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RESEARCH ARTICLE

Toxic metal accumulation, health risk, and distribution in road dust from the urban traffic-intensive environment

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Abstract

Owing to increasing levels of potentially toxic metals in road dust, air pollutants suspended in the air, pose significant health risks due to rapid, unplanned urbanization and industrialization. This study investigated the pollution status and health risks of trace metals (i.e., Cr, Cd, Ni, Cu, and Pb) in road dust collected from 16 locations across six land-use categories in Eskişehir, Türkiye, including residential, roadside, traffic, tram stations, and car industrial areas. The analysis of trace metals revealed distinct types of urban pollution based on these functional areas. In areas with heavy traffic, high concentrations of the elements, especially Zn, Cr, and Ni, would indicate significant toxic metal pollution. The overall contamination was evaluated using three indices: enrichment factor (EF 0.45–65.75), geo-accumulation index (I_{geo} −2.50–4.18), and pollution index (PI 0.27–27.22). Human health risks of potentially toxic trace metals in urban road dust were evaluated for children and adult groups based on hazardous index (HI) and total cancer risk (TCR). The health risk assessments revealed that children (mean $HI_{children}$ 8.62E−01; $TCR_{children}$ 6.99E+04) are more vulnerable to toxic metal exposure than adults (mean HI_{adults} 1.01E−01; TCR_{adults} 3.01E+04), with ingestion being the primary exposure route over dermal contact and inhalation. In conclusion, we have captured the interaction between road dust and health risks, especially for children.

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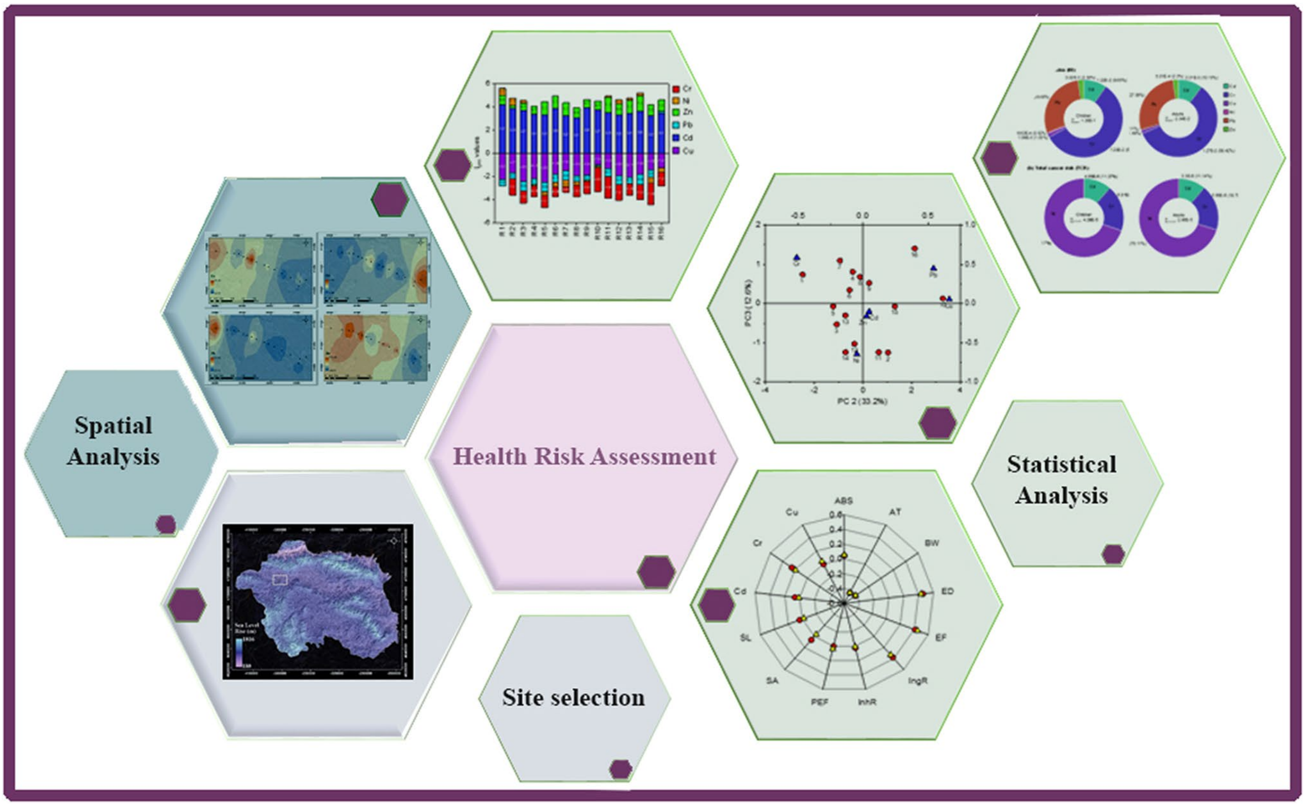
Graphical Abstract



Keywords Contamination indices · Potentially toxic metals · Spatial distribution · Pollution degree · Health risk assessment

Introduction

Considering potential urban pollution, the social development experienced, the rapid growth of urbanization, and the continuous improvement of people's material level have brought some environmental problems (Xie et al. 2019). Air pollution is of great environmental concern, and it is at the forefront of the emerging ecological effects and has become a serious global problem worldwide (Kaur and Pandey 2021). Approximately 80% of the population in industrialized and densely populated cities is affected by air pollution. According to the air quality guidelines of the World Health Organization (WHO), it has been reported that more than 97% of the cities in low and middle-income countries are affected by air pollution (WHO 2021). Air pollution manifests due to the unequal distribution of the increasing population in societies moving towards industrialization, the clustering of industries, and the heavy traffic volume. The topographic structure in some regions' geographical formations, such as mountains and hills, affects the accumulation of pollution. Urban conditions cause air pollutants not to disperse and polluting air to dominate (Yassine et al. 2024). In addition, pollutants mix with the air, water, and soil environments with the effect of wind. Toxic metals, which are at the forefront of these pollutants, can be fatal for humans because they accumulate in various environments after entering the environment at high levels, can be permanent, and do not break down easily. These metals reach the body through ingestion, inhalation, and dermal contact. They accumulate in the body and negatively affect the circulatory system, endocrine system, and central nervous system, causing vital diseases such as various types of cancer, growth retardation, and kidney diseases (Gholami et al. 2024).

