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Ecotoxicological and Human Health Risk Assessment of Toxic Metal Pollution in Urban Soils in Northwest Türkiye

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ABSTRACT
In this study, the soils in the Biga district's center, which are exposed to various anthropogenic effects, were examined. A total of 26 soil samples were obtained from the urban soils in five land-use types in Biga (Çanakkale, NW Türkiye). The study aims to determine the concentration of toxic metals (TMs) in soils of the study area, to evaluate the ecological and health risk assessment, to determine the sources of TMs. To determine TMs concentrations in soils, wet-digestion samples were analyzed using an ICP-OES device. TM concentrations (unit in mg kg^{-1}) were listed as follows: Fe (159245±87136) > Al (89540 ± 56535) > Mn (45095 ±27871) > Zn (5660±6244) > Cu (2940±3602) > Pb (1134±1528) > Ni (1117±1094) > Cr (175±118.3) > Co (0.71±2.16) > Cd (0.15±0.25). EF values for Cu, Zn, Pb, and Mn in soils are extremely high; I_{geo} values for Mn and Zn are in the moderately to heavily contaminated class; in terms of CF, Cu, Mn, Zn, Ni, and Pb are in the very high contamination class; PLI values for Cu, Mn, Ni, Pb, and Zn are in the high contamination class (between 8.60 E-31 and 3.57E+21). Er^1 is in the very high-risk class for Cu. $HQ_{ingestion}$ values in both children and adults are high risk for some TMs (Cr, Mn, Ni, Pb, and Zn); $HQ_{inhalation}$ value is high-risk only in Mn; HQ_{dermal} value is high-risk for some TMs (Cr, Mn, Ni, and Pb). HI values pose a health risk in some TMs (Cr, Mn, Ni, Pb, and Zn) for both children and adults. Al, Cr, Fe, Mn, Cu in the area were caused by natural factors, and some (Ni, Pb, Cd, and Zn) were caused by anthropogenic factors. The distribution of each TMs in the area also varied according to land use.

Keywords: Contamination indices**,** Health risk, Land use, Toxic metals, Urban soils

1. Introduction

Soil and sediment geochemistry is essential to infer the primary source of potential mineralization, soil provenance, environmental conditions, and TMs pollution (Tokatlı et al. 2023; Ustaoğlu et al. 2024; Ndema et al. 2025; Yiika et al. 2025). Industrialization and urbanization activities together with population increase and developing technology bring along environmental problems. One of the most important of these environmental problems is the TM pollution in the soils (Tiabou et al. 2024a; Suh et al. 2025). TMs from diverse sources accumulate in soil, are hard to remediate, and require long-term interventions. In addition to the negative effects of TMs on plant development and soil fertility, they can lead to acute and chronic diseases and even deaths in humans and biota due to their transition to the food-web transfer (Namlı et al. 2020; Plak et al. 2024; Siddig et al. 2025; Sigue et al. 2025).

Urbanization primarily causes increased emissions of potentially hazardous chemicals such as TMs into soil ecosystems (Ndema et al. 2024; Yiika et al. 2024; Tiabou et al. 2024b). TM pollution in cities negatively affects the quality of life and reduces the quality of life by causing an overall increase in diseases (Konstantinova et al. 2019; Sharma et al. 2024; Xie et al. 2023). Urban soils are places of accumulation for TMs from natural or anthropogenic origins (Tiabou et al. 2024c). Examples include geogenic weathering and anthropogenic inputs (traffic, industry, agrochemicals). Reports indicate rising urban TM concentrations in South Africa, Cameroon, Bangladesh, Pakistan, Türkiye, India, Nigeria, China, Brazil, Ethiopia, Sudan, and Ghana (Angon et al. 2024; Yıldız & Özkul 2024; Ndema et al. 2023; Afahnwie et al. 2025a; Tiabou et al. 2025a). The main reasons for this are rapid urbanization and some other anthropogenic factors (Yiika et al. 2022; Tiabou et al. 2025b). The most important sources of pollution in developing countries are chemicals, agricultural practices, industrial and household effluents, mining, and petroleum products (Yiika et al. 2023; Afahnwie et al. 2025b). In recent years, studies on TM pollution have been conducted in different countries. Tume et al. (2018) determined that some of the Talcahuano urban soils in Chile showed severe contamination through the geochemical index, enrichment factor, and contamination factor. Adimalla et al. (2020) analyzed 20 surface soils (0–10 cm) from Sangareddy, India. The results of the research showed that the average Cr, Cu, Ni, and Zn concentrations were higher than

the values in the earth's crust. Cr and Cu were found to be the highest TMs measured in the soil. Pollution indices showed that the soils of the survey area were mostly moderately to very polluted. Dartan et al. (2015) reported agricultural-soil metals (mg kg^{-1}) in Bandırma, Balıkesir (NW Turkey) as: Al > Fe > Mn > Cr > Zn > Ni > Cu > Cd > Co > Pb. Most of the soil samples showed moderate enrichment for Ni, Cu, Co, Zn, Pb, and Cr, and extremely high enrichment for Cd. In addition to high concentrations of Cr, Cd, Cu, Zn, Ni, and Pb in the soils of the study area, TMs pollution was thought to be caused by humans due to its high enrichment factors (2.54 and 372.87). Han et al. (2020) conducted TM analyses by taking soil samples from 6 parks and 7 schools in the Jiaozuo district of Henan Province, China. The results showed that the Zn, Cu, Pb, Cd, As, Ni, and Co concentrations in the soil were above the Chinese soil guideline values. In addition, serious Cd contamination was detected in the soils in the study area. Hareinda et al. 2023 stated that the urban soils of Ngaoundere (Cameroon) are unsuitable for crop production due to the risk of contamination in the food chain. In Sudan, cancer risks associated with Cr and Ni have been detected in more than 70% of the land across nine different land uses (Siddig et al. 2025).

Although studies have been conducted on the concentrations of TMs in urban soils, their sources, and the associated ecological and health risks, no such research has been conducted in northwestern Türkiye (Adimalla et al. 2020; Avendano et al.2021; Golia et al. 2021; Abbasi et al. 2022; Demirak et al. 2022; He et al. 2021; Goncharov et al. 2024; Plak et al. 2024; Yıldız & Özkul 2024). The aims of this study are 1) to assess the physicochemical properties and concentrations of TM in the soils of Biga district center; 2) to determine which TMs are at an alarming level by using TMs pollution indices; 3) to evalaute the sources of TMs with the help of multivariate statistical analyses; 4) to generate spatial distribution maps to understand the spatial distribution and identify hotspots for pollution in the study area; 5) to determine the health risks of TMs in the Biga district's center due to exposure to TMs in the soil.

