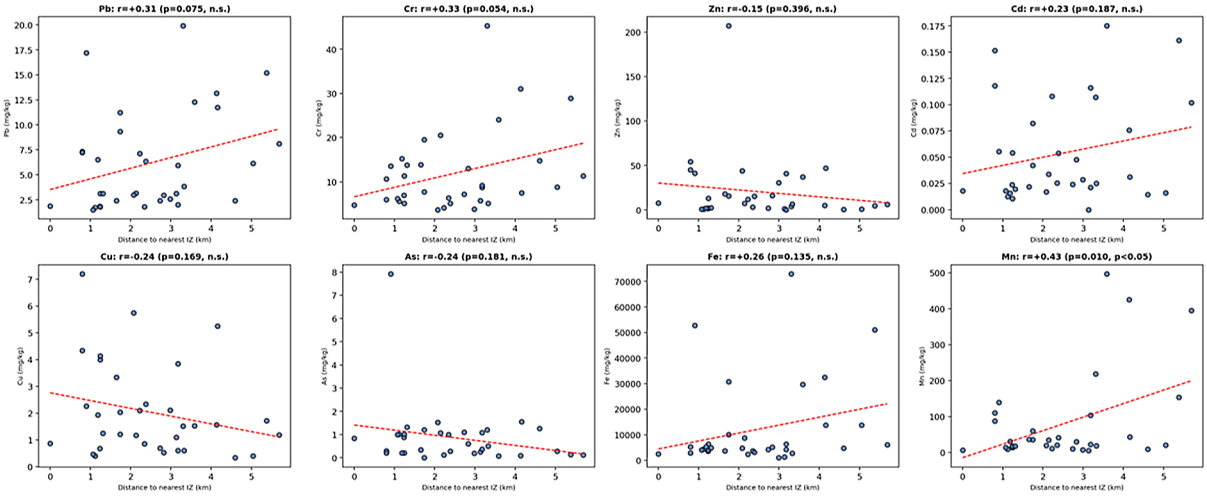


Figure 5. Correlation between distance to the industrial zone and heavy metal content in soil

Additionally, the correlation analysis revealed a positive correlation between Pb and Fe (r = 0.89), suggesting that Pb may be associated with Fe-rich soil. The Cd distribution map shows a scattered pattern; points with high contents, such as TH12 and TH06, fall into the very high contamination category, while TH05, TK02, TK03, TK10, and TU10 fall into the significant contamination category. These results suggest that there may be multiple independent local sources emitting Cd. Furthermore, the possibility of Cd contamination resulting from the application of phosphate fertilizers cannot be ruled out. Additionally, correlation analysis shows no significant correlation between Cd content and distance to the industrial zone ($p > 0.05$) and a weak correlation with Fe.

Chromium contents were positively correlated with distance to the industrial zone ($p < 0.01$) and varied linearly with Fe contents ($r = 0.83$) (Figure 5). However, the average EF value for Cr was quite low, at only 1.0–1.1. In addition, Fe contents also showed a positive correlation with distance to the industrial zone ($p < 0.05$). These results suggest that the positive correlation between Cr and distance to the industrial zone may be due to the influence of Fe. Therefore, the correlation between HM contents and spatial distance alone cannot conclusively indicate an anthropogenic source; the EF index must be considered to identify the actual source of pollution.

In addition, an analysis of NASA's POWER satellite data (MERRA-2) at the central coordinates of 11.02°N, 106.77°E examined wind direction at an altitude of 10 m. The results for wind direction during the dry season from 2018 to 2025 show that the proportion of the north-northeast-east wind direction group increased from 17.5% in 2018 to 56.4% in 2025. However, when considering only the 2023–2025 period, the results show that the proportions of these wind directions are balanced, at 48.3% and 46.9%, respectively. These results indicate that there is no consistent wind direction during the dry season across the years. The potential for wind-driven deposition of HM ions may be merely a contributing meteorological factor rather than compelling evidence in this study.

