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ORIGINAL PAPER

Ecological and human health risk assessment of potential toxic elements in agricultural soils in Muğla Province, Türkiye

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Abstract Potential toxic elements (PTEs) pollution has become an important ecological and environmental concern in agricultural soil. The aim of this study was to determine the concentrations and potential sources, besides the evaluation of ecological, environmental, and human health risks of PTEs in agricultural soils of Muğla province of Türkiye. For this purpose, 234 soil samples were taken and analysed for total cadmium (Cd), cobalt (Co), chromium (Cr), nickel (Ni), lead (Pb), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn). The mean concentrations of Cd, Co, Cr, Ni, Pb, Cu, Fe, Mn, and Zn were 1.95, 34.64, 156.3, 368.0, 53.95, 43.64, 31,467, 917.6, and 67.96 mg kg^{-1}. Mean concentrations of Cd, Co, Cr, Ni, Pb, Cu, and Mn exceeded the upper continental crust, world soil average and European soil average values. Pollution indices of soils indicated serious pollution for Cd and Ni. Principal component analyses and Pearson correlation analysis indicated that Co, Cr, and Fe mainly originated from lithogenic sources, while Cd, Cu, Pb, Mn, and Zn originated from anthropogenic sources. Hazard index (HI) values of PTEs were < 1, suggesting that absent non-carcinogenic health risks to adult residents. In addition, the total carcinogenic risk (TCR) values except for Cr, suggest that carcinogenic risks for residents were not expected. Ingestion was the main pathway of carcinogenic and non-carcinogenic risk to human health. The results showed that children were more sensitive to the non-carcinogenic and carcinogenic effects of PTEs. Agrochemicals were identified as major sources of PTEs contamination in the study area.

Keywords Soil contamination · Pollution · Cadmium · Nickel · Türkiye

Introduction

Potential toxic elements (PTEs) contamination of soil has become a global issue. PTEs had above 5 g cm^{-3} density, including arsenic (As), cadmium (Cd), chromium (Cr), cobalt (Co), nickel (Ni), lead (Pb), zinc (Zn), and copper (Cu). Globally, about 10 million polluted sites cover about 49.42 million acres of land, including hazardous PTEs polluting more than half of the area (Kumar et al., 2019). These elements may enter soil from natural factors (parent material, the migration and redistribution of soil debris, volcanic

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eruptions etc.) or anthropogenic activities (Sellami et al., 2022). PTEs concentration in soil sourced from natural usually stable character and emerges with very slow mineralization. Generally, soils are contaminated with PTEs via industrialization, urbanization, coal combustion wastes and ash, mine tailing, release of petrochemicals, use of chemical fertilizers, organic manures, raw wastewater sludge, pesticides and wastewater irrigation (Öktüren Asri et al., 2024a). Concentrations of As, Cd, and Pb in potassium and nitrogen fertilizers are rather low, but phosphate rocks and their fertilizer blends (mono-ammonium phosphate (MAP), di-ammonium phosphate (DAP), triple superphosphate (TSP) and NPK blends) and micronutrient supplements may be contaminated with As, Cd, and Pb. Phosphorus fertilizers were responsible 45% of the total Cd contamination of cropland in Europe (Jiao et al., 2012), because more than 97% of Cd with chemical phosphorus fertilizer remained in the soil (Wiggenhauser et al., 2019). Concentrations of Cd, As, Pb of wheat-cultivated soils (Atafar et al., 2010) and Cu, Zn in potato-cultivated soils (Orellana Mendoza et al., 2024) increased with the use of fertilizers. Bawa (2023) explained that pesticide fumigation of crops caused an increase in soil PTE concentrations compared to no-fumigated soil. Yerli et al., (2025) found that cadmium and nickel concentrations in soil increased with full irrigation with wastewater.

The accumulation of potentially toxic elements (PTEs) in agricultural lands can result in soil contamination. These elements may also be taken up by plants and crops, entering the food chain and affecting food quality and safety. Peirovi Minaee et al. (2024) stated that the highest cancer risk contribution was attributed to As and Ni for children, teenagers and adults in both raisins and grape pekmez samples. Taghavi et al. (2024) stated that concentrations of Cr and Ni in 84.4% and 100% of the soil samples in pistachio orchards in Feizabad city, Iran, exceeded the WHO allowable limits. Human exposure to high levels of Cd may cause lung cancer, bone problems and kidney dysfunction. Acute Pb has negative effects on the hematopoietic, reproductive, and central nervous system. Cr exposure causes gastrointestinal problems, and high Ni exposure associates with bronchitis and asthma (Taghavi et al., 2023). Potential toxic element contamination in agricultural soils has drawn increasing public attention throughout the world due to human health effects. Identification of potentially toxic elements contamination in soil and determination of contamination sources is critical for the implementation of strategies to prevent soil pollution and ensure its safe utilization. Thus, studies on PTEs contamination of soils, especially in emerging countries such as Türkiye, China, Iran, Nigeria, Brazil and Bangladesh have increased since the 1980s (Öktüren Asri et al., 2024a; Yildiz & Ozkul, 2024). Moderate levels of Cu, Ni, and Pb contamination in soils from the Morigaon district of India were reported by Gogoi et al. (2024). Soleimani et al. (2024) found that agricultural soils around the Urmia Lake, Iran, were polluted with Ni and Pb due to truck transfer from Iran to Türkiye. Choudhury et al. (2025) stated that Cd was the most hazardous to the urban ecosystem in Dhaka, Bangladesh, because of the mainly vehicular emissions and industrial activities. Pollution index studies using PTE concentrations, pollution levels in agricultural soils and health risk assessment in Türkiye have been few, e.g., Baltas et al. (2020) discovered that the concentrations of soil Cr, Ni, Zn, As, and Pb in the Sivas province of Türkiye were significantly influenced by human activities. Parlak et al. (2023) found that the concentrations of potential toxic elements in agricultural soils in the Ezine, Çanakkale province, Türkiye were influenced by geological structure, agrochemicals and vehicle traffic. The researchers reported that soil Cr and Pb concentrations exceeded the acceptable risk range for children, and Cr exceeded the threshold for adults.

Muğla is the second most developed province in the Aegean region of Türkiye. Tourism and agriculture are the most important sectors in the province and these sectors are intertwined in the districts bordering the coast. Olive groves account for 40% of the province's agricultural land, while pomegranates, citrus fruits, wheat, maize and vegetables are also extensively cultivated (Anonymous, 2025). Pesticides, chemical and organic fertilizers, which can lead to the accumulation of metals in soils, are intensively used to increase yield and quality of crops. There have not been studies about concentrations of PTEs in agricultural soil of the province until today, but it is necessary to perform a comprehensive study for assessing environmental, ecological and human health risks. This study aims to investigate the concentrations and potential sources of toxic elements, to evaluate the

ecological risks of these elements and to assess both non-carcinogenic and carcinogenic health risks for local residents exposed to PTEs in soils.

Material and method

Study area

The Muğla province (37°1′ 49″ N, 28°30′23″ E) is located in the Aegean Region of Türkiye. The province covers an area of 12,654 km^2 and has 1,081.867 population. Muğla has 2,050 km^2 of agricultural land on which many varieties of vegetables (1,176.6 km^2, 855 tons), fruits (1,201.02 km^2, 679 tons), cereals (4,399 km^2, 139 tons) are grown which main crops are orange (226 tons), pomegranate (69 tons), olive (183 tons), tomato (628,0 tons), cucurbit (43 tons), eggplant (35 tons), wheat (80 tons) and potato (22 tons) (Anonymous, 2025). The province has a Mediterranean climate. The average annual air temperature and precipitation values recorded in the province are 14.1 °C and 1041 mm, respectively (MGM, 2025).