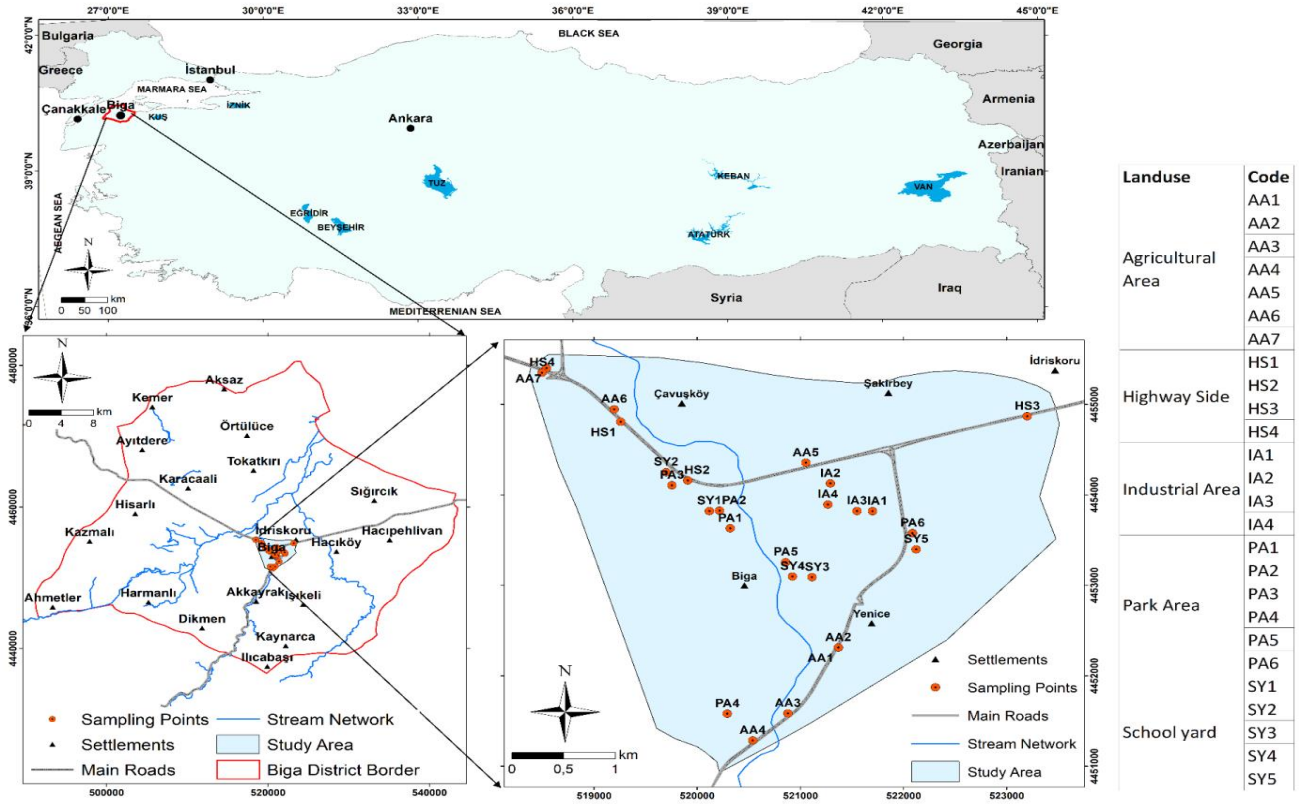
2. Material and Methods

2.1. Study area

Biga is the most populous district of Çanakkale Province, located on the Çanakkale peninsula, approximately 90 km from the provincial center. It is surrounded by Gönen in the east, Lapseki in the west, Çan in the south, and the Marmara Sea in the north. The study area is between 520458 E and 4452997 N (Universal Transverse Mercator-UTM-m, WGS84, Zone 35). As of 2020, the population of the district was 90,418 and the population of the district center was 54,900 (TÜİK 2020). Although the district has a transitional climate between the Mediterranean and Black Sea climates, the effect of the continental climate begins with the rise of the altitude 30-40 km from the coast. The hot and dry summers have the characteristics of the Mediterranean climate, the snowy and cold winters of the continental climate, the spring showers, and the excess humidity of the Black Sea climate. In the Gallipoli and Biga peninsulas, there are four tectonic zones before the tertiary extending in the direction of NE-SW. These are the Gallipoli, Ezine, Ayvacık-Karabiga, and Sakarya zones starting from the northwest. Sakarya Zone consists of the main Ida Mountain group metamorphites, Karakaya complex units that tectonically overlap these metamorphites, and post-Triassic sediments. It has been stated that the Karakaya Formation, in which the study area is located, is made of spilitic basalt, mudstone, radiolarite, feldspathic sandstone, quartzite, conglomerate, and siltstone covering exotic Permo-Carboniferous limestone blocks, shows very low-grade metamorphism and is tectonically incompatible with the gneisses of Mount Ida (Kazdağı) (Okay 1990).

2.2. Soil sampling and analyses

Sampling locations were determined by considering potential anthropogenic impacts in the study area. A total of 26 soil samples were taken from 5 areas with different land use (highway sides, park areas, schoolyards, agricultural areas, industrial areas) in Biga district's center according to the random sampling method. Of the 26 samples, 4 were from highway sides, 6 from parks, 5 from school yards, 7 from agricultural areas, and 4 from industrial areas (Figures 1 and 2). The coordinate values of the sampled locations were recorded with the help of GPS (global positioning device). Soil was sampled from 0–5 cm depth using an acid-washed polyethylene scoop, following Petersen & Calvin (1996). Three subsamples per site were collected within a ~5 m radius and composited into a single homogenized sample. Afterward, soil samples were brought to the laboratory, dried, and prepared for analysis by beating with a wooden mallet and sieving through a 2 mm sieve.



Landuse	Code
Agricultural Area	AA1
	AA2
	AA3
	AA4
	AA5
	AA6
	AA7
Highway Side	HS1
	HS2
	HS3
	HS4
Industrial Area	IA1
	IA2
	IA3
	IA4
Park Area	PA1
	PA2
	PA3
	PA4
	PA5
	PA6
School yard	SY1
	SY2
	SY3
	SY4
	SY5

Figure 1- Location of the study area



Figure 2- Different land uses where soil samples were taken
(A: Highway side, B: Park area, C: School yard, D: Agricultural area, E: Industrial area)

2.3. Soil analyses

Physical and chemical soil analyses used in this study are given in Table 1.

Table 1- Protocol measurements for some physicochemical properties

Parameters	*Unit*	*Protocol*	*References*
Texture (Clay, silt, and sand)	%	Hydrometer method	Gee & Or 2002
pH	1:2.5	(w:v) soil-water suspension	Thomas1996
Electrical conductivity (EC)	dS m^{-1}	(w:v) soil-water suspension	Rhoades 1996
Calcium carbonate ($CaCO_3$)	%	Scheibler calcimeter	Loeppert & Suarez1996
Organic matter	%	Wakley-Black wet digestion	Nelson & Sommers 1996
Total nitrogen	%	Kjeldahl	Bremner 1996
Available phosphorus	mg kg^{-1}	Sodium bicarbonate extraction, spectrophotometry detection	Kuo 1996
Available potassium	mg kg^{-1}	Ammonium acetate extraction, flame spectrometry detection	Helmke & Sparks 1996
Total heavy metal (Al,Cd,Cr,Co,Cu,Fe,Mn,Ni, Pb,Zn)	mg kg^{-1}	According to USEPA 3050B sing ICP-OES detection	USEPA 1996

In this study, the accuracy, precision, and recovery of the ICP-OES method used in the determination of total TMs were determined using certified reference material (NIM-GBW07424). n = 3; %RSD < 5%; recoveries were within the acceptance range of 92–99%. Results are reported in mg kg^{-1}. The limit of detection (LOD) and limit of quantification (LOQ) for each element were calculated (Table S1).

Table S1- Concentrations of metals found in certified reference material (NIM-GBW07424), recoveries, and limit of detection (LOD) and limit of quantification (LOQ) for toxic metals in this study

Metal	*Certified value (mg kg^{-1})*	*Measured value (mg kg^{-1})*	*Recovery (%)*	*LOD (mg kg^{-1})*	*LOQ (mg kg^{-1})*
Cd	0.11	0.12	92.09	0.005	0.012
Co	11.7	12.06	97	0.006	0.02
Cr	58	60	96.54	0.004	0.013
Cu	19	20	97	0.005	0.013
Fe	41700	39513	99.73	0.005	0.017
Mn	681	686	99.28	0.004	0.013
Ni	26	26.7	97.71	0.006	0.02
Pb	22	22.5	97.97	0.005	0.017
Zn	60	61.3	98.74	0.005	0.017

2.4. Soil pollution diagnosis

Enrichment factor (EF), geoaccumulation index (I_{geo}), contamination factor (CF), pollution load index (PLI), ecological risk factor (Er^i), ecological risk index (RI), toxic risk index (TRI), and toxicity analysis unit (TUs) parameters were used to evaluate the spread of pollution caused by TMs in soils and to determine their ecological consequences (Table 2). Among these parameters, the TRI has been developed to assess the possible hazardous risks of toxic metals to organisms (Suh et al. 2025).

Table 2- The indices used in this research are based on equations and explanations*

Index	*Classification*	*Specification*	*Equation*	*Description*
Enrichment factor, EF	EF<2	Minimal enrichment	$EF=\frac{(Cn/Al)Sample}{(Bn/Al)Background}$	Where, C_n is the measured elemental concentration in sediment and B_n is the background heavy metal concentration (Tekiner et al. 2025)
	2≤EF<5	Moderate enrichment		
	5≤EF<20	Significant enrichment		
	20≤EF<40	Very high enrichment		
	EF ≥ 40	Extremely high enrichment		
Geoaccumulation index, I_{geo}	$I_{geo}\leq 0$	Uncontaminated	$Igeo = log2(\frac{Cn}{1.5xBn})$	Where, C_n is the measured elemental concentration in sediment and B_n is the background heavy metal concentrations (Muller1981)
	$0 < I_{geo} \leq 1$	Uncontaminated to moderate		
	$1 < I_{geo} \leq 2$	Moderate contaminated		
	$2 < I_{geo} \leq 3)$	Moderately to heavily contaminated		
	$3 < I_{geo} \leq 4$	Heavily contaminated		
	$4 < I_{geo} \leq 5$	Heavily to extremely contaminated		
	$I_{geo}>5$	Extremely contaminated		
Contamination factor, CF	CF < 1	Low contamination	$CF=C_n / B_n$	Where, C_n and B_n are the measured and background elemental concentrations in sediment (Hakanson 1980)
	1 ≤ CF < 3	Moderate contamination		
	3 ≤ CF < 6	Considerable contamination		
	CF ≥ 6	Very high contamination		
Pollution load index, PLI	PLI ≤ 0	No contamination	PLI = $(CF_1 \text{ x } CF_2 \text{ x } CF_n)^{1/n}$	Where, CF is the contamination factor, n is the number of metals (Tekiner et al. 2025; Benhamdoun et al. 2023)
	PLI > 0–1	Low contamination		
	PLI > 1	High contamination		
Ecological risk factor, Er^i	$Er^i < 40$	Low risk	$Er^i = Tr^i \text{ x } CF^i$	Where, Tr^i is the biological toxic metal response factor (Cd = 30, Cu = 5, Cr = 2, Ni = 5, Pb = 2 and Zn = 1; Hakanson 1980) and CF is the contamination factor
	$40 \leq Er^i < 80$	Moderate risk		
	$80 \leq Er^i < 160$	Considerable risk		
	$160 \leq Er^i <320$	High risk		
	$Er^i \geq 320$	Very high risk		
Ecological risk index, RI	RI < 150	Low risk	$Er^i = Tr^i \text{ x } CF^i$	Where, Er^i is the potential ecological risk factor
	150 ≤ RI <300	Moderate risk		
	300 ≤ RI <600	Considerable risk		
	RI ≥ 600	High risk		
Toxic risk index, TRI	≤ 5	No toxic risk	$\text{TRI}_i = \sqrt{\frac{(\text{Ci/TEL})^2 + (\text{Ci/PEL})^2}{2}}$	Where, Ci is the content of element (i); TEL and PEL are threshold effect level and probable effect level of element (i), respectively (Afahnwie et al. 2025a; Tokatlı et al. 2023; MacDonald et al. 2000).
	5-10	Low toxic risk	$\text{TRI} = \sum_{i=1}^{n} \text{TRI}_i$	
	10-15	Moderate toxic risk		
	15-20	Considerable toxic risk		
	> 20	Very high toxic risk		
Toxicity analysis unit (TUs)	≤ 4	Low toxicity	TUs = Ci/Pi	Where, Ci is the mean trace metal contents in soil, and Pi represents the PEL values (Suh et al. 2025).
	4<TUs<6	Moderate toxicity		
	> 6	High toxicity		