There is a risk of carcinogenicity due to exposure to heavy metals in soil, road, and street dust. Studies have shown that children are more affected than adults (Sah et al. 2017; Shabbaj et al. 2018). Urban road dust (URD) in various environments disperses under the influence of gravity settling and wind particles in the air and can re-suspend. Heavy metals in URD pose severe threats to the ecological environment and human health, so they have both a source of pollution and a pollution absorber role (Rajaram et al. 2014). Therefore, the characterization of URD used in measuring urban environmental quality provides essential ideas.

These pollutants, which are released from natural sources, resuspension of soils and worn materials, and large-scale emissions from anthropogenic sources (Nargis et al. 2022), traffic sources (Krupnova et al. 2020) (exhaust gas, tire and brake wear, vehicle surface corrosion), residential fossil fuel combustion, industrial pollution sources (coal-fired electricity generation, solid waste incineration, metal smelting, pigment production, etc.), and urban construction activities (Trujillo-González et al. 2016), can remain in the air for more extended periods by adhering to particulate matter (PM 2.5) with an aerodynamic diameter of ≤ 2.5 µm and penetrate the lungs (Chen et al. 2015). In recent years, studies on toxic metals in URD samples conducted by various researchers have examined the pollution index, morphology, source, health risk assessment, and spatial distribution (Gupta et al. 2022). It has been found that metals released from various source conditions can penetrate the respiratory system of humans and cause heart and respiratory diseases depending on their concentration and exposure duration. Potentially toxic metals have been observed to accumulate in ecological systems and pose a risk to people living in urban and suburban areas, making children, in particular, more vulnerable to diseases (Bartholomew et al. 2020). Although excess metals necessary for human bio-functions, such as iron (Fe), copper (Cu), and zinc (Zn), are not carcinogenic to humans, they can cause oxidative stress and DNA damage in the body. However, potentially toxic metals such as cadmium (Cd), arsenic (As), chromium (Cr), nickel (Ni), and lead (Pb) are potentially carcinogenic to humans at deficient concentrations and have the ability to cause lung, bladder, and skin cancers (Zheng et al. 2010).

Industrialization in Eskişehir has been one of the leading factors that has driven urbanization for over a century. Industrial areas are concentrated at two extreme points, northeast and northwest of the city. The spine passing through the city's core, which has a single-centered growth, connects working and living areas. The location of the air base in the city allows low-rise construction due to the flight cone. Due to the high rent in the city center, journeys from working areas to living areas pass through the center, where traffic calming applications are made. Tourism attraction points are also located in the center, and there is a transit route for important cities. As a result of the fact that the old route of the city could not meet the increasing load, it has faced a serious number of vehicles. The fact that these vehicles do not use alternative routes and accumulate on certain roads causes an increase in toxic metals. The URD examined in this study is located in a location that can be considered the city's busiest street. Therefore, the main purpose of this study is (i) to determine the concentration of potentially toxic metals (Cr, Ni, Cu, Cd, Pb, and Zn) contained in the dust on the large organized industrial road in Eskişehir; (ii) to evaluate the pollution level of each heavy metal according to EF and I_{geo}; (iii) to determine the possible sources of heavy metals in URD based on multivariate statistics; (iv) to calculate the health risk assessments for each heavy metal and to reveal the risk to which road users and residents are exposed. It is aimed to be a basis for the analyses carried out during the production of urban development plans. It is aimed to provide a reference point for future studies on environmental conditions and the surroundings, including the risk assessment of URD and associated heavy metals, and to present appropriate reduction strategies for human health.

Materials and methods

Study sites

Eskişehir (39°46′00.1″N 30°31′32.6″E) is an important industrial city including various metal processing smelters and other industries, under the jurisdiction of 14 districts and 536 neighborhoods within the 20th largest city in Türkiye, an area of about 13,960 km^2 (Ministry of Culture and Tourism 2024), population of about 915,418 people (Turkish Statistical Institute 2023), and terrestrial climate prevails in Fig. 1. According to the General Directorate of Meteorology (MGM), the highest temperature is 41.6 ℃, the lowest temperature is – 28.6 ℃; the average 39°46′00.1″N 30°31′32.6″E temperature in summer in the urban area is 21.9 °C, whereas the average temperature in winter in the urban area is 1.5 °C; the mean annual precipitation in the urban area is 355.9 mm and the yearly average wind speed is 2.5 m/s (MGM 2024). In the last decade, rapid urbanization and the associated increase in motorized vehicles have caused a severe worsening of urban air quality. Roads can be very busy thanks to the transport sector extending to the Aegean and the Mediterranean regions of Türkiye. This can increase environmental problems and pose a greater threat to the health of the inhabitants. Therefore, it is very important to know the heavy metal pollution in URD in Eskişehir.

Sampling plan and analysis

The main considerations for collecting URD samples were (i) a day without rain and (ii) sampling on a day when the wind speed was lower than the average value. In this study, 16 sampling points were selected from the following roads: the connection of the industrial area to the city center, the route of the residential areas, and a road along the car industry. The determined sampling points are number 1: main road junction (point with heavy road junction and traffic); number 2: beginning of the street; number 3: in front of the school, number 4: non-residential area; number 5: small industrial zone; number 6: a small industrial zone; number 7: small industrial junction; number 8:

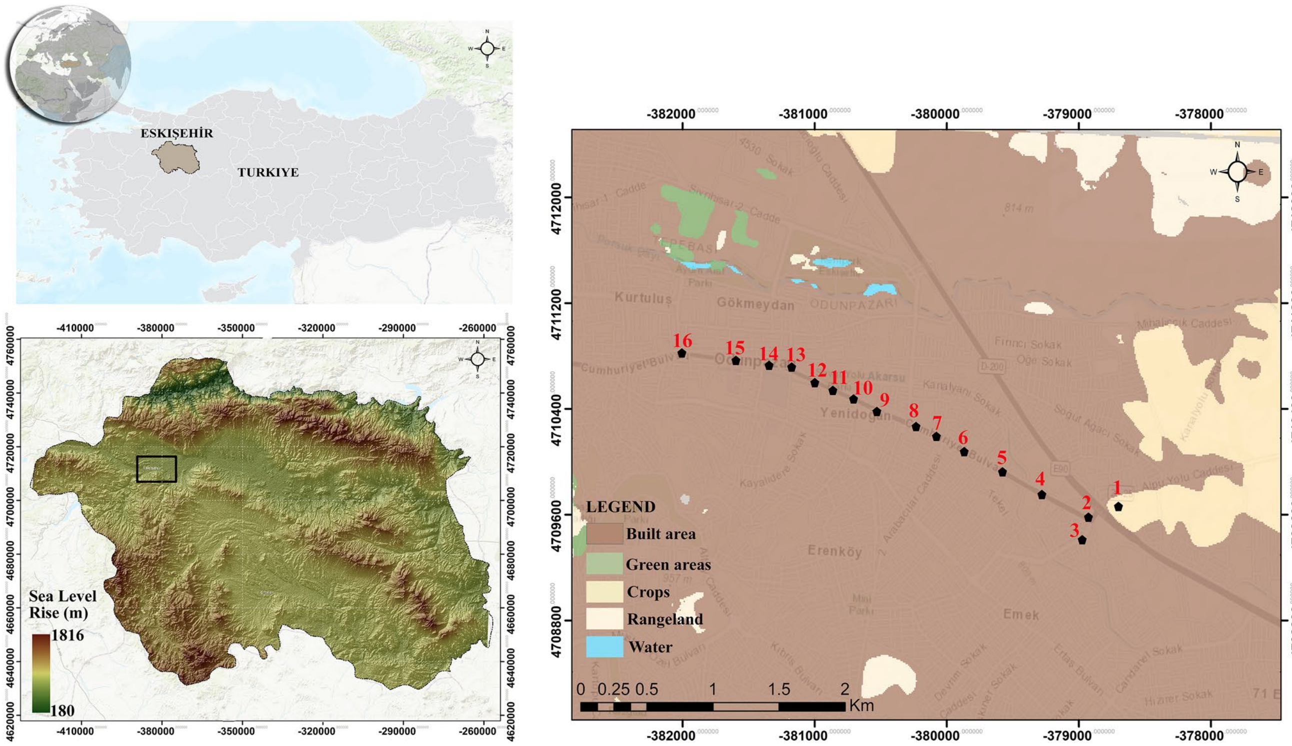


Fig. 1 Study area map covering the inner and outer city sampling sites in Eskişehir City

gas station junction; number 9: beginning of settlement, number 10: residential area; number 11: residential areas, fluid traffic, and tram stop; number 12: residential areas, fluid traffic, and tram line; number 13: residential areas, fluid traffic, and tram line; number 14 residential areas, fluid traffic, and tram line; number 15: residential areas, fluid traffic, and tram line; number 16: entrance of the city core.

Although it is a road leading to the industry, it is known that trucks carrying goods do not use this road intensively and that those working in the sector mostly use it for service-individual transportation purposes. Moreover, the tram line on this road connects to a part of the same road and provides public transportation service together with buses. It is experienced with serious density, especially during work entrance and exit hours. The density of motor vehicles forming long queues is quite important. There are few commercial shops on the road. There is also a school and a park on the inner side of the road. The region has a channel structure mutually limited by high-rise adjacent buildings. Accordingly, it is impossible to form air corridors using the streets and avenues along the artery where the samples were collected. In mid-August 2023, 3 replicate samples of 200 g were taken from the dust accumulated on the roadside with a clean plastic brush and a plastic shovel. The collected samples were placed in labeled polyethylene bags, and the sampling location was recorded using GPS. The collected samples were brought to the laboratory and stored at room temperature for further analysis.

The samples were dried in a temperature-regulated oven at 65 °C for 72h and then sieved through a nylon sieve to a particle size of less than a diameter of 75 µm which were selected due to a diameter of 75 µm can be bonded with trace metals in the air for a long time (Peng et al. 2023) and pose a threat to human health through inhalation (Malakootian et al. 2021). It was possible to determine the concentration of heavy metals, 1 g of URD was digested by aqua regia (Hydrochloric acid (HCl) and nitric acid (HNO_3) ratio was 3:1) on a heating plate, and a small amount of aqua regia solution was repeatedly stirred so that the sample solution continued to boil and eventually evaporated to near dryness.

Then, repeatedly clean the container with 10% dilute HNO_3, pour the cleaning solution into a 100-mL volumetric bottle, cool and constant volume. Finally, the clear detection solution was filtered out by a needle filter. The concentrations of Cr, Ni, Pb, Cu, Zn, Cd, and Al were measured by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES, SpectroBlue, Germany).

Contamination assessment

The mean concentration of some metals is slightly higher than the background level. The enrichment factor (EF) was performed to better characterize the level of metal enrichment and assist in recognizing natural and anthropogenic source contributions of metals in URD. The EF is defined as follows in Eq. (1):

$$EF = \frac{\left(C_n / C_{Fe} \right)_{\text{road dust}}}{\left(B_n / B_{Fe} \right)_{\text{background}}} \quad (1)$$

Here $\left(C_n / C_{Fe} \right)_{\text{road dust}}$ is the ratio of the concentration of an element to the Fe concentration at individual points of sampling and $\left(B_n / B_{Fe} \right)_{\text{background}}$ is the ratio of the concentration of this element to the Fe concentration in the soil background value (Taylor and McLennan 1995), which can select the background value of surface soil in the reference sample. According to Sutherland's categorization method, EF can be classified into five classes (Buat-Menard and Chesselet 1979; Sutherland 2000): the minimum (1–2), moderate (2–5), significant (5–20), very high (20–40), and extremely strong (> 40). Whereas an EF value of less than one means that the element originates principally from the earth's crust and other natural sources, an EF value greater than 1 means that it is affected by both human and natural factors (Ekwere and Edet 2021).