Soil sampling and chemical analysis

Soil samples were collected from 234 different agricultural lands in autumn 2017. These plots established grid points at 2.5 km × 2.5 km intervals. The sampling was carried out randomly from agricultural soils as far away from people's habitats as possible. Sample points were recorded using a handheld global positioning system and given in Fig. 1. Soil samples at each point were taken from 0 to 30 cm depth and obtained by mixing five random subsamples. Approximately 2 kg of soil was packed into a plastic bag for one sample and brought the laboratory. For analysis, soils were air-dried and sieved through a 2 mm and then a 0.5 mm. 0.05 mm sieved 0.5 g in dry weight soil sample was digested in 10 mL of HCl (37%, Merck, Germany) and HNO_3 (70%, Merck, Germany) (3:1) using a microwave digestion system (CEM MarsX5, USA) (Ateş et al., 2022). Solutions were passed through filter paper (Whatman, Grade 42, 2.5 µm) and completed to 50 mL with ultra-pure water (18 MΩ cm of resistivity) (TKA Ultra Pacific, Germany). Cd, Pb, Cr, Ni, Co, Fe, Zn, Mn and Cu concentrations of soils were determined by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES; Varian 720-ES; Agilent Technologies, Santa Clara, California, USA) (USEPA, 2007). Calibration standards were prepared by diluting a stock multi-element standard solution (1000 mg L^{-1}, Merck, Germany).

Quality assurance and control (QA/QC) conducted by certified reference materials (CRM) for soil (UME EnvCRM03, Ankara, Türkiye). CRM was digested and analyzed in every 10 soil samples. The LOQs of Cd, Cu, Cr, Pb, Co, Fe, Mn, Ni and Zn were 0.03, 0.004, 0.004, 0.005, 0.007, 0.004, 0.02, 0.003, and 0.015 mg kg^{-1}, respectively (Table S1). The recovery values were in 92–101% range as Cd (97%), Cu (100%), Cr (95%), Pb (97%), Co 92(%), Fe (94%,) Mn (101%), Ni (93%) and Zn (96%). All analyses were performed in two replicates. The relative deviation of replicated samples was within ± 5.

Evaluation of environmental risks

Enrichment factor (EF) is used to distinguish between anthropogenic and natural sources of potential toxic elements (Hakanson, 1980). EF is calculated by Eq. 1.

$$\mathrm{EF} = \frac{sample\left(\frac{C_i}{C_{Fe}}\right)}{backround(Ci/CFe)} \quad (1)$$

C_i is the concentration of metal in soil and C_{ref} is the concentration of reference metal in Eq. 1. There are no local geochemical background values in this study. Thus, as a background of potential toxic elements, upper continental crust (UCC) values were used Fe as a reference element in this study, due to its low variability in soils (Rudnick & Gao, 2003). EF is classified into five levels: minimal (EF < 2), moderate (2 ≤ EF < 5), significant (5 ≤ EF < 20), very high (20 ≤ EF < 40), and extremely high (EF ≥ 40) enrichment (Ateş et al., 2022).

The geo-accumulation index (I_{geo}) is used to determine and classify the level of PTE contamination in the soil (Müller, 1981). Geo-accumulation index (I_{geo}) is calculated using Eq. 2. C_i is the concentration of metals in soil and C_n is the background geochemical value of the element (Varol et al., 2021).

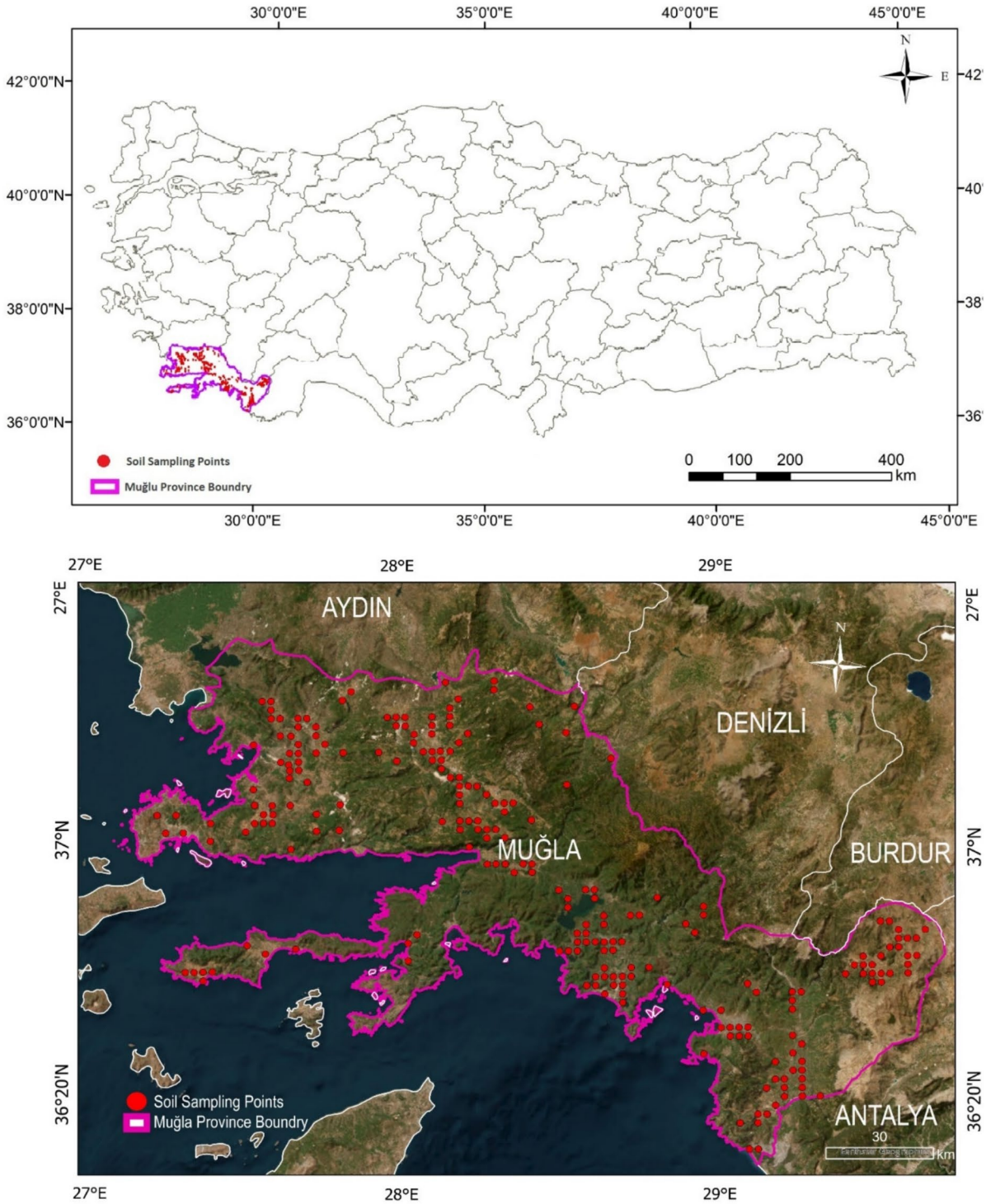


Fig. 1 Location and soil sampling pattern maps of the study area

$$\text{Igeo} = \frac{\log_2 Ci}{1.5xCn} \quad (2)$$

I_{geo} is classified as unpolluted ($I_{geo} \leq 0$), unpolluted to moderately polluted ($0 < I_{geo} \leq 1$), moderately polluted ($1 \leq I_{geo} < 2$), moderately to heavily polluted ($2 \leq I_{geo} < 3$), heavily polluted ($3 \leq I_{geo} < 4$) (Varol et al., 2021).