*, In our study, Al was chosen as the toxic metal (TM) used for background due to its abundant content and stability in soil (Tekiner et al. 2025)

2.5. Appraising human health implications

In this study, the health risks caused by TMs for children and adults living in the Biga district center (Çanakkale) were determined. TMs in soils pose a risk to human health through ingestion, inhalation, and dermal adsorption pathways (USEPA 2011; Goncharov et al. 2024; Parlak et al. 2024b). Both non-carcinogenic and carcinogenic health risks were calculated for hazard quotient (HQ) in TMs in soil (Tepanosyan et al. 2017; USEPA 2011; Parlak & Dengiz 2025). In this study, non-carcinogenic risk assessment was performed for Cd, Co, Cr, Cu, Ni, Pb, and Zn. Carcinogenic risks were calculated for Cd, Co, Cr, Ni, and Pb, as slope factors are unavailable for Cu, Mn, and Zn. Non-carcinogenic risk assessment in people living in the district center was determined with the help of the following equations (Eq. 1-7). Explanations for these equations are given in Tables S2 and S3. ADD, as shown in Table S3, stands for average daily dose.

$$ADD_{ing}\,(mg\ kg^{-1}day^{-1}) = Cx\ \frac{IngRxEFxED}{BWxAT}xCF \quad (1)$$

$$ADD_{inh}\,(mg\ kg^{-1}day^{-1}) = Cx\ \frac{InhRxEFxED}{PEFxBWxAT} \quad (2)$$

$$ADD_{der}\,(mg\ kg^{-1}day^{-1}) = Cx\ \frac{SAxSLxABSxEFxED}{BWxAT}xCF \quad (3)$$

$$HQ_{ing} = \frac{ADDing}{RfDing} \quad (4)$$

$$HQ_{inh} = \frac{ADDinh}{RfDinh} \quad (5)$$

$$HQ_{der} = \frac{ADDder}{RfDder} \quad (6)$$

$$HI = \sum_{i=1}^{n} HQ \quad (7)$$

The hazard index (HI) was determined as the sum of HQ_{ing}, HQ_{inh}, and HQ_{der} (Eq. 7). An HI below 1 indicates no non-carcinogenic risk (USEPA 2011). Carcinogenic risks were calculated with the help of Eq. 8. If the calculated carcinogenic risk values are between $1x10^{-6}$ and $1x10^{-4}$, it is thought that it does not pose a risk to human health (acceptable level) (USEPA 2011). TCR (total carcinogenic risk) value was calculated with the help of Eq. 9.

Carcinogenic risk (CR) = Average Daily Dose (ADD) X Slope Factor (SF) (8)

$$TCR = CR_{ing} + CR_{inh} + CR_{derm} \quad (9)$$

Table S2- Exposure factors of TMs (in mg kg^{-1} d^{-1}) used in this study

Parameters	*Symbols*	*Units*	*Values*	*References*
TMs concentration	C	$mg^{-1}\ kg^{-1}$	Present value	-
Ingestion rate-adult	$IngR_a$	$mg^{-1}\ day^{-1}$	20	USEPA 1997
Ingestion rate-child	$IngR_c$	$mg^{-1}\ day^{-1}$	200	USEPA 1997
Inhalation rate-adult	$InhR_a$	$mg^{-1}\ day^{-1}$	16	USEPA 2004
Inhalation rate- child	$IngR_c$	$mg^{-1}\ day^{-1}$	7.6	USEPA 2004
Skin surface available for exposure-adult	SA_a	cm^2	6032	USEPA 2004
Skin surface available for exposure-child	SA_c	cm^2	2800	USEPA 2004
Skin adherence factor-adult	AF_a	mg cm^{-2}	0.07	USEPA 2004
Skin adherence factor-child	AF_c	mg cm^{-2}	0.2	USEPA 2004
Dermal absorption factor	ABS	unitless	0.001	Botsou et al. 2020
Exposure frequency-adult	EF_a	days $year^{-1}$	350	USEPA 2011
Exposure frequency-child	EF_c	days $year^{-1}$	104	USEPA 2011
Exposure duration-adult	ED_a	year	20	Botsou et al. 2020
Exposure duration-child	ED_c	year	6	Botsou et al. 2020
Particulate emission factor	PEF	m^3kg^{-1}	$1.36x10^9$	USEPA 2011
Conservation factor	CF	kg mg^{-1}	10^{-6}	USEPA 2011
Body weight-adult	BW_a	kg	70	USEPA 2011
Body weight-child	BW_c	kg	15	USEPA 2011
Average time for non-carcinogenic effects-adult	AT_a	day	7300	USEPA 1989
Average time for non-carcinogenic effects-child	AT_c	day	2190	USEPA 1989

Table S3- Toxic metal reference doses and corresponding slope factors, adapted from Ferreira-Baptista and De Miguel (2005) and Parlak et al. (2024a)

TMs	*Cd*	*Co*	*Cr*	*Cu*	*Mn*	*Zn*	*Ni*	*Pb*
R_fD_{ing} (mg $kg^{-1}day^{-1}$)	1.00E-03	2.00E-02	3.00E-03	4.00E-02	4.60E-02	3.00E-01	2.00E-02	3.50E-03
R_fD_{inh} (mg $kg^{-1}day^{-1}$)	1.00E-03	5.71E-06	2.86E-05	4.02E-02	1.43E-05	3.00E-01	2.06E-02	3.52E-03
R_fD_{derm} ($mgkg^{-1}day^{-1}$)	1.00E-05	1.60E-02	6.00E-05	1.20E-02	1.84E-03	6.00E-02	5.40E-03	5.25E-04
SF ($mgkg^{-1}day^{-1}$)	6.30E-01	9.80E-00	4.20E+01	-	-	-	8.40E-01	4.20E-02

TMs: Toxic Metals

2.6. Data analysis and spatial distribution

The Shapiro-Wilk test was applied to check the normality of the data obtained by analyzing the soils in different land uses, and transformations were made when deemed necessary. One-way analysis of variance (ANOVA) was applied to compare soil properties and TM contents. The significance of the difference between the means ($P<0.05$) was found using the Duncan test. Multivariate statistical analyses (correlation analysis and principal component analysis (PCA)) were performed on the data (Kouankap et al. 2024). Bartlett's test of sphericity and Kaiser-Meyer-Olkin (KMO) analysis were applied to the data before PCA. Statistical analyses were conducted in IBM SPSS Statistics, version 26 (IBM Corp., Armonk, NY, USA). Geochemical mapping of TMs in soil samples was performed with the help of ArcGIS 10.1 software (ESRI 2009).