The geo-accumulation index (I_{geo}) rating method is applied to grading metal pollution by comparing the observed trace metal concentration with the background value (Müller 1969; Hakanson 1980). Geological and anthropogenic sources of heavy metals in urban URD can also be distinguished with the following Eq. (2).

$$I_{\text{geo}} = Log_2\left(\frac{C_n}{1.5B_n}\right) \quad (2)$$

where C_n represents the metal concentration (mg·kg^{-1}), B_n defines geochemical background values (mg·kg^{-1}) and the denominator multiplied by 1.5 to permit natural fluctuations and anthropogenic effects. If the I_{geo} value is greater than 1, metals are considered to be influenced by an anthropogenic source. If less than 0, not polluted, 0–1 slightly polluted, 1–2 moderately, 2–3 moderately to strongly, 3–4 strongly polluted, and greater than 4 extremely polluted.

Emission source identification

In this section, we introduce the identified emission sources of elements in URD, and hierarchical cluster analysis (CA), and principal component analysis (PCA) were simultaneously applied. The elements were grouped using the "centroid" cluster method and "Euclidean" distance type. For the PCA, a correlation matrix and Eigenvalues higher than unity were used to determine the number of principal components (PCs). Prior to performing CA and PCA, the element concentrations were normalized to eliminate the influence of elements with very high concentrations. Specifically, the concentration of each element in URD per sampling site was normalized by dividing by the total concentration of six elements at each site. Origin Pro 2020 (Origin Lab, USA) was used for the CA and PCA.

Health risk assessment

According to US Environmental Protection Agency (USEPA), to understand the effect of elements in URD on human health, human health risk was assessed for children (< 18 years old) and the adult group (18–70 years old) (USEPA 2009). A total of three exposure pathways were considered, including ingestion, inhalation, and dermal contact. The non-carcinogenic risks were evaluated based on the hazardous index (HI), which is a sum of the hazardous quotients (HQs) of individual exposure pathways. In addition, the carcinogenic risks associated with exposure to elements in URD were assessed using cancer risk (CR). The CR of individual exposure pathways was then summed to get the total cancer risk (TCR). Detailed information on human health risk calculation is described in Text S1 of Supplementary information (SI). Moreover, to understand the simultaneous risks of six target elements (i.e., Cr, Cu, Cd, Ni, Pb, and Zn) on human health, the total HI, considering ingestion, inhalation, and dermal contact pathways of the six elements (hereafter $\sum_6$HI), was computed. Similarly, the TCR of elements (i.e., Cr, Cd, and Ni) through the three target exposure pathways was also calculated (hereafter $\sum_3$TCR). Note that for Cd, two pathways (i.e., ingestion and inhalation) were considered due to the limited slope factor regarding dermal contact of Cd.

Data analysis

The Pearson correlation coefficient and cluster analysis (CA) were employed with the IBM SPSS 22 application for Windows in order to determine the relationship between toxic metals in URD and their possible origins. The spatial distribution maps were produced using ArcGIS version 10 from the selected locations.

Results and discussion

Total metal concentration

The concentrations of six elements in URD collected in Eskişehir (Türkiye) are illustrated, and the statistical description of toxic metal concentrations at all sampling sites is provided in Table S1. Additionally, the spatial distribution of element concentrations is shown in Fig. 3. Generally, the element concentrations followed the order

Zn > Cr > Ni > Pb > Cu > Cd, which is consistent with our previous studies investigating trace elements in rıad dust in Türkiye (Isinkaralar et al. 2024) and other regions (Goudarzi et al. 2018). The mean ± standard deviation (SD) of trace elements across the 16 sampling sites were 200 ± 36, 43 ± 17, 44 ± 12, 28 ± 6, 17 ± 5.2, and 2.1 ± 0.5 mg/kg for Zn, Cr, Ni, Pb, Cu, and Cd, respectively. Some elements, such as Zn, Cr, and Ni, exhibited extended whiskers and outliers (Fig. 2), reflecting greater variability in the concentrations of these elements across the sites. This observation suggests localized contamination or environmental factors contributing to concentration differences at various sampling sites. Cu and Pb generally showed moderate variability, likely due to a few highly contaminated locations (Table S1), possibly near traffic-heavy areas. Cd exhibited little variability in concentrations; however, its extended outliers suggest a potential concern at certain specific sites.

For spatial distribution, site L1 exhibited the highest concentration of several elements (Fig. 3), particularly Cr (92 mg/kg), Ni (65 mg/kg), and Cd (3.3 mg/kg). This suggests that L1 could be a notable site for the accumulation of these elements in URD, likely due to its proximity to a main road junction with high traffic density. Zn and Cu displayed similar spatial distributions, with higher concentrations in industrial areas (i.e., sites L5–L7) and residential areas (sites L11–L16). The concentrations of Zn and Cu at sites L5–L7 ranged from 219 to 226 mg/kg and from 10 to 20 mg/kg, respectively, while at sites L11–L16, they ranged from 199 to 261 mg/kg and from 14 to 25 mg/kg, respectively. The elevated concentrations of Zn and Cu in these industrial and residential areas suggested that car repair industrial activities and vehicular emissions (e.g., tire and brake wear) are likely contributing factors to the high levels of these elements in URD (Khan et al. 2023). The highest Pb concentration was observed at site L16 (46 mg/kg), located at the entrance to the city core, which experiences heavy traffic. This highlighted the impact of traffic activity on Pb pollution in the area.

Contamination assessment results

Several parameters were calculated to assess the pollution levels of trace elements in URD, including EF, I_{geo}, and PI. Their values are presented in Fig. 4 and Tables S2–S4. The results show that the EF and pollution levels of all trace elements in URD generally followed the order of Cd > Zn > Ni > Pb > Cr > Cu. Additionally, a gradual decline in the pollution levels of trace elements from site L1 (main road junction) to site L16 (entrance of the city core) was observed, indicating uncontrolled industrial emissions. Furthermore, the positive I_{geo} values for Cd, Zn, and Ni (Fig. 4b) suggested that these elements originate from anthropogenic sources.