Contamination factor (CF) is used to assess the contamination degree of each potential toxic element in soil (Hakanson, 1980). CF is calculated by Eq. 3. *Ci* is the concentration (mg kg^{-1}) of the potential toxic elements in each soil sample and C_n is the background concentration of the metal (Hakanson, 1980). C_n is the background (or pre-industrial) reference level (in mg kg^{-1}): 0.09 for Cd, 17.3 for Co, 92 for Cr, Ni for 47, Pb for 17, Zn for 67, Mn for 774 and 39,200 for Fe. The contamination levels are divided into four classes: low ($CF < 1$), moderate ($1 \leq CF < 3$), considerable ($3 \leq CF < 6$), and very high ($CF \geq 6$) (Hakanson, 1980).

$$\text{CF} = \frac{\text{Ci}}{\text{Cn}} \quad (3)$$

Pollution load index (PLI) integrates CF values of all the potential toxic elements and allows the assessment of overall soil pollution at each sample point. It is calculated by each metal's CF value (Eq. 4) (Hakanson, 1980). $PLI < 1$ indicates a good quality of the site, $PLI = 1$ indicates the presence of only baseline levels of pollutants, and $PLI > 1$ indicates a progressive deterioration in the quality of the site (Hakanson, 1980).

$$\text{PLI} = (\text{Cf1} \times \text{Cf2} \times \ldots \times \text{Cfn})^{1/\text{n}} \quad (4)$$

The Nemerow pollution index (NPI) can be used to estimate the total contamination level of potential toxic elements in soil. NPI is calculated by Eq. 5. The NPI is classified as unpolluted ($NPI \leq 0.7$), warning line of pollution ($0.7 < NPI \leq 1$), low polluted ($1 < NPI \leq 2$), moderately polluted ($2 < NPI \leq 3$) and strongly polluted ($NPI > 3$) (Deliboran et al., 2024).

$$\text{NPI} = \sqrt{\frac{(\text{CFmean})^2 + (\text{CFmax})^2}{2}} \quad (5)$$

Evaluation of ecological risks

Potential ecological risk factor (ER) determines the degree of ecological risk caused by a single metal in the soil. The potential ecological risk index (RI) determines the degree of ecological risk caused by multi-metals in the soil. ER and RI are calculated by Eq. 6 and 7. Tr_i denotes the biological toxicity factor and is defined as 30, 5, 5, 2 and 1 for Cd, Cu, Pb, Cr and Zn, respectively (Hakanson, 1980).

$$\text{ER} = \text{T}_{\text{ri}} \text{ x } \text{CF}_{\text{i}} \quad (6)$$

$$RI = \sum_{i=1}^{n} ER \quad (7)$$

ER was classified as low ($ER < 40$), moderate ($40 \leq ER < 80$), noticeable ($80 \leq ER < 160$), high ($160 \leq ER < 320$), or major ($ER \geq 320$) risk (Hakanson, 1980). RI is classified as low risk ($RI < 150$), moderate risk ($150 < RI < 300$), considerable risk ($300 < RI < 600$), and very high risk ($RI > 600$) (Hakanson, 1980).

Human health risk assessment

Humans are exposed to HMs through ingestion, dermal, and inhalation exposure pathways for soil. Hazard quotients (HQs) were used to estimate non-carcinogenic risks of the 11 HMs (Eq. 8, 9, 10) (USEPA, 2019). An HQ or Hazard index (HI; sum of $HQ_{ingestion}$, HQ_{dermal} and $HQ_{inhalation}$) value greater than one adds to the health risk associated with non-cancer risk (Varol et al., 2021).

Non-carcinogenic risks:

$$HQ_{ingestion} = \frac{CsxIRS \text{ x}RBAxEfxED}{BWxATxRfDox10^6} \quad (8)$$

$$HQ_{inhalation} = \frac{C_s xEfxED}{ATxRfCxPEF} \quad (9)$$

$$HQ_{dermal} = \frac{C_s xSAxAFxABSdxEfxED}{BWxATxRfDoxGIABSx10^6} \quad (10)$$

Carcinogenic risks (CRs) based on carcinogenic slope and inhalation unit risk factors are calculated for As, Cr, Co, Ni and Cd (Eq. 11, 12, 13) (USEPA, 2019). All terms in these equations were presented in

Tables S2 and S3. Hazard index (HI) and total carcinogenic risk (TCR) values are estimated by Eq. 14 and 15. When the CR of the carcinogen is less than 1×10^{-6}, the risk of developing cancer is minor and can be disregarded. However, cancer may result in CR values $>1\times10^{-4}$ (Varol et al., 2021).

Carcinogenic risks:

$$CR_{ingestion} = \frac{(Cs\ \mathrm{x}IFS\mathrm{x}RBA\mathrm{x}CSFo)}{\left(AT\mathrm{x}10^{6}\right)} \quad (11)$$

$$IFS = \frac{Ef\mathrm{x}EDa\mathrm{x}IRSa}{(BWa) + (Ef\ \mathrm{x}EDc\mathrm{x}IRSc)/(BWc)}$$

$$CR_{dermal} = \frac{(Cs\mathrm{x}DFS\mathrm{x}\ ABSd\mathrm{x}CSFo)}{\left(AT\mathrm{x}GIABS\mathrm{x}10^{6}\right)} \quad (12)$$

$$DFS = (Ef\mathrm{x}EDa\mathrm{x}SAa\mathrm{x}AFa)/(Ef\mathrm{x}EDc\mathrm{x}SAc\mathrm{x}AFc)/(BWc)$$

$$CR_{inhalation} = (Cs\mathrm{x}Ef\mathrm{x}ED\mathrm{x}IUR\mathrm{x}1000)/(AT\mathrm{x}PEF) \quad (13)$$

$$HI = HQ_{ing} + HQ_{inh} + HQ_{der} \quad (14)$$

$$TCR = CR_{ingestion} + CR_{dermal} + CR_{inhalation} \quad (15)$$

Statistical analysis

Pearson correlation analysis was performed to determine the relationships among PTEs ($p<0.05$). Bartlett's sphericity and Kaiser–Meyer–Olkin (KMO) tests were employed to determine the suitability of the data for principal component analysis (PCA). PCA was conducted to identify potential sources of PTEs. All statistical analyses were made in SPSS 27.0 (SPSS Inc., Chicago, Illinois, USA).

Results and discussion

Potential toxic elements (PTEs) in soil

Some descriptive statistics of PTEs in the agricultural soils of Muğla were presented in Table 1. The mean concentrations of PTEs followed the order of Fe > Mn > Ni > Cr > Zn > Pb > Cu > Co > Cd (Table 1). Mean concentrations of Cd, Co, Cr, Ni, Pb, Cu and Mn were higher than the world soil average (WSA), European soil (ESA) and upper continental crust (UCC) values. Among PTEs, only the mean concentration of Cr and Ni was higher 1.6 and 4.9 times than the Türkiye Soil Pollution Control Regulation (SPCR) (SPCR, 2005)

Table 1 Descriptive statistics of the concentrations of potential toxic elements and comparison regulation (unit in mg kg^{-1})