Origin of heavy metals in soil

The results of the correlation analysis indicate that Pb, Cr, and Cd are strongly positively correlated with one another (Figure 6). Specifically, Pb is positively correlated with Cr ($r = 0.71$; $p < 0.001$), Pb is positively correlated with Cd ($r = 0.63$; $p < 0.001$), and Cd is positively correlated with Cr ($r = 0.44$; $p < 0.01$). At the same time, all three HMs, Pb, Cr, and Cd, exhibit strong positive correlations with Fe and Mn. Specifically, Pb is positively correlated with Fe ($r = 0.89$; $p < 0.01$), Cr is positively correlated with Fe ($r = 0.83$; $p < 0.01$), Cd is positively correlated with Mn ($r = 0.66$; $p < 0.01$), and Cd is positively correlated with Fe ($r = 0.44$; $p < 0.01$). These results once again confirm that the distribution of these three HMs is closely related to the natural Fe-Mn-rich substrate; Pb is more concentrated and thus may have a stronger association, while Cd is more dispersed and thus has a weaker association. The Cu content showed no correlation with Fe-Mn; moreover, it was relatively low and evenly distributed (EF ≈ 0.7–1.0),

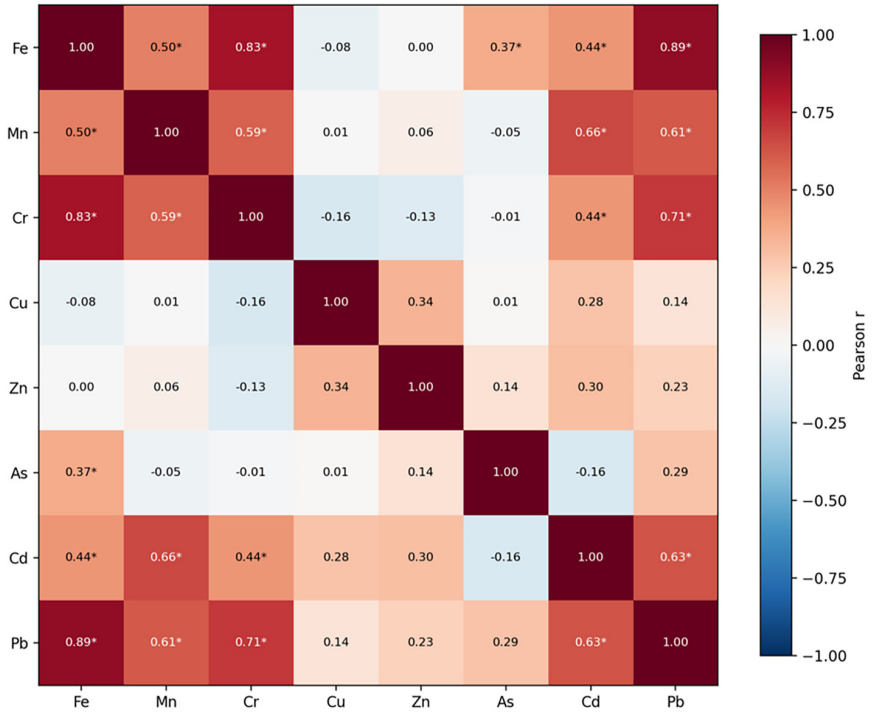


Figure 6. Correlation matrix between heavy metal content in soil (n = 34, *p < 0.05)

but Cu showed a slight correlation with Zn (r = 0.34; p = 0.052), suggesting that Cu may originate from the regional geological background. The As content showed no correlation with any other element, suggesting that As may come from a separate source. The Zn content also showed no correlation with Fe-Mn; however, a few locations had elevated Zn content, including TH03 and TK02 (EF values of 17.4 and 25.6, respectively), suggesting potential anthropogenic influence.

Principal component analysis showed that Cr, Pb, and Cd lie on the PC1 axis, while Cu and Zn lie on the PC2 axis; As, however, has low loading values on both axes (0.15 and 0.13) (Figure 7). Specifically, PC1 accounts for 38.2%, and PC2 accounts for 24.5%. The loading factors for