3. Results and Discussion

3.1. Physicochemical properties and TM contents of soils

The physical and chemical properties and TM content of the soil samples taken according to different land uses are given in Table 3. Clay content (%) in soil samples taken from highway sides, park areas, schoolyards, agricultural areas, and industrial areas are 18.40, 16.62, 14.48, 28.27, and 18.53, respectively. Silt contents (%) in soil samples with different land uses (from highway sides, park areas, schoolyards, agricultural areas, and industrial areas) are 26.66, 20.09, 26.49, 36.96, and 29.35, respectively. The fine sand (%) content of the soils on the highway sides, park areas, schoolyards, agricultural areas, and industrial areas were 44.19, 49.76, 48.99, 23.57, and 44.69, respectively. The coarse sand (%) contents of the soils sampled in the same order were determined as 10.73, 13.52, 10.02, 11.19, and 7.41, respectively.Textural classes were: highway/park—sandy loam, sandy clay loam; schoolyards—sandy loam, loam, sandy clay loam; agricultural—loam, clay loam, sandy loam, sandy clay loam; industrial—sandy loam, loam. Clay, silt, and fine sand amounts, organic matter, and total N contents of the soils in the research area differed statistically according to land use. Other properties (coarse sand, pH, EC, $CaCO_3$, available P and K, total Al, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Zn) did not differ significantly among land uses (all $P\geq0.05$). The highest clay content in the soils (28.27%) was found in the agricultural areas, the lowest clay content was found in the schoolyards (14.48%), the highest silt content was found in the agricultural areas (36.97%), and the lowest silt content was found in the park areas (20.09%). The minimum fine sand content (23.57%) was found in the soil in the agricultural areas. The highest organic matter content was determined in the industrial areas. Places sampled from industrial areas have not been plowed, and vegetation (weeds) has covered the soil surface. The fact that the soils were not cultivated and the vegetation was too much led to an increase in organic matter. Since tillage ventilates the soil, it also promotes aerobic decomposition (Ok & Camcı Cetin 2015). The pH values of the soil samples taken from the highway sides, parking areas, schoolyards, agricultural areas, and industrial areas are 7.45, 7.42, 7.38, 7.38, and 7.61, respectively. EC values (dS m^{-1}) in soil samples in different land uses (highway sides, park areas, schoolyards, agricultural areas, and industrial areas) are 0.7, 0.78, 0.59, 1.1, and 0.55, respectively. The lime (%) contents of the soils on the highway sites, parking areas, schoolyards, agricultural areas, and industrial areas are 25.5, 6.96, 10.48, 8.14, and 22.37, respectively. The total N (%) contents of the soils sampled in the same order were determined as 0.10, 0.13, 0.09, 0.14, and 0.2, respectively. While the available P and K contents were 11.18 mg kg^{-1} and 51 mg kg^{-1} in the soils in the park area, respectively, they were 22.62 mg kg^{-1} and 142.8 mg kg^{-1}in the soils in the agricultural area, respectively. Regarding the chemical properties of urban soils with different land uses, research has been conducted both in Türkiye and in other countries. Demirak et al. (2022) reported that the average pH, EC, lime, and organic matter in the surface soils taken from 12 different points in the center of Muğla were 8.2; 0.33 dS m^{-1}; 24.6% and 3.5%, respectively. Erşahin et al. (2018) took 50 samples from Çankırı urban soils and determined the average pH, EC (dS m^{-1}), lime (%), and organic matter (%) of the soils as 9.80, 1.17, 13.76, and 1.14, respectively. Golia et al. (2021) performed chemical analyses on 186 surface soils (0-15 cm) from the city of Volos (Greece). The average pH, EC, lime, and organic matter contents of the soils were determined as 7.44, 0.32 dS m^{-1}, 14.57%, and 2.44%, respectively. Horvath et al. (2015) determined some chemical properties of surface soils (0-10 cm depth) in 10 different land use (garden areas, forested areas, agricultural areas, viticulture areas, traffic areas, residential areas, industrial areas, parks, creek and lake banks, other) in Sopron district of Hungary. The researchers found the average pH of the soils in agricultural areas, areas with traffic, industrial areas, and park areas as 7.3, 7.7, 7.8, and 7.7, respectively, and the organic matter (%) as 5.74, 7.07, 5.55, and 6.79, respectively. Moghtaderi et al. (2020) reported that the average pH in 143 surface soils (0–20 cm depth) in Shiraz (Southwest Iran) was 7.7%, and the average organic carbon was 2.69%.

There was no statistical difference between the TM contents in soils with different land uses (Table 3). In soils on the highway sides, park areas, schoolyards, agricultural areas, and industrial areas, Al content was 71302, 122208, 102242, 70628, and 75994 mg kg^{-1}, respectively. In soils with different land uses, Cd content ranges from 0.3 mg kg^{-1} (agricultural area) to 0.043 mg kg^{-1} (highway side); the highest Co content was determined in the schoolyards (2.1 mg kg^{-1}), the lowest Co content was in the agricultural areas (0.07 mg kg^{-1}); the highest Cr content in the park areas (217 mg kg^{-1}), the lowest Cr content in the highway sides (143.52 mg kg^{-1}); the highest Cu content in the agricultural areas (4013 mg kg^{-1}) the lowest Cu content on the highway sides (2210 mg kg^{-1}); the highest Fe content on highway sides (19 465 mg kg^{-1}), and the lowest in agricultural areas (13 474 mg kg^{-1}); the highest Mn content in the schoolyards (57802 mg kg^{-1}) the lowest Mn content on the highway sides (33436 mg kg^{-1}); the highest Ni content in the park areas (1375.42 mg kg^{-1}), the lowest Ni content in the agricultural areas (924.89 mg kg^{-1}); the highest Pb content in the agricultural areas (1736.28 mg kg^{-1}) lowest Pb content on the highway sides (694.2 mg kg^{-1}); the highest Zn concentration in agricultural areas (9191.61 mg kg^{-1}), with the lowest

Zn concentration on the highway sides (3660.7 mg kg^{-1}). Moghtaderi et al. (2020) found that Fe (83 000 mg kg^{-1}), Cr (60 mg kg^{-1}), Co (8-10 mg kg^{-1}), Ni (8-10 mg kg^{-1}) concentrations in soils sampled from Shiran (Iran) industrial areas were higher than the values in the Earth's crust (35 000 mg kg^{-1} for Fe, 90.07 mg kg^{-1} for Cr, 12.42 mg $kg^{-1}$for Co, 122.12 mg $kg^{-1}$for Ni). In Sydney (Australia), traffic emissions contributed 72–84% of Cu, Pb, and Zn contamination in the soil of arterially surrounded parks (Wang et al. 2022). He et al. (2021) found higher TM concentrations (Pb, Cd, Cu, Zn, Cr, and Ni) in soils on the edges of parks and highways compared to agricultural areas in Changsha (China). Solgi and Mahmoudi (2022) stated that TMs (Cd, Pb, Cr, Cu, Co, Mn, Zn, and Ni) in the urban soils in the city of Kermanshah (Iran) are caused by anthropogenic activities, especially traffic. Okereke & Amadi (2017) determined that Zn, Mn, and Cu were of natural origin and Fe and Cr were of anthropogenic origin in the soils of the schoolyards of Harcourt metropolitan port (Nigeria). Yang et al. (2018) reported that contamination with TMs in soils is more serious in industrial regions than in agricultural regions.

Table 3- Physicochemical properties and total TM contents of soils with different land uses (mean± standard deviation)*

Land use	*C*	*Si*	*Fs*	*Cs*	*pH*	*EC*	*$CaCO_3$*	*OM*	*TN*	*Av. P*	*Av. K*	*Al*	*Cd*	*Co*	*Cr*	*Cu*	*Fe*	*Mn*	*Ni*	*Pb*	*Zn*
	%					*dS m^{-1}*		*%*		*mg kg^{-1}*											
HS (n=4)	18.4± 10.74 **AB**	26.66± 5.29 **AB**	44.19± 6.83 **A**	10.73± 2.86	7.45± 0.35	0.7± 0.42	25.5± 40.35	1.79± 0.69 **B**	0.10± 0.02 **B**	18.27± 6.35	58.5± 45.6	71302± 45823	0.043± 0.035	1.37± 2.63	143.52± 89.92	2210± 2153	19465± 11594	33436± 22946	939.37± 1016	694.28± 804.88	3660.7± 3894.6
PA (n=6)	16.62± 6.35 **AB**	20.09± 4.17 **B**	49.76± 11.04 **A**	13.52± 7.85	7.42± 0.31	0.78± 0.33	6.96± 8.84	2.51± 1.08 **AB**	0.13± 0.02 **B**	11.18± 4.48	51± 30.99	122208± 5432	0.11± 0.05	0.28± 0.44	217± 93.07	2355± 1136	159180± 70479	47595± 25865	1375.42± 1055.36	711.18± 736.92	4637.25± 2392.12
SY (n=5)	14.48± 3.95 **B**	26.49± 6.65 **AB**	48.99± 13.23 **A**	10.02± 3.95	7.38± 0.49	0.59± 0.19	10.48± 18.33	1.88± 1.28 **B**	0.09± 0.03 **B**	19.58± 5.99	72.4± 38.57	102242± 32230	0.1± 0.06	2.11± 4.41	172.29± 52.31	3038± 1967	175375± 54716	57802± 23097	1057.49± 938.03	1350.97± 1732.69	4651.34± 2304.39
AA (n=7)	28.27± 5.41 **A**	36.97± 7.31 **A**	23.57± 15.0 **B**	11.19± 6.47	7.38± 0.35	1.1± 0.5	8.14± 10.93	2.61± 1.07 **AB**	0.14± 0.03 **B**	22.62± 12.66	142.85± 110.31	70627.9± 59691	0.3± 0.47	0.07± 0.03	167.59± 165.35	4013± 6513	134748± 69911	38551± 27214	924.89± 1274.84	1736.28± 2356.02	9191.61± 10707.52
IA (n=4)	18.53± 6.41 **AB**	29.35± 7.09 **AB**	44.69± 18.12 **A**	7.41± 4.86	7.61± 0.22	0.55± 0.21	22.37± 25.37	4.47± 2.07 **A**	0.2± 0.03 **A**	14.5± 6.73	74.25± 32.71	75994± 84737	0.13± 0.07	0.09± 0.05	160.83± 174.69	2547± 2652	146645± 155311	48577± 45389	1318.43± 1539.64	888.05± 1087.94	4273.9± 4801.1

*: The difference between the averages shown with different letters in the same column is significant (P<0.05), HS: Highway side; PA: Park area; SY: School yard; AA: Agricultural area; IA: Industrial area.C: Clay; Si: Silt; Fs: Fine sand; Cs: Coarse sand; EC: Electrical conductivity; OM: Organic matter; TN: Total N; Av. P: Available P; Av. K: Available K

The comparison of the average TM contents in the soils sampled from the study area in Biga and the values in other countries is given in Table 4. Al concentration was higher than Iran, continental crust averages, and global soils; Cd concentration was higher than Çankırı but lower than others (Greece, Mersin, China, Iran, Bingöl, continental crust, global soils); Co concentration was lower than others (Çankırı, Greece, Russia, Mersin, Armenia, Bingöl, continental crust, global soils); Cr concentration lower than Cyprus Island and Russia, Çankırı, Greece, Mersin, Iran, Armenia, Bingöl, continental crust, Turkish soil pollution control regulation and worldwide soils; Cu concentrations higher than others (Cyprus Island, Çankırı, Greece, Russia, Mersin, China, Iran, Armenia, Bingöl, continental crust, Turkish soil pollution control regulation, and global soils); Fe concentration higher than others (Çankırı, Mersin, China, Armenia, continental crust, and worldwide soils); Mn concentration higher than others (Cyprus Island, Çankırı, Greece, Mersin, China, Armenia, continental crust, and worldwide soils); Pb concentrations and Zn concentrations higher than others (Cyprus, Çankırı, Greece, Russia, Mersin, China, Iran, Armenia, continental crust, Turkish soil pollution regulation, and global soils). The TM concentrations in the soils sampled from the Biga district center and the differences in other countries may be due to current land use, sampling depth, vehicular exhausts, industrial activities, population density, agricultural activities, spatial heterogenicity in soil properties, measuring methods, and geological structure (Konstantinova et al. 2019; Parlak et al. 2022; 2023; 2024b; Saleem et al. 2023; Adewumi & Ogundele 2024; Tiabou et al. 2025c).