	Cd	Co	Cr	Ni	Pb	Cu	Fe	Mn	Zn	References
Minimum	0.43	3.24	5.0	8.20	6.54	12.88	6305	132.0	0.53	Present study
Maximum	5.43	137.0	1111.5	2478	159.4	183.5	83,877	2640	244.1	Present study
Median	1.78	26.07	91.82	136.2	50.05	41.82	31,303	834.0	65.11	Present study
Mean	1.95	34.64	156.3	368.0	53.95	43.64	31,467	917.6	67.96	Present study
Standart deviation	0.86	26.38	163.8	498.4	26.02	17.95	12,359	477.5	28.33	Present study
CV	43.96	76.15	104.8	135.4	48.22	41.12	39.28	52.03	41.68	Present study
WSA[a]	0.41	11.3	59.5	29	27	38.9	–	488	70	Kabata Pendias (2010)
ESA[b]	0.28	10.4	94.8	37	32	17.3	–	524	68.1	Kabata Pendias (2010)
UCC[c]	0.09	17.3	92	47	17	28	39,200	774	67	Kabata Pendias (2010)
SPCR[d]	–	–	100	75	300	140	–	–	300	Kabata Pendias (2010)
İzmir province, Türkiye	0.18	7.58	44.9	37.9	8.85	19.1	15,821	352	34.9	Deliboran et al. (2024)
Uşak province, Türkiye	–	–	–	265.3	15.9	17.3	–	596	–	Yildiz and Özkul (2024)
Antalya province, Türkiye	4.54	23.92	94.00	145.8	64.68	44.91	28,264	763.3	63.67	Öktüren Asri et al. (2024a)
Hamedan, Iran	0.53	–	78.4	63.3	33.7	71.1	–	–	88.0	Akbarimorad et al. (2025)
Campania, Italy	0.40	12.5	24.0	22.0	59.9	86.0	–	–	103.6	Zuzolo et al. (2020)

[a]WSA: Word soil average values, [b]ESA: European soil average values, [c]UCC: Upper continental crust values, [d]SPCR: Soil Pollution Control Regulation

Mean concentrations of studied PTEs were compared to those in agricultural soils of different regions in Türkiye (Table 1). All of the PTEs in this study had concentrations above those in soils from İzmir province, Türkiye (Deliboran et al., 2024). Ni, Pb, Cu and Mn concentrations of soils in this current study were above compared to Uşak province soils of Türkiye (Yildiz & Özkul, 2024). Co, Cr, Ni, Fe, Mn and Zn concentrations of fruit orchard soils in Antalya province of Türkiye were lower than this study soils while concentrations of Cd, Pb and Cu were higher (Öktüren Asri et al., 2024a). In addition, mean concentrations of PTEs in this study were compared to those in agricultural soils of other countries (Table 1). Cd, Cr, and Ni concentrations of soils in the study area were higher than those of Hamedan district soils of Iran (Akbarimorad et al., 2025) and Campania district of Italy (Zuzolo et al., 2020), while Zn and Cu concentrations were below. These different PTE concentrations may result from the heterogeneity of the parent material, natural mineral weathering, and anthropogenic activities (Öktüren Asri et al., 2024b).

Elements dominated by a natural source are expected to have low CVs, while those affected by anthropogenic sources and with high non-homogeneity typically exhibit high CVs (Öktüren Asri et al., 2024b). The coefficient of variations (CV) of Ni, Cr, Co, Mn, Pb, Cd, Zn, Cu, and Fe were 135.4%, 104.8%, 76.15%, 52.03%, 48.22%, 43.96%, 41.68%, 41.12%, and 39.28% (Table 1), indicating that the spatial distribution of PTEs in soil was not only affected by the geological background but also by human activities.

Soil contamination indices

The enrichment factor (EF), geo-accumulation index (I_{geo}), contamination factor (CF), pollution load index (PLI), potential ecological risk factor (ER) and potential ecological risk index (RI) values were given in Fig. 2. The EF allows assessment of the degree of intensity of anthropogenic activities. The EF values decreased in the following order Cd (27.89) > Ni (8.03) > Pb (4.05) > Co (2.37) > Cu (2.13) > Cr (1.86) > Mn (1.51) > Zn (1.37) > Fe (1.0) (Fig. 2). Results of the EF of Cr, Mn, Zn and Fe showed no enrichment (< 2). Cu, Co and Pb showed moderate enrichment ($2 \le EF < 5$), Ni indicated significant enrichment ($5 \le EF < 20$) and the results of Cd represented high enrichment ($20 \le EF < 40$) (Rudnick & Gao, 2003).

The geo-accumulation Index (I_{geo}) is a widely used index to verify the magnitude of the contamination of an individual element. The order of mean I_{geo} values was Cd (3.72) > Ni (1.17) > Pb (0.89) > Co (0.05) > Cu (−0.03) > Cr (−0.50) > Mn (−0.55) > Zn (−0.70) > Fe (−1.02) (Fig. 2). The results of the I_{geo} for Cu, Cr, Mn, Zn, and Fe indicated particularly uncontaminated ($I_{geo} \le 0$), Pb and Co showed unpolluted to moderately polluted ($0 \le I_{geo} < 1$) and Ni indicated moderately polluted ($1 \le I_{geo} < 2$) and Cd demonstrated heavily polluted. Contamination Factor (CF) is used to assess the level of soil contamination and to infer anthropogenic inputs from natural inputs (Hakanson, 1980). The order of mean CF values was Cd (21.7) > Ni (7.83) > Pb (3.17) > Co (2.0) > Cr (1.70) > Cu (1.56) > Mn (1.19) > Zn (1.01) > Fe (0.80). According to CF values of soils had low contamination (CF < 1) in Fe, moderate contamination ($1 \le CF < 3$) in Co, Cr, Cu, Mn and Zn, considerable contamination ($3 \le CF < 6$) in Pb, very high contamination ($CF \ge 6$) in Cd and Ni. The CF of Cd ranged from 4.78 to 60.33, and 99% of the samples were classified as very high contamination.

The pollution load index (PLI) provides the level of metal pollution. PLI values ranged from 0.35 to 6.82, and the mean value was 2.16. 87% of the soils had PLI > 1, indicating that soil in the study area were seriously PTEs polluted. Yıldız and Özkul (2024) reported that 75% of agricultural soils of Uşak province in Türkiye had moderately multi-metal contamination. Nemerow pollution index (NPI) values for Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb and Zn were 45, 5.77, 8.62, 4.76, 1.61, 2.55, 37.69, 7.0 and 2.67, respectively, with a mean of 12.85. The mean NPI showed strong pollution (NPI > 3).

Potential ecological risk factor (ER) indicates the concept of single metal pollution (Hakanson, 1980). The mean ER values of Zn (1.01), Cr (3.40), Cu (7.79), Pb (15.87) and Ni (39.15) (Fig. 2) were less than 40, indicating that had low ecological risk. ER values of Cd ranged from 143.3 to 1810 and 93% of the sampling areas indicated a major risk ($ER \ge 320$). Potential ecological risk index (RI) values of PTEs ranged from 154 to 2061, with a mean of 718. 57% of sample sites indicated considerable ($300 < RI < 600$) and 38% of very high potential risk (RI > 600) for PTEs. Cd alone accounted for 91% of the overall