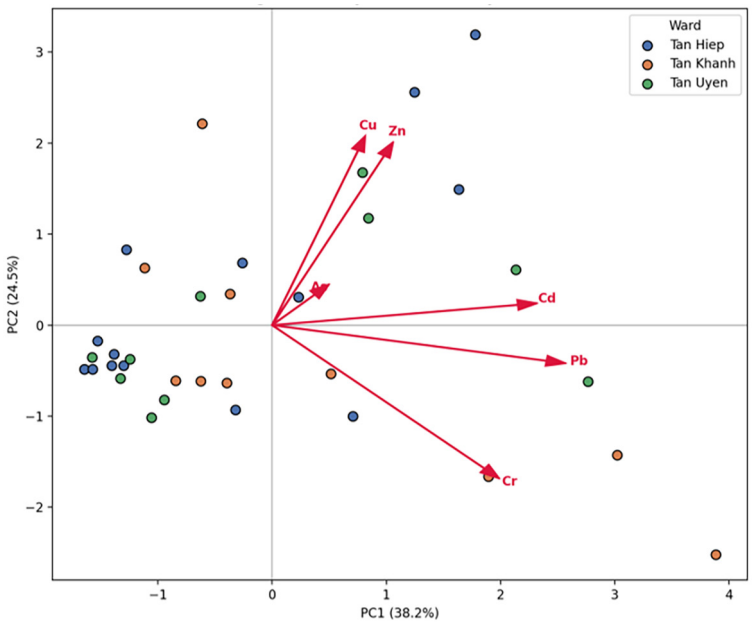


Figure 7. Principal component analysis of heavy metals

Cr, Pb, and Cd are 0.73, 0.94, and 0.84, respectively; those for Cu and Zn are 0.75 and 0.73, respectively. These results can be explained by the fact that the three HMs, Cr, Pb, and Cd, exhibit a strong positive correlation, thereby confirming that this group originates from industrial activities. Among them, points TK05 and TK04 have the highest PC1 scores, at 3.94 and 3.07, respectively, which can be explained by the cluster of Pb hotspots distributed in the southern part of Tan Khanh ward. Points TH03 and TH06 have the highest PC2 scores, at 3.24 and 2.60, respectively, which can be explained by the cluster of three Zn hotspots located in Tan Hiep ward. Additionally, Cr has a value of –0.61 on the PC2 axis, likely due to its negative correlation with Cu and Zn.

According to the results in the previous section, Pb and Cr are correlated with the distance to the industrial park. However, when the study conducted a one-way analysis of variance, the results for Pb and Cr still followed the same trend as above, increasing or decreasing with distance, but Pb and Cr did not reach statistical significance, with F values of 1.05 and 3.17, respectively ($p > 0.05$). This result may be due to the conversion of continuous variables into discrete ones; therefore, the results from the correlation analysis cannot be dismissed.

The study also analyzed the correlation between HMs content and distance to infrastructure (railways, gas stations, traffic lights, roads, major thoroughfares, and road density within a 500-meter radius) to further assess potential sources of impact (Figure 8). The results showed that Pb, Cr, and Mn had statistically significant inverse correlations with distance to railroads, with correlation coefficients of $r = –0.41$, $r = –0.36$, and $r = –0.42$, respectively ($p < 0.05$). However, all sampling points were located quite far from the railroad, ranging from 4.5 to 17.5, so this may not be the cause. One hypothesis for this issue could be the north–south distribution of soil. The contents of Pb, Cr, and Cd were not correlated with the distance to traffic lights, roads, major thoroughfares, or road density within a 500-meter radius. These results support the conclusion that Pb, Cr, and Cd originate from industrial activities in the aforementioned areas. Cadmium content is inversely correlated with distance to gas stations ($r = –0.36$; $p < 0.05$); however, this result requires further evaluation.

Ecological risk assessment

The results of the potential ecological risk index calculations show that all values are below 150, falling within the low-risk threshold. Among these, Cd accounts for 80% of the total PERI (Figure 9). The average Er value for Cd is tens of times higher than that of the other HMs, reaching 17.88. Tan Khanh had the highest PERI value in the region, at 25.4, with high Er values for Cd and Pb, at 20.91 and 2.38, respectively. Tan Uyen ranked second with a PERI of 21.6, and Tan Hiep