Table 4- Comparison of TMs in the territory of Biga district center (Çanakkale, Türkiye) with those in other countries (unit in mg kg^{-1})

Country	*Al*	*Cd*	*Co*	*Cr*	*Cu*	*Fe*	*Mn*	*Ni*	*Pb*	*Zn*	*References*
Biga, Çanakkale City, Türkiye	89540	0.15	0.71	175	2940	159245	45095	1117	1134	5660	This study
Standard deviation	56535	0.25	2.16	118.30	3602	87136	27871	1094	1528	6244	This study
Minimum-maximum	2934-197461	0.01-1.38	0.02-9.99	0.10-486.49	0.1-18290	352-345103	1640-95956	0.10-3266.4	0.10-6566.4	0.30-30442	This study
Northern Cyprus	-	-	-	230.5	48.2	-	950.6	186.8	15.1	87.5	Abbasi et al. 2022
Çankırı City, Türkiye	-	0.03	1.12	12.14	1.94	1122.6	35.8	9	0.1	2.9	Erşahin et al. 2018
Volos City, Greece	-	0.94	22.56	93.24	53.91	-	663.71	67.28	35.94	131.02	Golia et al. 2021
Ufa City, Russia	-	-	17.9	346	51.1	-	-	101	45.4	150	Goncharov et al. 2024
Mersin City, Türkiye	-	0.51	20.8	117.1	42.5	28713	582.8	227.7	43.5	128	Kurt 2018
Guangzhou, China	-	0.32	-	-	35.8	27900	218	18.7	87.6	107	Lu et al. 2016
Kerman City, Iran	2000	0.16	-	42.3	38.7	-	-	58.1	12.9	153.1	Mahvi et al. 2022
Yerevan City, Armenia	-	-	13.7	122	103	36400	776	61.9	110	262	Tepanosyan et al. 2017
Bingöl City, Türkiye	-	0.81	10.31	26.88	14.67	-	-	31.92	30.11	58.42	Vural et al. 2021
Continental crust	80000	0.3	19	90	45	47200	850	68	20	95	Turekian & Wedepohl 1961
Turkish Soil Pollution Control Regulation, Türkiye	-	-	-	100	140	-	-	75	300	300	Regulation 2005
Worldwide soils	78000	0.41	11.3	59.5	38.9	35000	488	29	27	70	Kabata-Pendias 2010

TMs: Toxic Metals

3.2. Ecotoxicological assessment

In this study, EF, I_{geo} and CF indices were used to estimate the sources of pollution in the soil and to determine whether it is lithogenic or anthropogenic (Yiika et al. 2024; Afahnwie et al. 2025a, 2025b) EF is an index showing TM enrichment in the soil (Benhamdoun et al. 2023; Tiabou et al. 2024a, 2024c, 2025c). The mean EF values of Cu, Zn, Pb, Mn, Ni, Cd, Cr, and Co in the soils in the study area were determined as 117.37, 87.95, 72.41, 60.67, 13.64, 4.43, 1.21, and 0.41, respectively (Table 5). EF indicated extremely high enrichment for Cu, Zn, Pb, Mn; significant for Ni; moderate for Cd; and minimal for Co, Cr. Selahvarzi et al. (2024) stated that Zn, Cu, Pb, and Mn were extremely enriched in the surface soils (0-20 cm depth) in the city of Khorramabad (Iran). I_{geo} is an index showing the degree of contamination (Demirak et al. 2022; Benhamdoun et al. 2023; Sigue et al. 2025). I_{geo} for Mn = 2.84 and Zn = 2.27, both moderately to heavily contaminated; Cu = 1.95, Ni = 1.82, Pb = 1.16 (moderately contaminated); Co = 0.27 (uncontaminated to moderately); Cd = −2.21 (uncontaminated). Yıldız & Ozkul (2024) stated that the l_{geo} values of Ni, Pb, and Cd in the urban soils in Uşak were greater than zero and contaminated with various degrees of anthropogenic resources. Pan et al. (2018) stated that EF and I_{geo} values in urban soils in 32 cities of China were at a moderate pollution level, and these were probably affected by anthropogenic activities. CF is an effective method for monitoring

soil pollution (Demirak et al. 2022; Benhamdoun et al. 2023; Ndema et al. 2023, 2024). The CF values of the soils were found to be 117.61, 87.07, 76.67, 62.98, and 19.94 for Cu, Zn, Pb, Mn, and Ni, respectively. According to the CF values, Cu, Zn, Pb, Mn, and Ni were determined in the very high contamination class. The mean CF values of Cd and Cr were 1.53 and 1.39 and were determined to be in the moderate contamination class, and the mean CF value of Co was 0.03 and in the low contamination class. Tume et al. (2018) found that the pollution factor of Cr and Mn was very high in the soils of Talcahuano (Chile), which is a heavily industrialized city. PLI is used to evaluate TM pollution in each soil sample (Benhamdoun et al. 2023; Demirak et al. 2021). The pollution load indices of the soils in the research area are given in Table 5. The average PLI = 6.09, indicating overall polluted status (PLI > 1) driven mainly by Cu, Mn, Ni, Pb, Zn. Yıldız & Özkul (2024) found that Uşak urban soils were not contaminated and moderately contaminated in terms of load pollutant index. Demirak et al. (2022) determined the pollution load indices for Cd and Pb in soils with different land uses in Muğla city center between 7 and 10.4.

Ecological risk assessment is performed to evaluate the effects of TMs on the environment and the ecosystem (Yiika et al. 2022; 2023; Adewumi & Ogundele 2024; Ustaoğlu et al. 2024; Suh et al. 2025). Er^1, RI, TRI, and TUs were used as ecological risk indices in this study. Er^1 values for Cd, Cu, Cr, Ni, Pb, and Zn were found to be 45.92, 588.06, 2.77, 99.74, 153.34, and 87.07, respectively (Table 5). In the soils in the research area, a moderate risk for Cd, a very high risk for Cu, a low risk for Cr, and a considerable risk for Ni, Pb, and Zn were found. RI classes: <150 low, 150–300 moderate, 300–600 considerable, >600 very high; the mean RI = 550.92 falls in considerable. Ghanavati et al. (2019) detected low ecological risk in 57%, moderate risk in 40%, and high ecological risk in 3% of all samples in the surface soils of Ahvaz urban area of Iran. Abbasi et al. (2022), who conducted research on urban soils in Northern Cyprus, found that 34% of the soils in the sampling area had a high ecological risk level. Mahvi et al. (2022), who investigated the soils of Kerman city in Iran, found the RI values in all areas between 17.40 and 1835.91, and the average RI value was 364.64 (considerable ecological risk). The TRI value in the study area was determined to be 121.28 (very high toxic risk). The TUs values determined in the order of Ni > Zn > Cu > Pb > Cr > Cd.