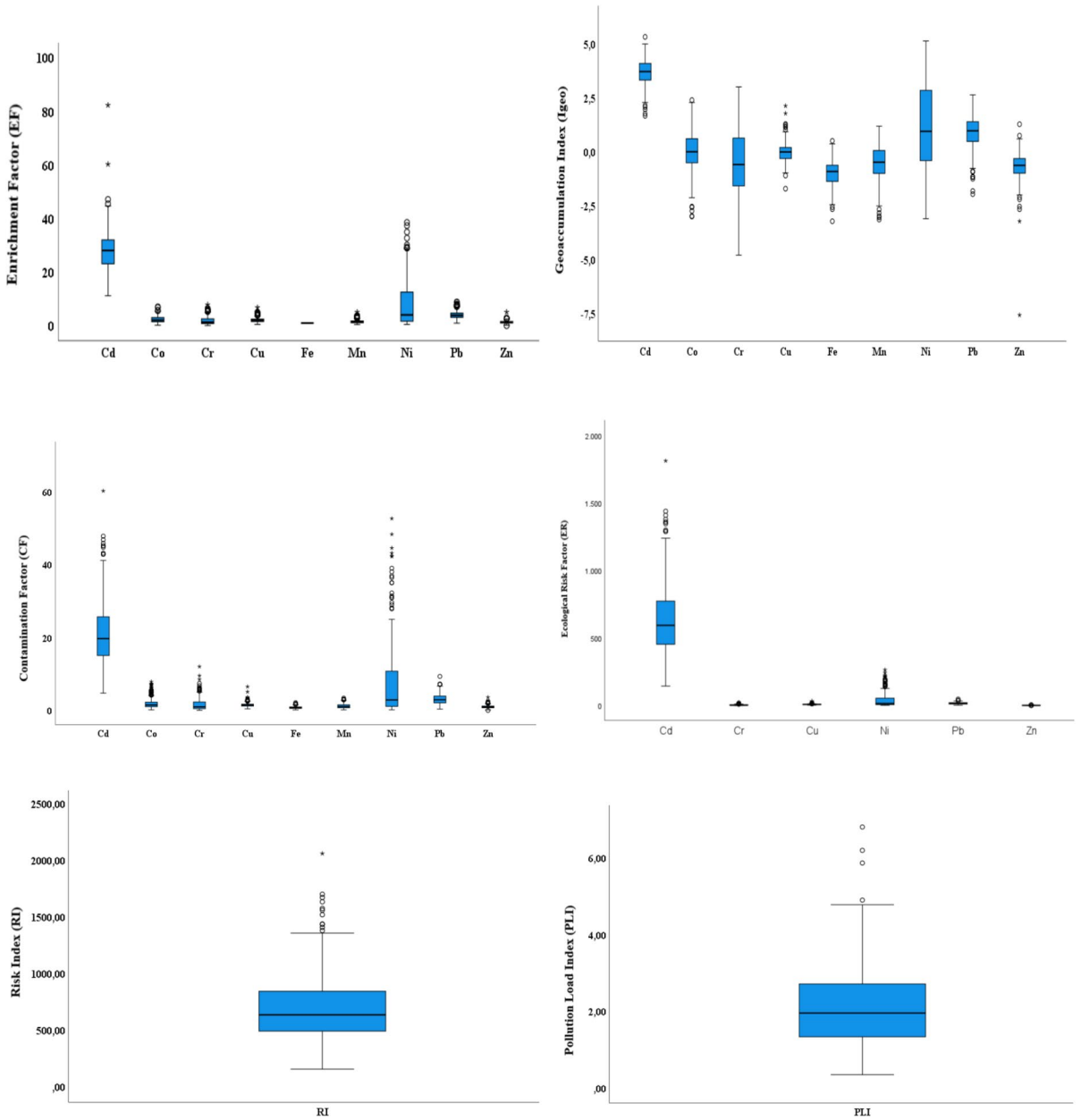


Fig. 2 Enrichment factor (EF), geo-accumulation index (I_{geo}), contamination factor (CF), ecological risk factor (ER), risk index (RI), and pollution load index (PLI) values of the analysed PTEs in agricultural soils

potential ecological risk. All pollution indices in this study indicate heavy pollution in the region due to Cd. Cadmium has two major sources: one is natural, and the other is anthropogenic. Anthropogenic sources include industrial waste from factories, i.e., the manufacture of plastics, batteries containing Cd, mining, electroplating, alloy preparation, paint pigments and composts or fertilisers (Kabata Pendias, 2010). For agricultural lands, studies have revealed that Cd in soil can generally be found as a result of intensive use of agrochemicals (Öktüren Asri et al., 2024a; Taşpınar et al., 2022; Varol et al., 2021).

The relationships between PTEs in soils of the research area were determined by Pearson correlation

analysis. The strong significant correlation indicates that the metals have the same geological origin and the role of weathering parent material in controlling metal concentration in soils (Öktüren Asri et al., 2024b). The strongest correlations (>0.75) were found between Ni and Co (r = 0.89), Ni and Cr (r = 0.88), Co and Cr (r = 0.83), Fe and Cd (r = 0.78) (Fig. 3). A positive correlation was found between Fe and Cr, Co, and Ni due to the high affinity of these elements with Fe-oxides in the soil. Moreover, the Fe concentrations were directly related to the oxides, hydroxides and oxyhydroxides of the soils (Frierdich et al., 2011).

Kaiser–Meyer–Olkin (KMO) index was 0.85 > 0.60 ($p < 0.001$), indicating suitability for principal component analysis (PCA). The PCA produced two principal components, whose eigenvalues were > 1, explaining 68.72% of the total variance (Table 2). The first factor (PC1) had a characteristic root of 5.25 and contributed 38.12%. PC1 was influenced by Co, Cr, Fe and Ni. There was a strong positive correlation between these PTEs (Fig. 3). Mean Co, Cr and Ni concentrations exceeded the WSA, UCC and ESA values. The mean concentrations Cr and Ni were about 1.56 and 4.91 times higher than their corresponding limit values in SPCR. The mean EF and CF values for Ni showed significant enrichment ($5 \le EF < 20$) and very high contamination ($CF \ge 6$), suggesting anthropogenic sources. But ultramafic soils are highly enriched in Ni, Cr and Co, which are siderophile elements. Many studies

Table 2 Principal component analysis of potential toxic elements

	PC1	PC2
Cd	0.46	**0.69**
Co	**0.88**	0.33
Cr	**0.88**	0.23
Cu	0.04	**0.63**
Fe	**0.60**	0.63
Mn	0.36	**0.44**
Ni	**0.96**	0.12
Pb	0.44	**0.74**
Zn	0.12	**0.74**
Eigenvalues	5.25	1.49
% of variance	38.12	30.60
Cumulative %	38.12	68.72

Bold values represent strong and moderate loadings

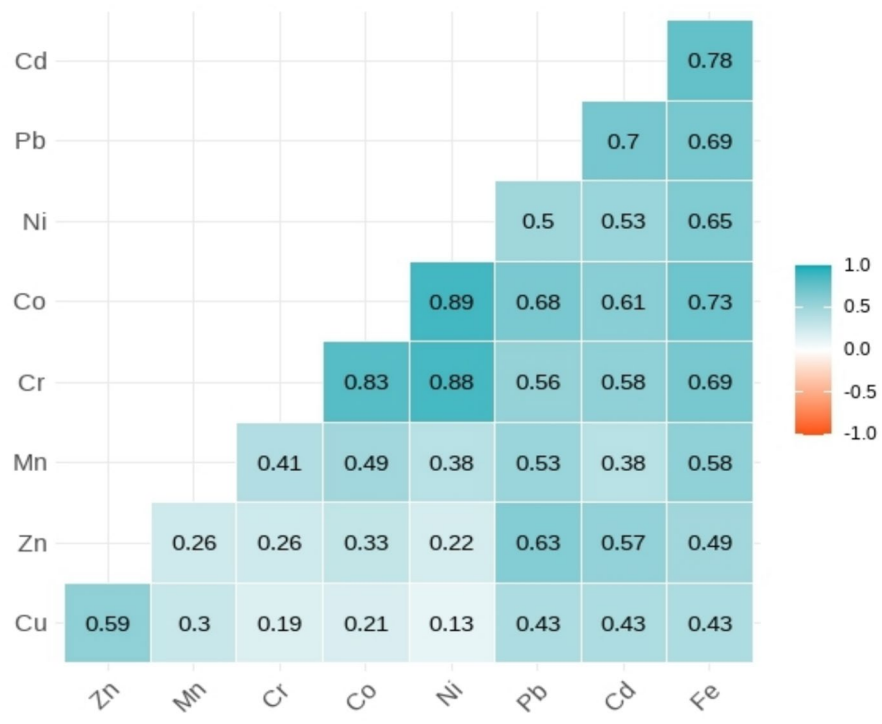


Fig. 3 Pearson correlation analysis of potential toxic elements

reported that Türkiye soils contained high concentrations of these elements and originated from natural sources (Ateş et al., 2022; Öktüren Asri et al., 2024a; Taşpınar et al., 2022). Considering all these results together reveals that nickel had both lithogenic and anthropogenic origins. It concluded that PC1 was mainly related to lithogenic sources.