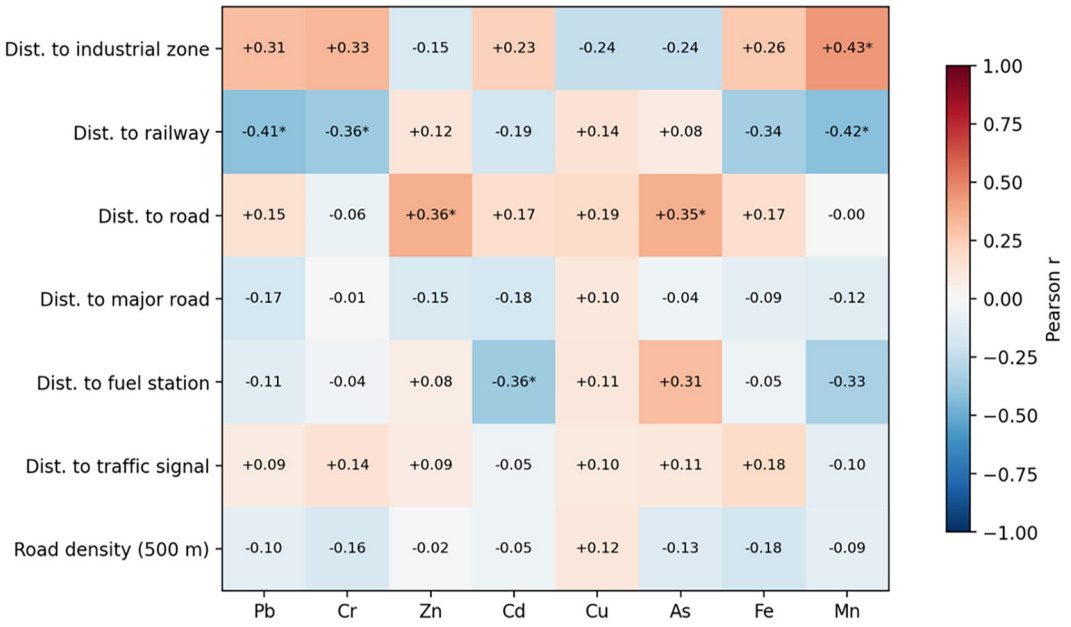


Figure 8. The correlation between heavy metal contents and distance to infrastructure (*$p < 0.05$)

came in last with a PERI of 20.9. The highest Er value for As was recorded in Tan Uyen at 2.85; the highest Er values for Zn and Cu were recorded in Tan Hiep at 0.40 and 0.39, respectively. The highest PERI value was recorded at the local hotspot TU09 in Tan Uyen, at 63.5. Additionally, Tan Hiep also has a local hotspot, TH05, with a PERI value of 55.1. These results indicate that the two wards of Tan Uyen and Tan Hiep have hotspots with high localized PERI values, but their overall PERI values remain lower than those of Tan Khanh ward, possibly due to Cd.

Similarly, the PERI index interpolation map also reveals three distinct hotspots dependent on Cd content (Figure 9). The highest hotspot is located in the east at point TU09 with a value of 63.5; the second hotspot is located in the south at clusters TK04 and TK05, with values of 59.5 and 45.3, respectively; the third hotspot is located in the west at clusters TH05 and TH06, with values of 55.1 and 44.0, respectively. These results are consistent with the findings above, indicating that Cd originates from multiple independent sources, and these hotspots help identify spatial areas that should be prioritized for monitoring.

DISCUSSION

The HM contents at all sampling points in the study area did not exceed the thresholds set by QCVN 03:2023/BTNMT; furthermore, the average content remained below the UCC background levels. However, there are emerging signs of HM accumulation, with concentrations exceeding UCC background levels at certain hotspots, including Zn at TH03, Cd at TU09, and Pb at TK05. Furthermore, calculations of the EF and I_{geo} indices clearly indicate increased Zn, Cd, and Pb contents, likely attributable to industrial activities, with sites with EF > 20 classified as having a very high level of contamination. Indeed, the soil surrounding the industrial zone may not be widely contaminated with HMs but may instead be