Table 5- Contamination indices of TMs in the urban soil samples

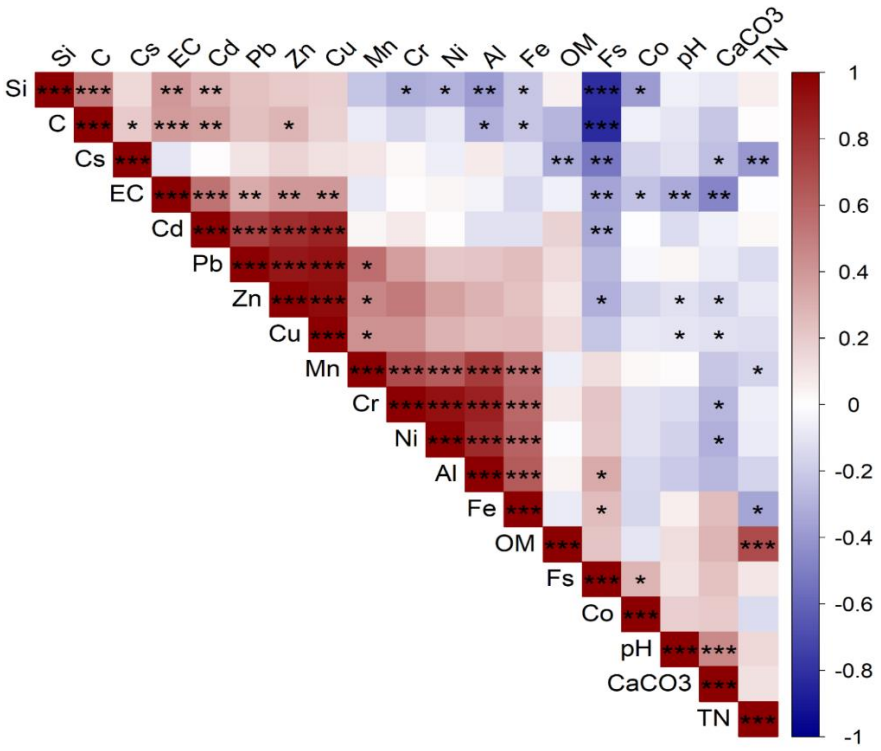
			EF				I_{geo}	
Toxic metals	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
Cd	4.43	11.67	0.06	56.96	-2.21	0.41	-2.18	-1.04
Co	0.41	0.12	0.004	0.59	0.27	0.63	-0.49	2.20
Cu	117.37	215.84	0.03	1150.21	1.95	0.88	-2.17	2.45
Cr	1.21	0.52	0.02	2.78	9.13	36.69	-0.11	189
Mn	60.67	27.71	25.72	140.54	2.84	0.92	2.56	2.94
Ni	13.64	12.64	0.05	39.18	1.82	0.83	-0.81	2.35
Pb	72.41	141.36	0.01	697.53	1.16	1.33	-1.76	2.26
Zn	87.95	140.29	0.03	736.31	2.27	0.47	0.16	2.61
			CF				Er^1	
Toxic metals	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
Cd	1.53	2.57	0.10	13.80	45.92	77.18	3	414
Co	0.03	0.09	0.0008	0.42	-	-	-	-
Cu	117.61	144.09	0.004	731.60	588.06	720.44	0.02	3658
Cr	1.39	0.94	0.001	3.86	2.77	1.87	0.002	7.72
Mn	62.98	38.93	2.34	134.02	-	-	-	-
Ni	19.94	19.54	0.002	58.32	99.74	99.72	0.01	291.60
Pb	76.67	103.26	0.007	443.68	153.34	206.51	0.02	887.36
Zn	87.07	96. 06	0.005	468.34	87.07	96.06	0.72	468.34
			PLI				RI	
	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
	6.09	1.26	8.60E-31	3.57E+21	550.92	552.19	12.16	2045.96
			TRI					
	Mean	S.D.	Min	Max				
	121.28	115.93	0.14	533.86				
			TUs					
Toxic metals	Mean	S.D.	Min	Max				
Cd	0.04	0.07	0.002	0.390				
Cu	14.92	18.28	0.01	92.84				
Cr	1.94	1.31	0.01	5.40				
Ni	31.03	30.40	0.01	90.73				
Pb	12.42	16.73	0.01	71.92				
Zn	17.96	19.82	0.01	96.64				

TMs: Toxic Metal

3.3. Origin prediction of TMs

The relationships between the TM contents and physicochemical properties of the soils sampled from lands with different uses in the Biga district center are given in Figure 3. A positive relationship is determined at 0.1% level between Al and Mn, Cr, Ni; a positive relationship at 0.1% level between Cd and Cu, Pb, Zn, EC; a negative relationship at 5% level between Co and silt; a negative relationship at 5% level between fine sand and Al, Fe; a positive relationship at 1% level between fine sand and coarse sand, EC , Cd; a positive relationship at 1% level between Cd and clay and silt; a positive relationship at 1% level between EC

and Pb, Cu, Zn; a positive relationship at 0.1% level between Fe and Mn, Ni, Cr, Al; a positive relationship at 0.1% level between Mn and Cr, Ni, Al, Fe; a positive relationship at 5% level between Al and clay; a positive relationship at 0.1% level between Pb and Zn, Cu; a positive relationship at 1% level between Zn and EC; a positive relationship at 0.1% level between clay and silt; a negative relationship at 0.1% level between silt and fine sand; a positive relationship at 1% level between silt and EC; a positive relationship at 0.1% level between pH and lime; a negative relationship at 1% level between EC and lime.
Islam et al. (2022), one of the scientists working on soils with different land uses, found a positive correlation between Cu and Cr, Cr and Cd, Mn, and Zn; Avendano et al. (2021) found a positive correlation between Pb and Cr; Mahvi et al. (2022) found a positive correlation between Al and Ni, Cd and Pb, Cu and Ni, Cu and Zn, Pb and Zn; Modabberi et al. (2018) found a positive correlation between Cd and Pb, Cr and Mn, Cu and Zn, Pb and Zn; He et al. (2021) found a positive correlation between Cd and Pb, Cr and Cu, Cr and Zn, Zn and Cd.



C (Clay) (%), Si (Silt) (%), Fs (Fine sand) (%), Cs (Coarse sand) (%), EC (Electrical conductivity) (dS m^{-1}), OM (Organic matter) (%), TN (Total N), *** 0.1%, ** 1%, * 5%

Figure 3- Pearson correlation coefficients between TMs contents and physicochemical parameters in urban soil samples

A total of 10 TM variables were analyzed to infer the underlying (latent) factors affecting soils in the district center of Biga using principal component/factor analysis. In the factor analysis applied to group soils according to their toxic metal content, Bartlett's test and the Kaiser–Meyer–Olkin (KMO) test were used to determine the suitability of the data set, principal component analysis (PCA) was used to identify the factors, and the Varimax technique was used to perform the rotation. The KMO(Kaiser-Meyer-Olkin) measure of sampling adequacy was 0.666, indicating middling adequacy. Eigenvalues > 1 were selected (Kaiser's criterion) to retain principal components explaining variance in the data.

The percentage of variance, cumulative variance, and factor loadings (after rotation) are reported in Table 6. According to the total percentage variances after rotation, 4 factors explain 66.6% of the total variance. Parameter loads (component matrix) greater than 0.7 determined for 4 factors after rotation are given in Table 6.

Table 6- Varimax rotated component matrix for TMs in soil*

Parameter	*Factor 1*	*Factor 2*	*Factor 3*	*Factor 4*
Al	**0.913**	-0.039	-0.078	0.022
Cr	**0.904**	-0.107	0.065	-0.024
Fe	**0.752**	-0.080	-0.350	0.288
Mn	**0.864**	0.018	0.145	0.033
Ni	0.328	**0.748**	-0.162	-0.311
Pb	-0.087	**0.813**	0.111	0.200
Zn	0.100	0.048	0.018	**0.948**
Co	-0.119	0.484	0.083	0.012
Cu	**0.750**	0.077	0.439	-0.043
Cd	0.082	0.098	**0.950**	0.038
Eigenvalues	3.701	1.583	1.194	1.105
% of variance	37.007	15.832	11.941	11.054
Cumulative %	37.007	52.839	64.781	75.835
Kaiser- Meyer- Olkin measure of sampling adequacy				0.666
Bartlett's test of sphericity				0.000

***: Bold values are factor loadings of the principal components,** TMs: Toxic Metal

Factor 1 (37% of variance) loaded on Al, Cr, Fe, Mn, and Cu. Factor 2 (15.83%) loaded on Ni and Pb. Factor 3 (11.94%) loaded on Cd. The fourth factor explained 11.05% of the total variance and was determined to be in relation to the Zn variable. In this factor, all parameters were determined as strongly positively charged (Table 6). Factor 1 likely reflects geogenic control. Variables in this factor (Al, Cr, Fe, Mn, Cu) showed strong positive loadings (> 0.70). PCA grouping of these elements in Factor 1 suggests a shared source. These elements are mostly formed by the weathering of minerals and rocks (Parlak et al. 2023; Saleem et al. 2023; Kouankap et al. 2024; He et al. 2005). This pattern is consistent with Fe–Mn oxides and aluminosilicate/clay weathering products. Fe, Al, and Mn are the most common elements found in the earth crust (Tekiner et al. 2025; Yalçın et al. 2008). Other factors (2nd, 3rd, and 4th factors) are due to anthropogenic factors. Ni and Cd are mostly caused by human activities (Akbarimorad et al. 2024). Pb, an important indicator of vehicle emissions, is not only caused by traffic pollution but is also associated with atmospheric accumulation and agricultural inputs (Ndema et al. 2023; 2024; Akbarimorad et al. 2024; Yiika et al. 2024). The current USEPA (2024), soil screening guideline level of 200 mg kg^{-1} Pb. Legacy Pb from past leaded gasoline can persist in urban soils and resuspend via dust. Cd is caused by the use of phosphorus fertilizers and traffic activities (emissions from lubricating oil, brake pads, and vehicle tires) (Akbarimorad et al. 2024; Tiabou et al. 2024a; 2024b; 2024c). Major urban sources of Zn include brake linings and brake-wear particles (Parlak et al. 2022). Zn is also present in some agrochemicals including fungicides, pesticides, and herbicides (He et al. 2005; Tiabou et al. 2025a; 2025b; 2025c).