The second factor (PC2) had a characteristic root of 1.49, contributing 30.60%, and was primarily influenced by Cd, Cu, Pb, Mn and Zn. The mean concentrations of Cd, Cu and Pb exceeded the WSA, ESA and UCC values, but the mean Zn concentration exceeded only the UCC value. The EF values indicated minimal enrichment ($EF < 2$) for Zn, moderate enrichment ($2 \leq EF < 5$) for Pb and Cu, and high enrichment ($20 \leq EF < 40$) for Cd. The mean I_{geo} values showed no pollution ($I_{geo} < 0$) for Cu and Zn. Pb was classified as unpolluted to moderately polluted ($0 \leq I_{geo} < 1$), and Cd as highly polluted ($3 \leq I_{geo} < 4$). The CF values showed considerable Pb ($3 \leq CF < 6$) and high contamination for Cd ($CF \geq 6$). Zhuang et al. (2020) reported that the long-term application of blended fertilizers (30% animal manure and 70% phosphate fertilizers) or animal manure could increase Cd pollution risk. Su et al. (2022) reported that traffic discharges in the farmland caused an increase in Pb and Cd concentrations of soils, and Zn and Cu concentrations were increased with organic fertilizers. Kabata Pendias (2010) reported that Cd concentration in soil was mainly based on phosphate fertilisers and traffic activities such as emissions from lubricating oil and brake pads and vehicle tire were main sources of. Akbarimorad et al. (2025) stated that Cu concentration in soil was resulted from the traffic emissions (releasing from brake and tire wear), copper-based agrochemicals and organic fertilisers. Besides agricultural applications, Laha et al. (2024) reported that PTEs detected in the soil result from atmospheric deposition from small-scale metallurgical industries, coal and oil combustion, municipal waste incineration, and fugitive emissions from road dust. Soleimani et al. (2024) reported that agricultural soils around the Urmia Lake, Iran, polluted with PTEs due to truck transfer. For these reasons, the second component was primarily associated with anthropogenic sources, such as fertilisers and atmospheric deposition.

Health risk assessment indices

Human health risk assessment is the process of assessing the nature and possibility of adverse health effects in humans who may be exposed to chemicals in polluted environmental media. The hazard quotient (HQ), cumulative hazard quotient (CHQ; sum of all HQs), hazard index (HI; sum of $HQ_{ingestion}$, HQ_{dermal} and $HQ_{inhalation}$) and total hazard index (THI; sum of all HIs) values calculated with equations for adults and children are given in Fig. 4. The hazard quotient (HQ) values for ingestion, dermal and inhalation pathways followed the order of Co > Cr > Fe > Pb > Mn > Ni > Cu > Zn > Cd. HQ values for adults and children decreased in order of $HQ_{ingestion} > HQ_{dermal} > HQ_{inhalation}$. $HQ_{ingestion}$ values accounted for 99% of THI for children and adults. The HQ values of PTEs except for Co in children were lower than the acceptable non-carcinogenic risk level of 1 (Fig. 4). HQ_{Co}, HQ_{Cr}, HQ_{Fe} and HQ_{Pb} contributed to the HI for adults by 36.90%, 16.65%, 14.36%, and 12.32%, respectively, accounting for more than 80.23% of the total contribution. Therefore, Co, Cr, Fe and Pb were the main contributors to the HI in the study area.

Cumulative hazard quotient results for the ingestion pathway were 4.0 for children and 0.429 for adults, while CHQ values for dermal contact and inhalation routes were 0.0095 and 0.00011 for children and 0.0018 and 0.00006 for adults, respectively. These values were below the risk threshold (less than 1) except for ingestion by children. Thus, there was no expected to non-carcinogenic health due to PTEs exposure, except for ingestion by children. Previous studies also suggested that ingestion emerged as the primary pathway for children PTEs exposure (Laha et al., 2024; Öktüren Asri et al., 2024a; Yan et al., 2021). In this study, the hazard index (HI) values of all PTEs for both children and adults were below the risk threshold. All PTEs for children were higher than those for adults. The total hazard index (THI) value for children (4.01) was higher than the acceptable non-carcinogenic risk threshold, but the adult value (0.43) was lower than this threshold. THI value for children was 9.3 times higher than that for adults. This result demonstrated that children were more prone to non-carcinogenic health risks than adults. Similar findings were reported by Varol et al. (2021), Taşpınar et al. (2022) and Öktüren Asri et al. (2024a).