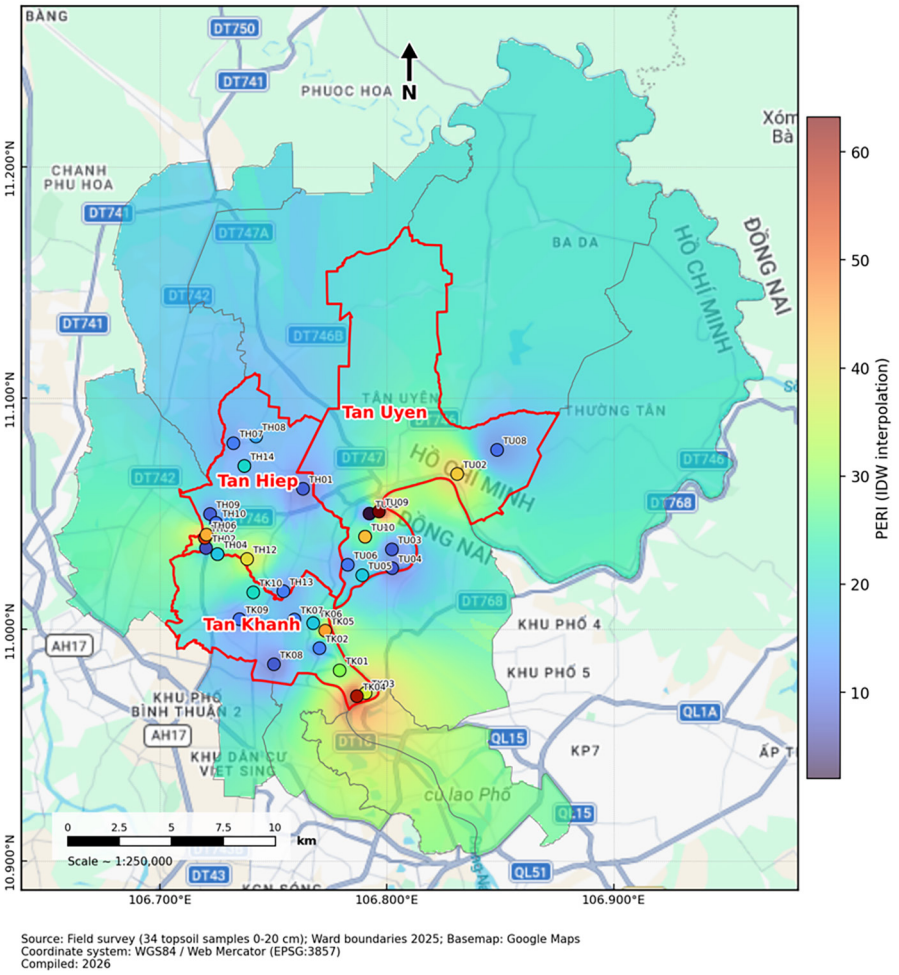


Figure 9. The spatial distribution of the potential ecological risk index

locally contaminated by anthropogenic sources; therefore, in addition to comparing contents with regulatory standards, it is necessary to calculate geochemical indices. The results of this study are fully consistent with a study on agricultural soil surrounding an industrial zone in Shanxi province, China, which also showed that the contents of Pb, Cd, As, Cr, Zn, and Cu, while not yet exceeding the national regulatory limits for HM contents in agricultural soil, had already surpassed local background values; and when the I_{geo} index was calculated, Cd fell into the mild contamination category (Zhao et al., 2025). Similarly, another study in Shanghai, China, involving more than 4,000 agricultural soil samples, also showed that although HM contents were unevenly distributed and fluctuated over time, their levels did not exceed the national limit for HMs in agricultural soil (Li et al., 2023). Furthermore, the study also showed that Cd, Hg, and Cr levels were elevated due to industrial activities, with the highest contents found in industrial production areas (Li et al., 2023). In Vietnam, most studies have focused on areas severely and directly affected by industrial activities, such as metal mines. A study at a polymetallic mine in Thai Nguyen province, Vietnam, showed that Cd concentrations in rice paddy soil were 23 times higher than the national limit for HM contents in agricultural soil (Nguyen et al., 2020b). Similarly, a study in a lead-recycling village in Thai Nguyen province, Vietnam, revealed severe Cd and Pb contamination (Chu, 2011). A global study synthesizing over 1,400 research papers also indicates that approximately 14–17% of agricultural land is contaminated with HMs (Hou et al., 2025). Therefore, it is necessary to investigate the extent of HM accumulation in agricultural soils in industrial areas to enable early warning.