The high contamination of Cd at most sampling sites was determined through EF (mean 29.7), I_{geo} (mean 3.5), and PI (mean 17.9). Significant Cd pollution was notably observed at sites L1 (main road junction) and L2 (beginning of the street), both of which experience high traffic density including vehicular tires, indicating the effect of traffic exhaust on Cd contamination at these locations. Additionally, Cd has

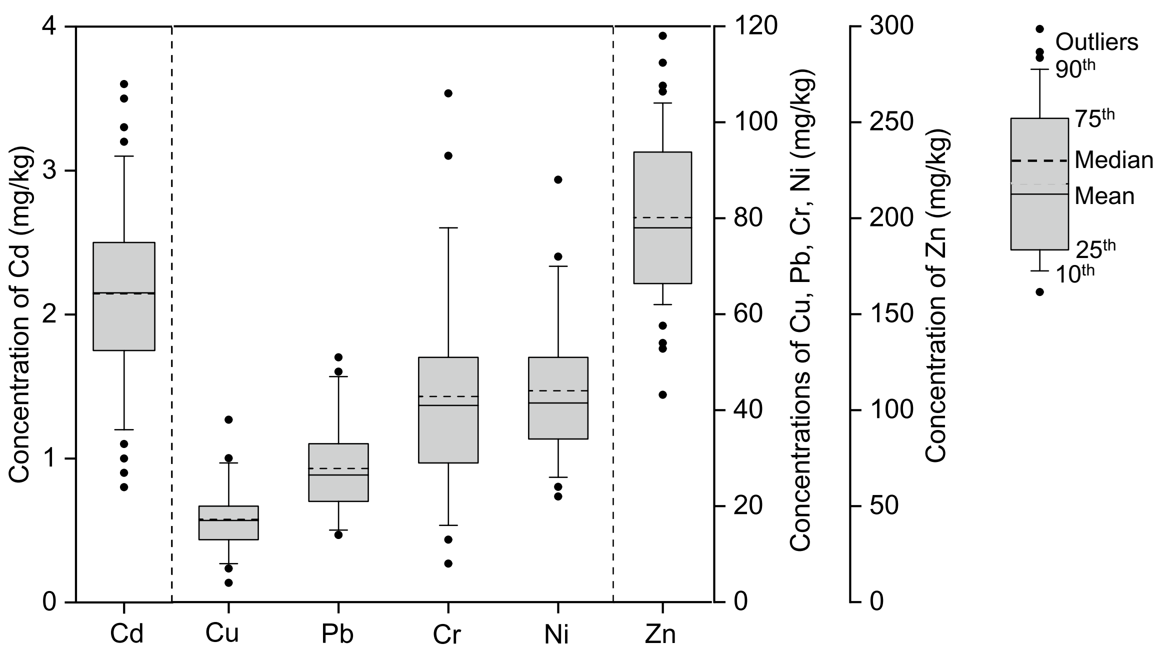


Fig. 2 Cr, Cu, Cd, Ni, Pb, and Zn concentrations in URD

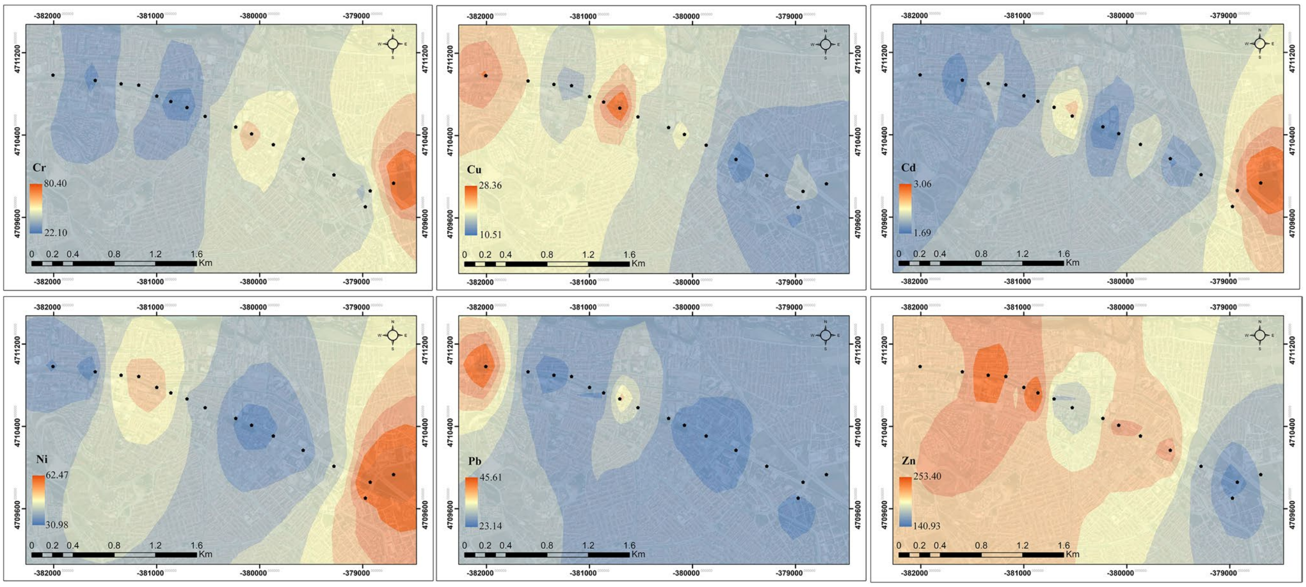


Fig. 3 Prediction map of Cr, Cu, Cd, Ni, Pb, and Zn distribution in study sites

been reported to originate from industrial processes (e.g., iron and steel smelting, coal-fired power plants) and the weathering of building materials and plastic batteries (Han et al. 2017). Therefore, efforts should be made to reduce Cd pollution at the sampling sites. Our results also showed moderate contamination of Zn at all sites, except for sites L1 (main road junction) and L5–L6 (industrial areas), which exhibited higher EF, I_{geo}, and PI values. Sites L1–L7 also experienced moderate contamination of Ni (EF 3.3), suggesting that traffic and industrial activities contribute to the accumulation of Zn and Ni in URD. Higher pollution levels of toxic, carcinogenic metals were observed in areas with dense traffic and industrial activities (Mohmand et al. 2015). The values of Cd were divided by 10 for the EF and PI. Other trace elements, including Cu, Pb, and Cr, were generally classified as unpolluted to slightly polluted across most sampling sites.