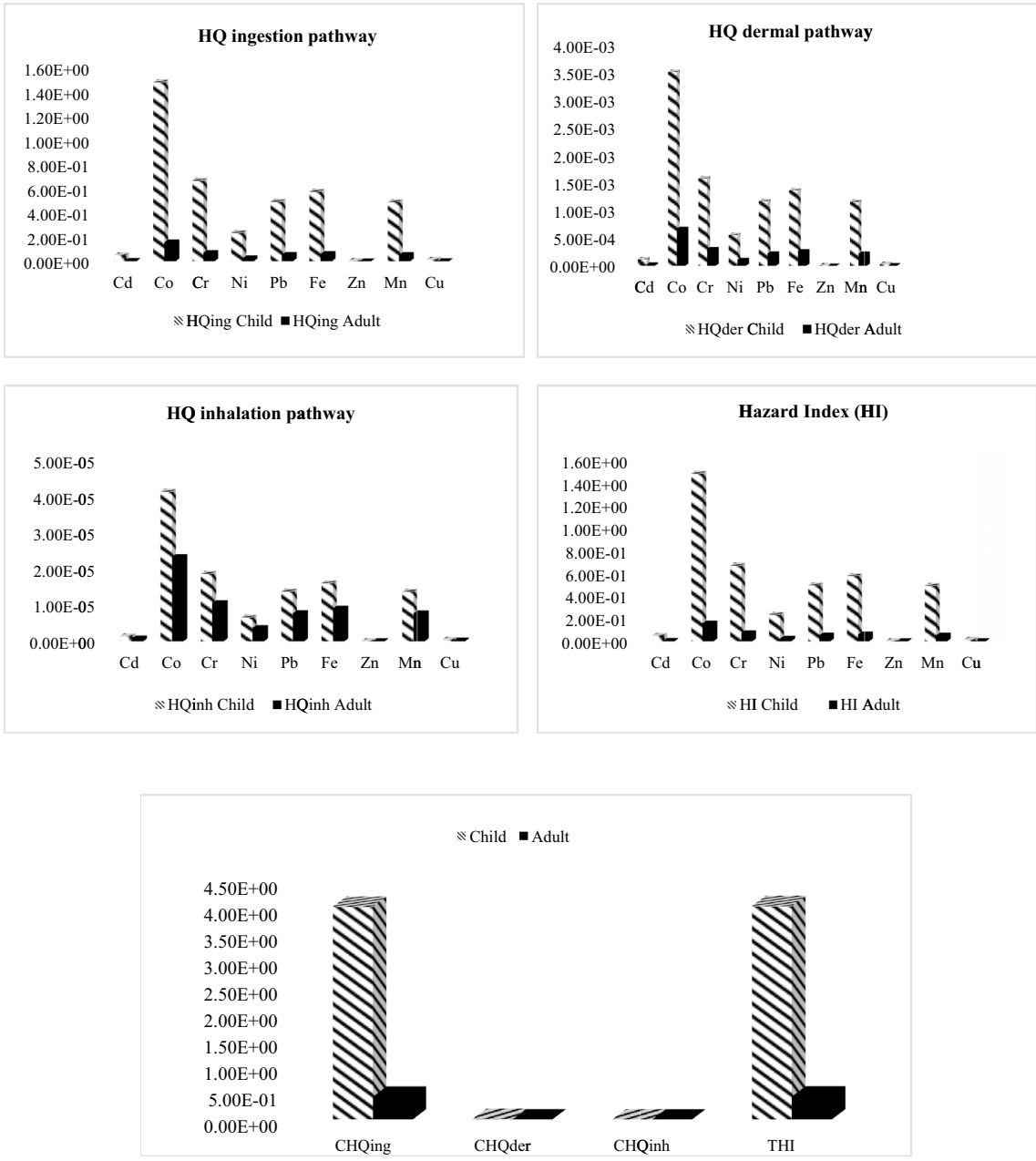


Fig. 4 Non-carcinogenic health risks of potential toxic elements for residents via ingestion, dermal contact, and inhalation (HQ, hazard quotient; CHQ, cumulative HQ; HI, hazard index; THI, total HI)

The reason can be explained by the fact that children are at higher risk due to their behavioral patterns such as they are highly likely to engage in hand- to- mouth behavior and play habits. As their systems are still developing, it makes then very sensitive to the toxicity of metals (Shetty et al., 2024).

The carcinogenic risk (CR) values of Cd, Co, Cr and Ni through ingestion, dermal and inhalation pathways and these elements' total carcinogenic risk (TCR) values are given in Table 3. If the TCR is less than 1×10^{-6}, it means the potential carcinogenic health caused by PTEs exposure can be negligible.

Table 3 Carcinogenic health risks of potential toxic elements for residential receptors

	$CR_{ingestion}$	CR_{dermal}	$CR_{inhalation}$	TCR
Carcinogenic risks				
Cd	–	–	2.06E−10	2.06E−10
Co	–	–	1.93E−09	1.93E−09
Cr	1.90E−06	9.19E-07	8.44E−08	2.90E−06
Ni			2.22E−10	2.22E−10
	CCR	CCR	CCR	CTCR
	1.90E−06	9.19E−07	8.68E−08	2.90E−06

CR, carcinogenic risk; CCR, cumulative CR; TCR, total CR; CTCR, cumulative TCR

Except for Cr, total carcinogenic risk values of these PTEs are within or below the acceptable risk range. These results revealed that carcinogenic health risks from exposure to Cd, Co, and Ni in the soils of the study region are not expected for residents.

The cumulative carcinogenic risk (CCR) values for three exposure pathways followed the order of $CCR_{ingestion} > CCR_{dermal} > CCR_{inhalation}$, that is consistent with previous investigations (Öktüren Asri, 2025; Öktüren Asri et al., 2024b; Varol et al., 2021). The $CCR_{ingestion}$ value was 2.1 and 21.9 times higher than CCR_{dermal} and $CCR_{inhalation}$ values, respectively. The $CCR_{ingestion}$, CCR_{dermal} and $CCR_{inhalation}$ accounted for 65.3%, 31.7% and 3.0% of the cumulative TCR value, respectively. Chromium was the main contributor to the CTCR through ingestion contact, with the highest contributions of 65.5%. Öktüren Asri et al. (2024b) and Varol et al. (2021) reported that carcinogenic risk via ingestion of Cr was above than the acceptable risk threshold. There are quite limited data from human studies about adverse health effects from oral exposure to Cr (Sun et al., 2015). Cr ingestion can cause nasosinusal, dermatitis, gastrointestinal symptoms, hypotension, liver and kidney failure (Alvarez et al., 2021).

Soil Cr concentration in this study is mainly originates from parent material, but anthropogenic activities such as agronomic applications may contribute. As is known, phosphorus (P) is one of the most important essential elements for plants and phosphorus fertilizers is manufactured by using sulphuric and phosphoric acids. During the processing, phosphorus fertilizers are contaminated with Cd, Cr and Pb (Ahmad & Ansari, 2022). The long-term use of phosphorus fertilisers may lead to Cd, Cr and Ni accumulation in the soil (Nadarajan and Sukumann, 2021). Therefore, the potential toxic element contents of fertilizers and pesticides applied to crops on agricultural land in the study area should be monitored through analysis and the amount and type of agrochemicals used by the producers should be limited.

Conclusions

Potential toxic element pollution of agricultural soils is one of the most important concerns for living organisms health and food safety. Concentrations of Cd, Co, Cr, Pb and Ni in soil were 4.8, 3.1, 2.6, 2 and 12.7 times higher than world soil average values. Principal component analyses and Pearson correlation analysis indicated that Co, Cr, Fe and Ni were mainly originated from lithogenic sources, while Cd, Cu, Pb, Mn and Zn were anthropogenic sources. Mean EF, I_{geo}, CF, PLI, ER and RI values indicated that the research area soils were polluted with mainly Cd. Hazard index value showed that children was more sensitive than adults. The HQ values of PTEs except for Co in children were lower than the acceptable non-carcinogenic risk level of 1. Except for Cr, the total carcinogenic risk values of these PTEs within or below the acceptable risk range. Ingestion was the main PTEs exposure pathway for non-carcinogenic and carcinogenic health risks. Main anthropogenic sources of PTEs in the research area were fertilisers and pesticides. Therefore, excessive use of fertilisers and pesticides should be limited for the prevention of soil contamination. The results of the study may be valuable for researchers in environmental quality and human health risk assessment, and the methods applied can also be used for contamination

assessment in other environments in agricultural areas where agro-chemicals are intensively used.

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Author contribution Işıl Demirtaş, Nuri Arı, Cevdet Fehmi Özkan, Memiş Ensar Ertürk, Murat Şimşek, Ömer Özbek, Filiz Öktüren Asri and Dilek Güven collected the soil samples. Işıl Demirtaş, Filiz Öktüren Asri and Murat Şimşek performed heavy metal analysis of the samples by ICP-OES. Nuri çağlayan analyzed the data. Filiz Öktüren Asri completed data interpretation and drafted the manuscript. All authors read and approved the final manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

References

Ahmad, I., & Ansari, T. M. (2022). Occurrence and translocation of heavy metals in phosphate ores and fertilisers by GFAAS. *International Journal of Environmental Analytical Chemistry, 102*(1), 196–221. https://doi.org/10.1080/03067319.2020.1720008

Akbarimorad, S., Bolonio Martin, D., & Sobhan Ardakani, S. (2025). Concentrations, source identification and environmental risk assessment of potentially hazardous elements in agricultural soils of Hamedan, west of Iran. *International Journal of Environmental Analytical Chemistry, 105*(11), 2649–2663. https://doi.org/10.1080/03067319.2024.2328762

Alvarez, C. C., Bravo Gómez, M. E., & Hernandez Zavala, A. (2021). Hexavalent chromium: Regulation and health effects. *Journal of Trace Elements in Medicine and Biology, 65*, Article 126729. https://doi.org/10.1016/j.jtemb.2021.126729