3.4. Spatial distribution of TMs in the soils

The spatial distribution of the mean values of TMs in the soils in the research area is given in Figure 4. Al concentration is determined to be in the range of 50 000-100 000 mg kg^{-1} in more than 1/3 of the sampled area; Cd concentration is below 1.38 mg kg^{-1} near almost the entire sampling area; Co concentration is below 1.17 mg kg^{-1} in 89% of the study area; Cu concentration is in the range of 1000-5000 mg kg^{-1} in more than half of the sample area (58%); Cr concentration is in the range of 150-250 mg kg^{-1} in about 1/3 of the study area (31%); Fe concentration is in the range of 175 000-275 000 mg kg^{-1} in most of the 1/3 of the sample area (35%); Mn concentration is in the range of 10000-50000 mg kg^{-1} in 46% of the research area, >50000 mg kg^{-1} in 39% of the research area; Ni concentration is in the range of 1000-2000 mg kg^{-1} in 27% of the sampling area, 2000-3000 mg kg^{-1} in 17% of the sampling area, >3000 mg kg^{-1} in 4% of the sampling area; Pb concentration is in the range of <200 mg kg^{-1} in 47% of the study area, in1000-3000 mg kg^{-1} in 46% of the study area, >3000 mg kg^{-1} in 7% of the study area; Zn concentration is in the range of <1000 mg kg^{-1} in 16% of the sampling area, 1000-3000 mg kg^{-1} in 27% of the sampling area, 3000-5000 mg kg^{-1} in 13% of the sampling area, 5000-10000 mg kg^{-1} in 27% of the sampling area, >10000 mg kg^{-1} in 17% of the sampling area.

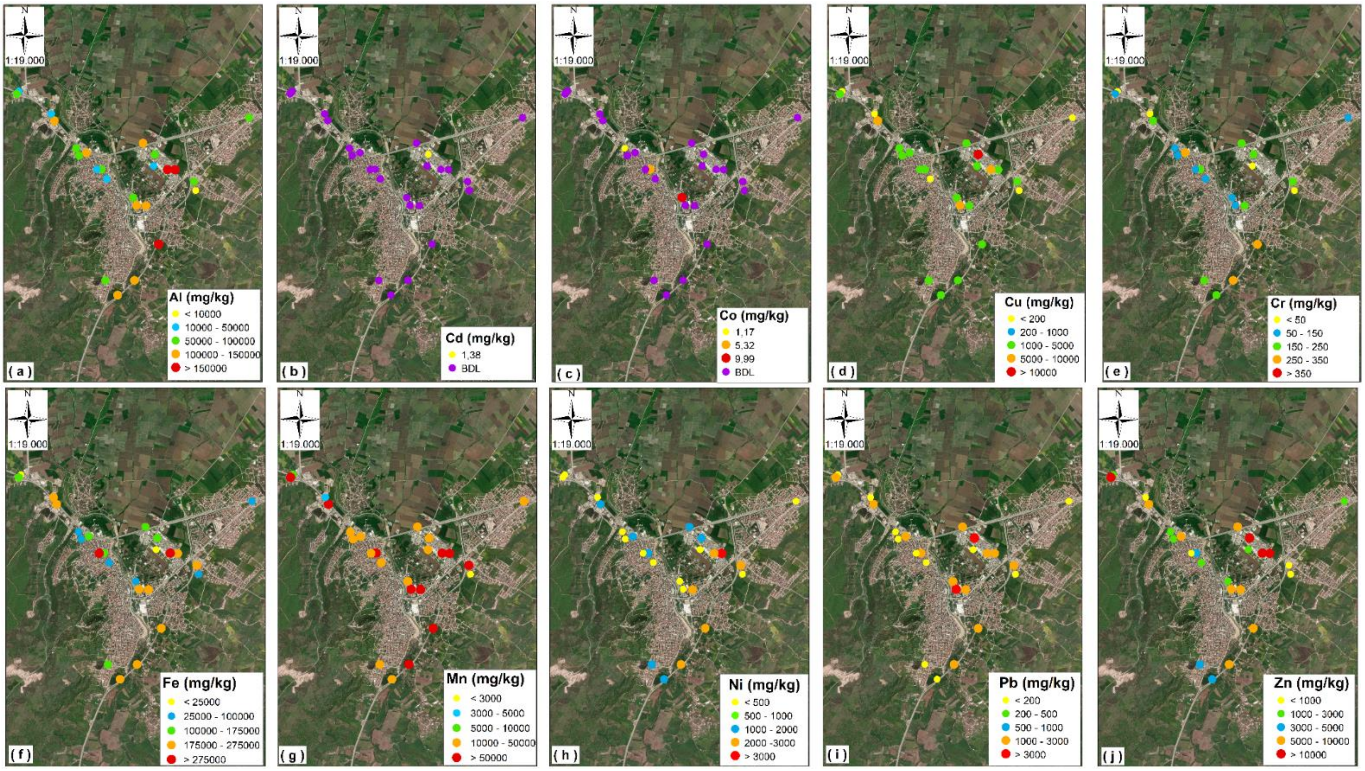


Figure 4- Spatial distribution of concentrations of TMs (Al, Cd, Co, Cu, Cr, Fe, Mn, Ni, Pb, and Zn) in soils with different land uses (BDL: Below detection limit)

3.5. Potential child and adult health risk assessment

3.5.1. Non-carcinogenic risk

The ADD (ADD = average daily dose; see Eqs. 1–3) results of ingestion, inhalation, and dermal absorption pathways of TMs in soil for children and adults are given in Table S4. ADD values in children via ingestion were found to be highest for Mn (1.28E-01), lowest for Cd (4.36E-07); highest for Mn (3.59E-06), lowest for Cd (1.43E-11) via inhalation (pathway), highest for Mn (3.60E-04), lowest for Cd (1.22E-09) via dermal contact. In children, total ADD (sum of pathways) values ranged from 1.28E-01(Mn) to 4.37E-07(Cd); in adults, they ranged from 1.27E-02 (Mn) to 4.28E-08(Cd). Here, total ADD = ADD_{ing} + ADD_{inh} + ADD_{derm} for each TM. In adults, ADD_{ing}, ADD_{inh}, ADD_{der} values were determined highest for Mn (1.24 E-02; 7.26E-06, 2.61E-04, respectively) and lowest for Cd (4.19E-08, 2.47E-11, 8.85E-10, respectively). Thus, ingestion is the dominant exposure pathway, followed by dermal, with inhalation contributing least.

Table S4- Estimated daily intake of TMs from soils in the study area for both children and adults (mg kg^{-1} day^{-1})

TMs	*Children*				*Adults*			
	ADD_{ing}	ADD_{inh}	ADD_{der}	ADD_{total}	ADD_{ing}	ADD_{inh}	ADD_{der}	ADD_{total}
Cd	4.36E-07	1.22E-11	1.22E-09	4.37E-07	4.19E-08	2.47E-11	8.85E-10	4.28E-08
Co	2.02E-06	5.65E-11	5.67E-09	2.03E-06	1.76E-06	1.03E-09	3.73E-08	1.80E-06
Cr	4.99E-04	1.39E-08	1.40E-06	5.00E-04	4.80E-05	2.82E-08	1.01E-06	4.90E-05
Cu	8.38E-03	2.34E-07	2.34E-05	8.04E-03	1.44E-05	8.50E-09	3.05E-07	1.47E-05
Mn	1.28E-01	3.59E-06	3.60E-04	1.28E-01	1.24E-02	7.26E-06	2.61E-04	1.27E-02
Ni	3.18E-03	8.89E-08	8.91E-06	3.19E-03	3.06E-04	1.80E-07	6.46E-06	3.13E-04
Pb	3.23E-03	9.03E-08	9.05E-06	3.24E-03	3.11E-04	1.82E-07	6.56E-06	3.18E-04
Zn	1.61E-02	1.77E-07	4.51E-05	1.61E-02	1.55E-03	1.71E-07	3.27E-05	1.58E-03

TMs: Toxic Metals

HQ, CHQ, HI, and THI (non-carcinogenic risk) values and CR (carcinogenic risk) values of TMs for children and adults living in the district center of Biga are given in Figure 5 and Table 5. HQ_{ing} values in children were above the acceptable level in other TMs (Cr, Cu, Mn, Ni, Pb, and Zn) except for Cd and Co (Figure 4). HQ_{inh} values were minimal for Cd and Zn; exceeded tolerable limit levels for Mn, and were within the acceptable range for Co, Cr, Cu, Ni, and Pb. HQ_{derm} values are at an acceptable level for Cd and Zn, negligible for Co, and constitute health risk for other TMs (Cr, Cu, Mn, Ni, Pb). HI values in children pose a

health risk for TMs (Co, Cr, Cu, Mn, Ni, Pb, and Zn) other than Cd. In adults, HQ $_{ing}$ values were in the permissible range for Cd, Co, and Cu exceeded the limit value for other TMs (Cr, Mn, Ni, Pb, and Zn). HQ$_{inh}$ was < 0.1 for Cd, Zn, < 1 for Co, Cr, Cu, Ni, Pb, and > 1 only for Mn. HQ$_{derm}$ < 1 for Cd, Co, Cu, Zn, but HQ$_{derm}$ > 1 for Cr, Mn, Ni, Pb. HI < 1 for Cd, Co, Cu, but HI > 1 for Cr, Mn, Ni, Pb, Zn.

CHQ$_{ing}$, CHQ$_{inh}$, CHQ$_{derm}$, and the total hazard index (THI) were higher in children than in adults. THI value was detected as >1 in both children and adults. It was calculated as 6.15 for children and 1.20 for adults. Children exhibited greater non-carcinogenic risk than adults. Other researchers (Saleem et al. 2023; Parlak et al. 2024b; Tepanosyan et al. 2017) reported similar situations.