Health risk assessment results

For human health risk assessment, the carcinogenic and non-carcinogenic risks of elements in URD were evaluated based on three exposure pathways: ingestion, inhalation, and dermal contact. The HI and CR were calculated for the non-carcinogenic and carcinogenic effects, respectively. Generally, the $\sum_6$HI values for children (mean ± SD 1.36E − 01 ± 3.12E − 02) were 5.8 times higher than those for adults (mean ± SD 2.34E − 02 ± 5.42E − 03). The $\sum_3$TCR also showed a similar pattern, reflecting greater values for children (mean ± SD 4.39E − 05 ± 1.03E − 05) compared to adults (mean ± SD 2.96E − 05 ± 6.94E − 06) (Fig. 5). These findings are consistent with previous studies reporting higher risks for children from exposure to elements in URD (Liu et al. 2023) because the immune system of children is not fully developed compared to that of adults.

Considering the human health risks of each trace element, the HI and TCR values of elements were in the same order for children and adult groups, which is Cr > Pb > Cd > Zn > Cu > Ni for HI and Ni > Cr > Cd for TCR (Fig. 5). The highest HI value of Cr (mean ± SD 7.28E − 02 ± 1.76E − 02 for children and 1.27E − 02 ± 3.10E − 03 for adults), which would be its high concentrations (mean 42.85 mg/kg) and its lowest RfD values (Table S1), also led to the greatest contribution of Cr to the $\sum_6$HI. Of these trace elements considered for the TCR (i.e., Ni, Cr, and Cd), Ni showed the highest TCR value and, thus, contributed the most (i.e., 60–70%) to the $\sum_3$TCR (Fig. 5). This result would be explained by the higher concentration of Ni (mean 44.04 mg/kg) compared to Cd (mean 2.14 mg/kg) and Cr (mean 42.85 mg/kg). Additionally, SF values of Ni considering three exposure pathways (i.e., ingestion, inhalation, and dermal contact) were 3–4 times higher than those of Cd and Cr (Table S1).

Regarding human health risks for each exposure pathway, the HQ and CR values for children and adult groups exhibited similar patterns, showing the highest risks for ingestion, followed by dermal contact and inhalation (Tables S7 and S8). These results were also consistent with previous studies on assessing human health risks of elements in URD (Li et al. 2018; Candeias et al. 2020). To understand the effect of the health risk parameters on the risk results, a correlation analysis was performed. The results revealed that AT had a highly negative correlation with the HI and CR values (Fig. 6), suggesting that lower exposure times to URD