The results of the statistical analysis show that the three HMs, Pb, Cr, and Cd, exhibit a strong correlation with one another and with Fe/Mn; furthermore, they all lie on the PC1 axis (38.2% of the variance). Similarly, a study of agricultural soil around an industrial zone in Shanxi province, China, also showed that As, Cr, and Ni lie on the PC1 axis (27.75% of the variance), originating from both industrial activities and natural sources (Zhao et al., 2025). Regarding Cr, although it lies on the same axis with high loading coefficients as Pb and Cd and shows a strong positive correlation with Fe ($r = 0.83$) and a positive correlation with distance to the industrial zone ($r = 0.45$), its low EF index indicates that it primarily originates from the geochemical background, indirectly via Fe, rather than may be from industrial activities like Pb and Cd. This explains the limitations of methods such as statistical analysis: even when results show high correlation with one another or lie on the same high-load axis, this is not sufficient evidence to conclusively establish a common source; therefore, the EF index should be considered as well, but the selection of the reference element and background values for EF calculations must be approached with caution. Indeed, if the selected reference element is influenced by soil formation processes, the EF index may not accurately reflect the impact of human activities (Reimann and Caritat, 2000). In addition, the contents of Pb, Cr, and Cd showed no correlation with the distance to infrastructure (traffic lights, roads, major thoroughfares, and road density within a 500-meter radius). However, several other studies in Vietnam have shown that traffic-related activities are a source of HM emissions. Specifically, a study of eight HMs in road dust samples in Ho Chi Minh City found that transportation activities accounted for the highest proportion, at 32.38% (Nguyen et al., 2021). Similarly, in China, a study on Pb emissions in industrial zones in Beijing also found that transportation accounted for 69.75% (Jia et al., 2023); a study on Pb and Hg emissions in an industrial zone in Shanxi province also showed that they fell along the PC3 axis, with 19.89% attributable to transportation sources (Zhao et al., 2025). This contrast can be explained by the low traffic density in the study area, making industrial activities the primary cause. Regarding sources, another study in Nam Dinh province, Vietnam, also found that Cr is of natural origin, while Cd originates from human activities (Nguyen et al., 2020a).

The correlation results between HM contents show that Pb and Cr are strongly correlated with Fe, with r values of 0.89 and 0.83, respectively. Fe–Mn oxides/hydroxides in soil have a large specific surface area, facilitating electrostatic adsorption, chemical precipitation, or complex formation with other HMs, thereby helping to immobilize them (Gadde and Laitinen, 1974; Komárek et al., 2018). Indeed, the average Fe content in Tan Khanh ward was the highest among the three wards, at 18,695.61 mg/kg, which caused the average contents of most other HMs to increase due to adsorption affinity or their ability to be immobilized. However, this capacity also varies with the HM, depending on ionic radius and electronegativity

(Komárek et al., 2018). Cadmium has the highest EF index but shows a weak correlation with Fe (r = 0.44); therefore, Cd is distributed more widely, whereas Pb binds to the Fe matrix. Both Pb and Cr show a strong correlation with Fe, but Cr has an EF index of approximately 1.0–1.1, whereas Pb has an EF index exceeding the background level by approximately 3.0. These results indicate that both Pb and Cr are strongly bound to the Fe matrix, but Cr originates primarily from soil-forming processes rather than anthropogenic sources, whereas Pb appears to stem from human activities. Therefore, further comparison with the EF index is necessary to accurately determine the source. Furthermore, the study showed that wind-driven HM deposition is only a contributing factor; it is not the primary mechanism of accumulation. Wind data for the 2018–2025 period indicate that no single wind direction predominates during the dry season (NASA POWER, MERRA-2). This result is in stark contrast to some previous similar studies. Specifically, a 79-month multi-site observational study on the atmospheric deposition of Cu and Cd and their accumulation in the soil-crop system showed that wind frequency and distance to emission sources govern the distribution of HMs (Zhou et al., 2024). This discrepancy may be due to multiple emission sources from industrial zones in the study area, which mask signals from different wind directions. Additionally, the relatively small size of the study area means it falls within only one or a few grid cells of the satellite data (MERRA-2), so wind direction variations within the study area are not clearly captured. Therefore, future studies of the region should analyze higher-resolution satellite data or incorporate quantitative atmospheric dispersion models to yield more detailed results (Nguyen et al., 2026).