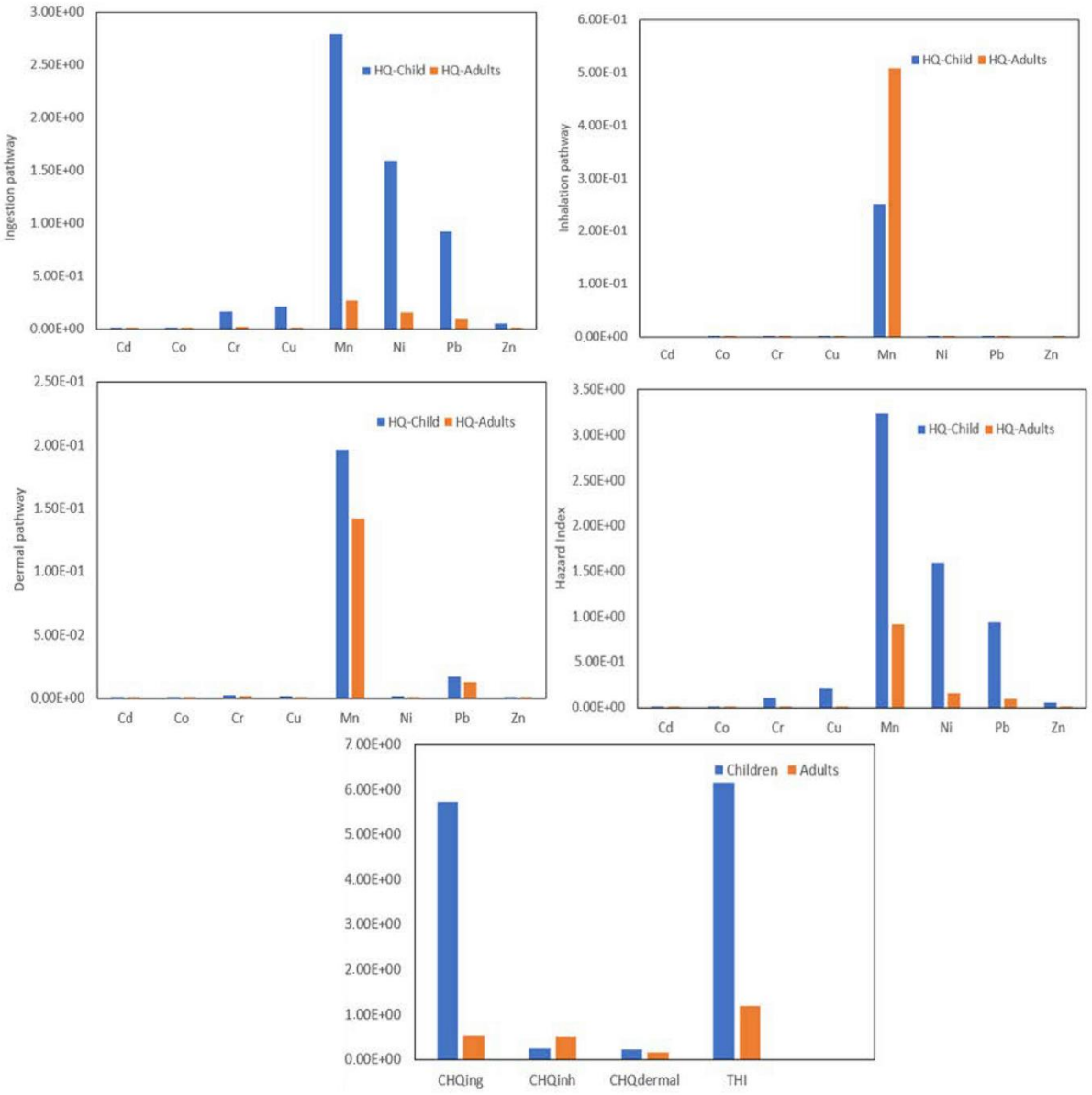


Figure 5- Calculated exposure values corresponding to non-carcinogenic risk for both adults and children within the study area

3.5.2. Carcinogenic risk

CR $_{ing}$ value in children was found to be high risk for Cr and Pb; CR $_{inh}$ value was negligible for Cd and Co, posed a health risk for Cr, and was within the permissible range for Ni and Pb; CR $_{der}$ value was found to be high risk for Cr, at an acceptable level for Pb (Table 7). TCR < 1×10^{-6} for Cd and Co; TCR > 1×10^{-4} for Cr and Pb; and TCR = 1×10^{-6}–1×10^{-4} for Ni. In adults, CR$_{ing}$ > 1×10^{-4} for Cr and Pb; CR$_{inh}$ < 1×10^{-6} for Cd, Co, > 1×10^{-4} for Cr, and 1×10^{-6}–1×10^{-4} for Ni, Pb; CR $_{derm}$ > 1×10^{-4} for Cr and 1×10^{-6}–1×10^{-4} for Pb. TCR < 1×10^{-6} for Cd, Co; TCR > 1×10^{-4} for Cr, Pb; TCR = 1×10^{-6}–1×10^{-4} for Ni.

In children, the CCR $_{ing}$ value constitutes 98.26% of the CTCR value, and in adults, the CCR $_{ing}$ value constitutes 81.30% of the CTCR value. This shows that the receptors are exposed to TMs in the soil, especially through the ingestion pathway. The findings of other researchers also support this conclusion (Adewumi & Ogundele 2024; Goncharov et al. 2024).

Table 7- Carcinogenic risks of TMs in soil samples in the study area

TMs	*Children*				*Adults*			
	CR $_{ing}$	*CR $_{inh}$*	*CR $_{der}$*	*TCR*	*CR $_{ingestion}$*	*CR $_{inhalation}$*	*CR $_{dermal}$*	*TCR*
Cd	-	7.68E-11	-	7.68E-11	-	1.55E-10	-	1.55E-10
Co	-	5.54E-10	-	5.54E-10	-	1.01E-08	-	1.01E-08
Cr	6.99E-01	2.05E-03	9.78E-03	7.11E-01	6.72E-02	4.15E-03	7.09E-03	7.84E-02
Ni	-	3.63E-06	-	3.63E-06	-	7.34E-06	-	7.34E-06
Pb	3.88E-02	1.08E-06	7.24E-04	3.95E-02	3.73E-03	2.18E-06	5.25E-04	4.26E-03
	CCR	CCR	CCR	*CTCR*	CCR	CCR	CCR	CTCR
	7.38E-01	*4.11E-04*	*1.05E-02*	*7.51E-01*	*7.09E-02*	*4.16E-03*	*7.62E-03*	*8.72E-02*

TM: Toxic Metal; CR, carcinogenic risk; CCR, cumulative CR; TCR, total CR; CTCR, cumulative TCR

While chromium poses a great threat to the health of people due to its high concentration all over the Biga district center, whereas lead burdens tend to rise with urbanization, industrial activity, and traffic emissions. Cr is not a problem for health when taken within the daily dose limits. However, inhalation of Cr is associated with nasal irritation/ulceration up to septal perforation and asthma exacerbations. In addition, it may also cause skin, kidney, liver, gastrointestinal tract, heart, lung cancer, and stomach cancer (Yerli et al. 2020; Parlak et al. 2023; Adewumi & Ogundele 2024). Lead is an important TM with metal features since ancient times but is highly damaging to human metabolism. There is no known safe blood lead level; absorbed Pb distributes via blood and accumulates in bone, with neurodevelopmental and renal toxicity. Pb exposure is associated with reduced fertility, low birth weight and preterm delivery, and in adults with cognitive impairment and hypertension.

4. Conclusions

In this comprehensive study, we used a statistical approach to evaluate TM accumulation in soils with different land uses in Biga, which is the largest district by population in Çanakkale (NW Türkiye), and provides baseline evidence and decision support regarding TM-related risks. The average concentrations of TMs in the soil (in mg kg^{-1}) are in the order of Co<Cr<Ni<Pb<Cu<Zn<Mn<Al<Fe. Al, Cr, Cu, Fe, Mn, Ni, Pb, and Zn concentrations in the soils in the study area were found to be higher than those of worldwide soils; Cd and Co concentrations were found to be lower than those of worldwide soils. The results obtained from EF, $I_{geo,}$ and CF evaluation indicate that there is excessive contamination for some TMs in the soils in the study area. The application of PLI, Er^1, RI, TRI, and TUs allowed the detection of TM pollution and the calculated indices show high ecological risk. Multivariate statistics results corroborated EF-based patterns: Factor 1 (Al, Cr, Fe, Mn, Cu) suggests geogenic control, while Factors 2–4 (Ni, Pb; Cd; Zn) likely reflect anthropogenic inputs. HQ, THI, and CR results show that children and adults living in the district face significant health risks associated with TMs in the soil. Our research has made significant contributions to understanding the TM dynamics in urban soils. However, in addition to the small number of samples in the study area, the inability to determine As and Hg concentrations that adversely affect human health is also an important limitation. Our research contributes to the literature in terms of evaluating the effects of TM accumulation on human health in urban soils in NW Türkiye. Research data constitute an important source for environmental monitoring and management. Local authorities should implement risk communication and targeted management actions informed by the hotspots identified. Future work should evaluate remediation options (e.g., phytoremediation, immobilization with biochar or Fe–Mn oxides, soil washing) and quantify source-control effectiveness. We also recommend longitudinal mapping and health-oriented exposure assessments.

Author Declarations

Authors' contributions: Concept: T.T., M.P., Design: T.T., M.P., Data collection: T.T., V.İ, M.P., Analysis: T.T., V.İ., M.P. Writing: T.T., V.İ, M.P.

Conflict of interest/Competing interests: The author(s) declare no conflict of interest.

Ethics approval/declarations: No need/ Not applicable.

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Consent to participate: No need/ Not applicable.

Consent for publication: No need/ Not applicable.

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