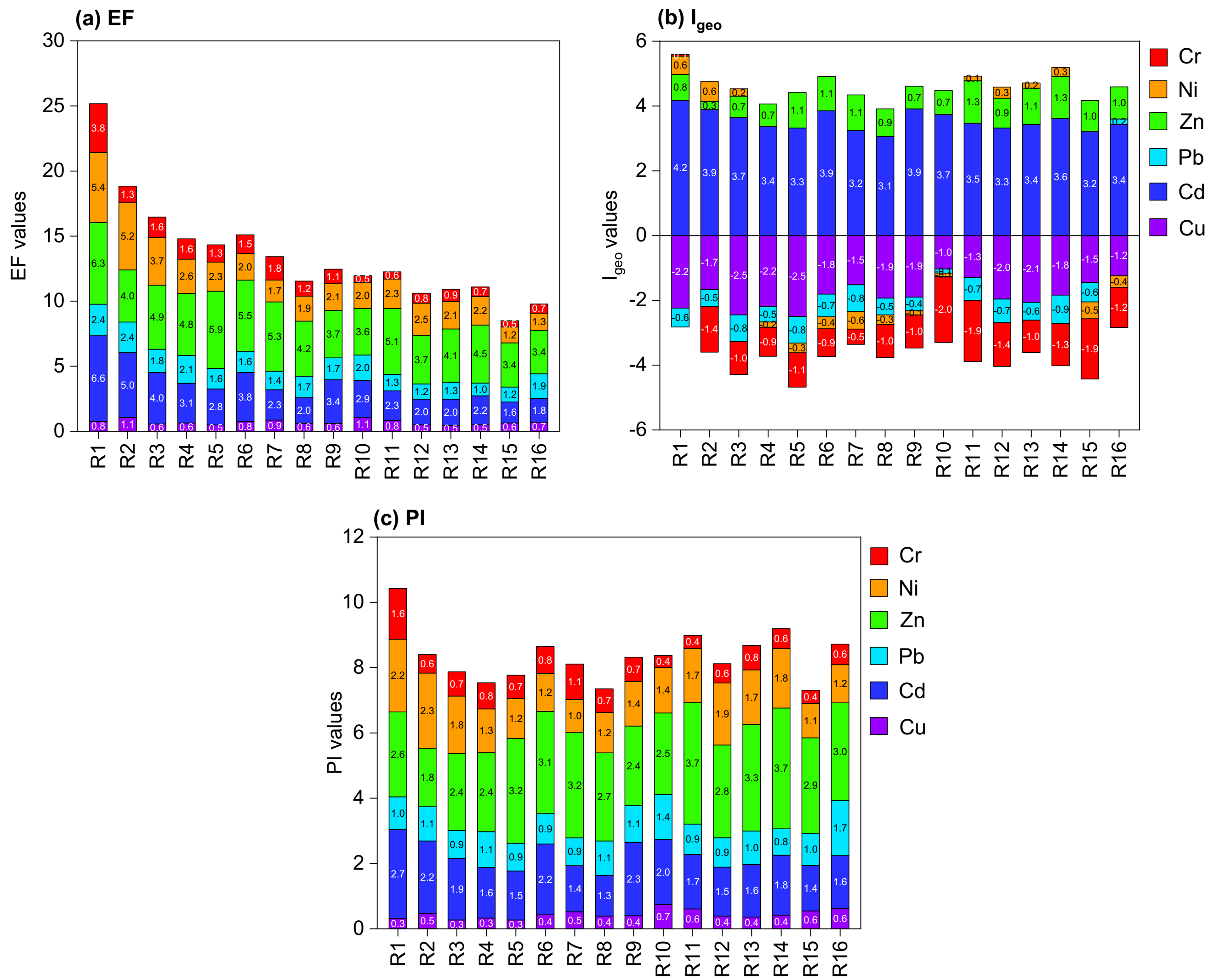


Fig. 4 EF, I_{geo}, and PI values of Cr, Cu, Cd, Ni, Pb, and Zn in URD

would probably reduce the human health risks for both target groups. The ED and EF values also showed highly positive correlations with HI and CR, meaning that greater exposure duration and frequency would lead to greater human health risks and vice versa. In addition, the ingestion rate (IngR) was highly correlated with the HI and TCR values (Fig. 6), likely due to the highest contribution of the ingestion exposure pathway to the health risks (Tables S7 and S8).

Emission source identification

The CA and PCA were used simultaneously to identify emission sources of trace elements in URD collected in Eskişehir, Türkiye. The cluster dendrogram visually represents the results of a hierarchical clustering analysis for six trace elements, with each vertical line representing a cluster and the merging lines indicating the joining of clusters. The PCA results identified three principal components (PCs), which together explained 91.6% of the total variance (PC1 45.8%, PC2 33.2%, and PC3 12.6%). PCA biplots, displaying both the sampling sites and trace element variables, were used to identify emission sources of trace elements in URD.

As shown in the cluster dendrogram, Zn was separated into its own cluster (Fig. 7a), suggesting that its emission sources may differ from those of the other elements. In the PCA biplots, several sites, including L5–L7 (industrial area) and L11–L16 (residential area), were located on the left side of the plots and were characterized by high concentrations of Zn (Fig. 7b, c). Elevated Zn concentrations were also observed at these sites. In the industrial area, Zn might be emitted through processes such as coating (e.g., galvanizing steel), metal smelting, and refining (Cheng et al. 2018). In the residential area, Zn in URD could originate from vehicle emissions (e.g., tire and brake wear) (Lough et al. 2005),

Fig. 5 Mean values and contribution of Cr, Cu, Cd, Ni, Pb, and Zn individuals to the **a** HI and **b** TCR

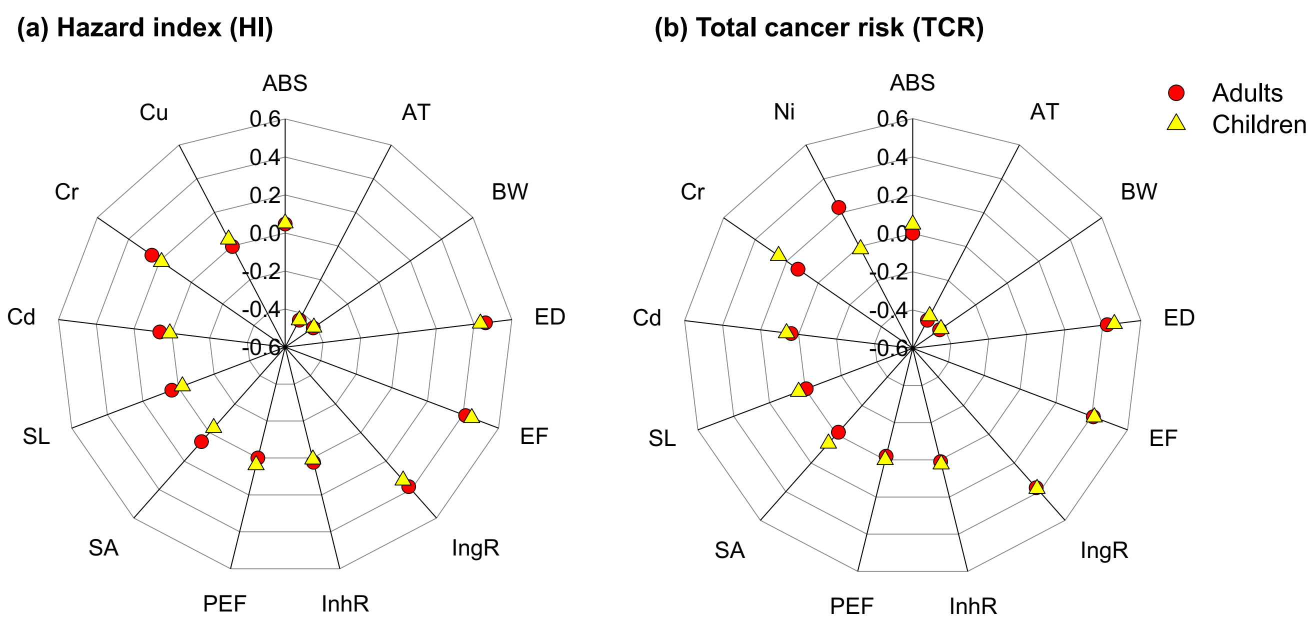


Fig. 6 Correlation coefficient of the health risk parameters to **a** HI and **b** TCR for both children and adult groups

as Zn is a component of rubber tires and brake pads, which release Zn into the environment through abrasion. Additionally, the combustion of fossil fuels (e.g., coal and oil) can also emit Zn. Therefore, Zn in the study area, particularly at sites L5–L7 and L11–L16, likely originated from both industrial activities and vehicle emissions.