Regarding Zn, the study identified hotspot TH03, with a content up to 207.24 mg/kg, three times the UCC background value. This hotspot is located approximately 3 km from the Song Than 3 industrial park. Some previous studies have also shown that Zn typically originates from localized sources rather than being widely distributed. A study on Zn pollution at a Zn-plating plant in Poland also reported elevated Zn content s relative to background levels, attributable to leaks during the production process (Świercz et al., 2023). Similarly, a study of 10 electroplating facilities in China also found that soil is severely contaminated with Zn due to production activities (Wei et al., 2023). The current study does not precisely identify which industrial emission sources are immediately adjacent to sampling point TH03; however, the Song Than 3 industrial park houses numerous mechanical and metallurgical companies, suggesting that attributing the increase in Zn levels to industrial activities is entirely reasonable. Regarding Cd, the study hypothesizes that it originates from various local emission sources; in addition to industrial production, it suggests it may also stem from the use of phosphate fertilizers in agriculture. Indeed, as early as 1950, studies demonstrated that phosphate fertilizers released Cd into the soil at levels exceeding those from agricultural activities (Davidova et al., 2024). Furthermore, this study showed that Cd levels were not correlated with distance to industrial areas. Previous studies have also yielded results consistent with this hypothesis. A study in Yunnan, China, also showed that Cd and Pb originated from industrial and transportation sources, while Cr was closely associated with the parent material (Li et al., 2025). A study at the Nui Phao mine in Thai Nguyen province, Vietnam, also documented a Cd distribution pattern similar to that observed in this study. Another study also showed that Cd contents did not decrease significantly with distance (Nguyen et al., 2020b).

Interestingly, Cd accounts for 80% of the ecological risk in the entire region but has the lowest contents, at only 0.05 mg/kg. This result can be explained by its high biological toxicity (Tr = 30). In addition, Cd accumulates in the body over a period of 10 to 30 years due to its very long biological half-life (Järup & Åkesson, 2009). Consequently, exposure to Cd can lead to kidney disease, osteoporosis, and cancer. Similarly, a study on HM deposition in Ho Chi Minh City, Vietnam, yielded comparable results. Although Pb had the lowest content, it still accounted for nearly 60% of the PERI (Nguyen et al., 2026). These results demonstrate that the high toxicity of HMs is of significant importance for ecological risk, rather than necessarily being related to high contents. Therefore, the PERI index can be considered an early warning tool for ecological risks posed by HMs in soil. The PERI interpolation map also identifies hotspots in three clusters of sites: east (TU09), south (TK04–TK05), and west (TH05–TH06). These results align with the distribution map of Cd. After Cd, the study identified Pb as the second most significant heavy metal posing an ecological risk. High Pb concentrations were also observed at the two sampling points TK05

and TH05. Therefore, the PERI hotspots identified in this study are locations with high contents of both Cd and Pb; specifically, Cd is dispersed across multiple emission sources, whereas Pb is distributed locally and tightly bound to Fe.

CONCLUSIONS

According to the results of soil studies conducted in the three wards of Tan Hiep, Tan Khanh, and Tan Uyen, Ho Chi Minh City is currently not contaminated with HMs, but there are signs of localized accumulation at points TH03 (Zn = 207.24 mg/kg), TK05 (Pb = 19.91 mg/kg), and TU09 (Cd = 0.18 mg/kg). Calculations of geochemical indices, interpolated maps of spatial distribution, and correlation analyses indicate that Pb, Zn, and Cd originate from industrial activities, while Cr, Cu, and As primarily stem from the geochemical background. Chromium shows a positive correlation with distance to industrial zones; the enrichment factor (EF) is low, and it also exhibits a strong correlation with Fe, indicating a natural origin. Zn shows localized accumulation, Pb is concentrated and associated with the Fe background, while Cd is dispersed and may originate from agricultural activities. Almost none of the HMs correlate with transportation factors, and there is no clear evidence of the impact of wind deposition. The area has a low ecological risk level with an average PERI of 22.48; Cd accounts for 80% of the PERI value due to its high toxicity.

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