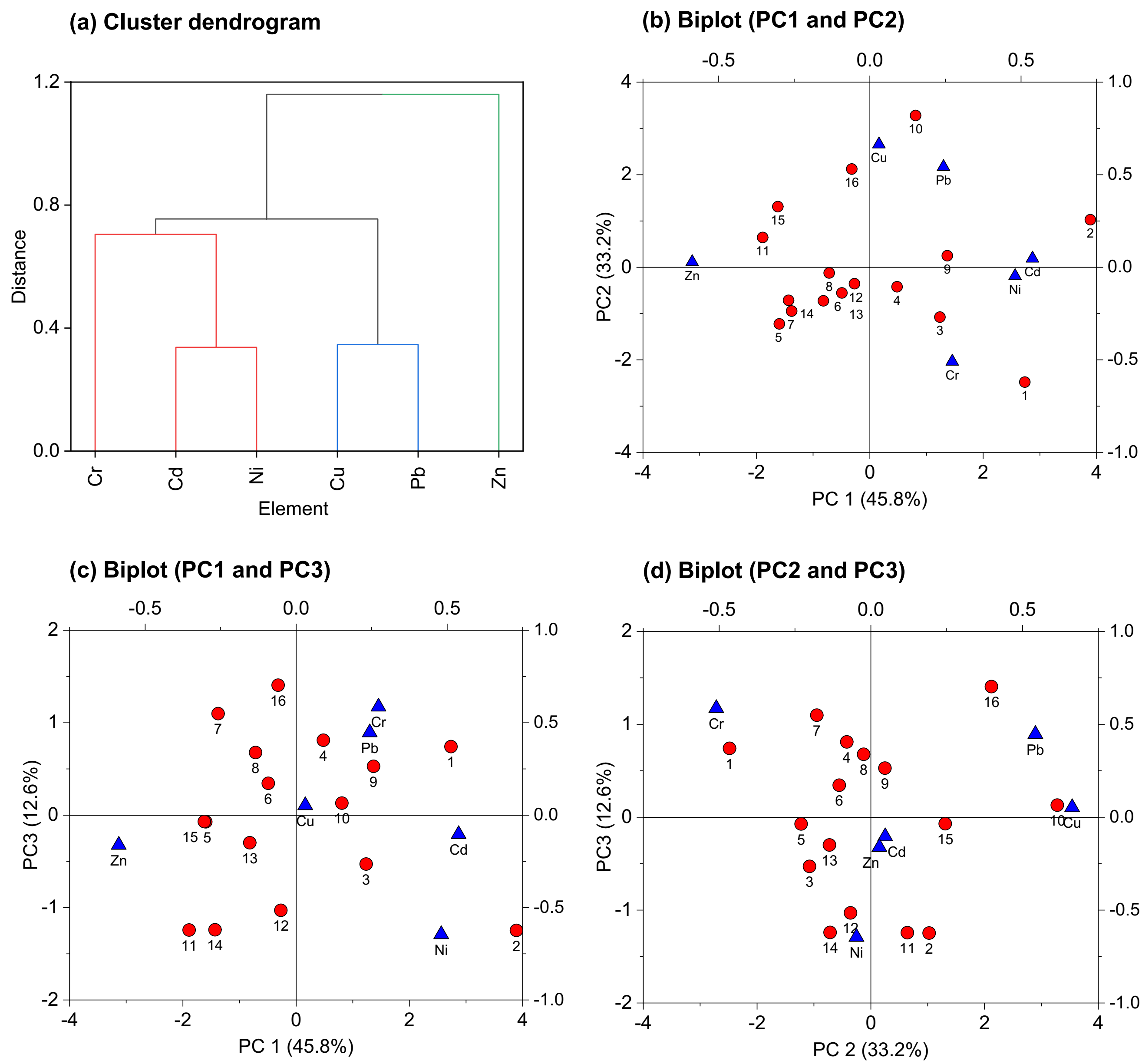


Fig. 7 CA and PCA results

In addition, Cr, Cd, and Ni were clustered together (Fig. 7a), suggesting they originated from similar emission sources. Several sites, including L1–L4 and L9–L14, were generally located on the right side of the biplots and were characterized by Cr, Ni, and Cd (Fig. 7b, d). These elements are likely emitted from fossil fuel combustion (Eary et al. 1990). Additionally, Ni is a component in some brake pads and vehicle exhaust systems and can be released through wear and tear or exhaust emissions (Lee et al. 2008; Mehmood et al. 2019). Therefore, the emission sources of Cr, Cd, and Ni in the study area would be likely fossil fuel combustion and brake wear, with their influence more pronounced at sites with higher traffic density, such as sites L1–L4 and L9–L14. Furthermore, Cu and Pb likely shared many common emission sources, as they were grouped in the same cluster (Fig. 7a). These sources can be vehicle emissions and fossil fuel combustion (Alias et al. 2020). Furthermore, the biplots show that Cu and Pb are associated with sites L9–L10 and L15–L16 (Fig. 7b, d), indicating a stronger influence of these emission sources at those locations.

Conclusions

The growing activities in industrial zones have led to an increased demand for intra-city transportation. Effective management of transportation requires a focus on public transportation, road infrastructure, and traffic regulations. In cities with organized industrial zones, managing transportation to these areas efficiently and offering alternative options is especially important. Providing public transport such as trams, metros, suburban trains, buses, metrobuses, and minibuses is crucial for accommodating the tens of thousands of people commuting to and from these zones at the start and end of the workday. Challenges such as housing shortages, unplanned construction, traffic congestion, environmental degradation, social inequality, and economic losses complicate efforts to make cities sustainable and livable. Therefore, when planning residential areas, it is vital to carefully consider the regions where automobile traffic and industrial activities occur. In Eskişehir, the absence of alternative central hubs has contributed to a decline in the spatial quality of the city center. The linear development of the city, focused around a single center, has resulted in technical infrastructure, traffic issues, and higher transportation costs. Further research is required to provide more data for selected locations.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-024-35253-y.

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Author contribution Oznur Isinkaralar: visualization, validation, writing—original draft, writing—reviewing and editing. Kaan Isinkaralar: conceptualization, methodology, investigation, formal analysis, data curation, writing—original draft. Tuyet Nam Thi Nguyen: formal analysis, writing—reviewing and editing.

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Data availability The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Declarations

Ethics approval All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare that they have no competing interests.

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