Anonymous. (2025). *Republic of Türkiye Ministry of Agriculture and Forestry Directorate of Muğla*. Retrieved May 28, 2025)https://www.tarimorman.gov.tr/TRGM/TARYAT/Belgeler/il_yatirim_rehberleri/mugla.pdf

Atafar, Z., Mesdaghinia, A., Nouri, J., Homaee, M., Yunesian, M., Ahmadimoghaddam, M., & Mahvi, A. H. (2010). Effect of fertilizer application on soil heavy metal concentration. *Environmental Monitoring and Assessment, 160*, 83–89. https://doi.org/10.1007/s10661-008-0659-x

Ateş, Ö., Taşpınar, K., Yalçın, G., Kızılaslan, F., Pınar, M. Ö., Toprak, S., Alveroğlu, V., Yavuz, R., & Özen, D. (2022). Ecological and contamination assessment of soil in the region of coal-fired thermal power plant. *International Journal of Environmental Health Research, 33*(12), 1558–1567. https://doi.org/10.1080/09603123.2022.2108384

Baltas, H., Sirin, M., Gökbayrak, E., & Özçelik, A. E. (2020). A case study on pollution and a human health risk assessment of heavy metals in agricultural soils around Sinop province, Turkey. *Chemosphere, 241*, Article 125015. https://doi.org/10.1016/j.chemosphere.2019.125015

Bawa, U. (2023). Heavy metals concentration in food crops irrigated with pesticides and their associated human health risks in Paki, Kaduna State, Nigeria. *Cogent Food & Agriculture*. https://doi.org/10.1080/23311932.2023.2191889

Choudhury, T. R., Ahshan, T., Alam, M. N. E., Sowrav, S. F. F., Rahman, S. M. M., Rahman, M. S., & Rahman, Md. M. (2025). Heavy metal in roadside dust, soil and perennial plants of Dhaka mega south city corporation, Bangladesh: Accumulation characteristics, sources and risk factors. *Environmental Pollution and Management, 2*, 271–285. https://doi.org/10.1016/j.epm.2025.08.001

Deliboran, A., Varol, M., & Aytop, H. (2024). Evaluation of ecological and health risks of trace elements in soils of olive orchards and apportionment of their sources using the APCS-MLR receptor model. *Environmental Geochemistry and Health, 46*, 320. https://doi.org/10.1007/s10653-024-02108-x

Frierdich, A. J., Hasenmueller, E. A., & Catalano, J. G. (2011). Composition and structure of nanocrystalline Fe and Mn oxide cave deposits: Implications for trace element mobility in karst systems. *Chemical Geology, 284*(1–2), 82–96. https://doi.org/10.1016/j.chemgeo.2011.02.009

Gogoi, N., Sarma, A., Choudhury, M., Samanta, P., Faizan, M., & Sadhak, S. (2024). Soil heavy metal pollution and ecological risk assessment in disturbed and undisturbed soil of Morigaon, Assam. *Discover Environment, 2*(1), Article 13. https://doi.org/10.1007/s44274-024-00039-z

Hakanson, L. (1980). An ecological risk index for aquatic pollution control, a sedimentological approach. *Water Research, 14*(8), 975–1001. https://doi.org/10.1016/0043-1354(80)90143-8

Jiao, W., Chen, W., Chang, A. C., & Page, A. L. (2012). Environmental risks of trace elements associated with long-term phosphate fertilizers applications: A review. *Environmental Pollution, 168*, 44–53. https://doi.org/10.1016/j.envpol.2012.03.052

Kabata Pendias, A. (2010). *Trace elements in soils and plants.* (4th ed., pp. 28–534). CRC Press.

Kumar, S., Prasad, S., Yadav, K. K., Shrivastava, M., Gupta, N., Nagar, S., Bach, Q. V., Kamyab, H., Khan, S. A., Yadav, S., & Malav, L. C. (2019). Hazardous heavy metals contamination of vegetables and food chain: Role of sustainable remediation approaches- A review. *Environmental Research, 179*, Article 108792. https://doi.org/10.1016/j.envres.2019.108792

Laha, T., Gupta, N., Pal, M., Koley, A., Masto, R. E., Hoque, R. R., & Balachandran, S. (2024). Chemical speciation and health risk assessment of potentially toxic elements in playground soil of bell metal commercial town of Eastern India. *Environmental Geochemistry and Health, 46*, 453. https://doi.org/10.1007/s10653-024-02240-8

MGM. (2025). *Republic of Türkiye Ministry Of Environment, Urbanisation and Climate Change, General Directorate of Meteorology*. Retrieved June 10, 2025, www.mgm.gov.tr

Müller, G. (1981). Die Schwermetallbelastung der sedimente des Neckars und seiner Nebenflusse: Eine Bestandsaufnahme. *Chemiker-Zeitung, 105*, 157–164.

Nadarajan, S., & Sukumaran, S. (2021). Chemistry and toxicology behind chemical fertilizers. In F.B. Lewu, T. Volova., S, Thomas., & K. R. Rakhimol (Eds.), *Controlled release fertilizers for sustainable agriculture* (pp. 195–229). Academic press

Öktüren Asri, F., Demirtaş, E.I., Şimşek, M., Ertürk, M.E., Özkan, C.F., Arı, N., Özbek, Ö., & Güven, D. (2024b). Heavy metal contamination and human health risk assessment in the soils grown field crops in Antalya, Türkiye. *International Journal of Environmental Analytical Chemistry*. https://doi.org/10.1080/03067319.2024.2383339

Öktüren Asri, F. (2025). Ecological and human health risk assessment of heavy metals in agricultural soils of Acıpayam Plain, Denizli, Türkiye. *Soil and Sediment Contamination: An International Journal*. https://doi.org/10.1080/15320383.2025.2557453

Öktüren Asri, F., Demirtaş, E. I., Şimşek, M., Ertürk, M. E., Arı, N., Özkan, C. F., Güven, D., & Özbek, Ö. (2024a). Potential ecological and human health risk assessments of soil heavy metals in orchards of Antalya province in Türkiye. *International Journal of Environmental Analytical Chemistry*. https://doi.org/10.1080/03067319.2024.2355267

Orellana Mendoza, E., Camel, V., Yallico, L., Quispe Coquil, V., & Cosme, R. (2024). Effect of fertilization on the accumulation and health risk for heavy metals in native Andean potatoes in the highlands of Perú. *Toxicology Reports, 12*, 594–606. https://doi.org/10.1016/j.toxrep.2024.05.006

Parlak, M., Everest, T., & Tunçay, T. (2023). Spatial distribution of heavy metals in soils around cement factory and health risk assessment: A case study of Canakkale-Ezine (NW Turkey). *Environmental Geochemistry and Health, 45*, 5163–5179. https://doi.org/10.1007/s10653-023-01578-9

Peirovi Minaee, R., Alami, A., Esmaeili, F., & Zarei, A. (2024). Analysis of trace elements in processed products of grapes and potential health risk assessment. *Environmental Science and Pollution Research, 31*(16), 24051–24063. https://doi.org/10.1007/s11356-024-32654-x

Rudnick, R.L., & Gao, S. (2003). Composition of the continental crust. In D. Heinrich, H.D. Holland, K.K. Turekian (Eds.), *Treatise on geochemistry, pergamon* (pp. 1–64). https://doi.org/10.1016/B0-08-043751-6/03016-4

Sellami, S., Zeghouan, O., Dhahri, F., Mechi, L., Moussaoui, Y., & Kebabi, B. (2022). Assessment of heavy metal pollution in urban and peri-urban soil of Setif city (High plains, eastern Algeria). *Environmental Monitoring and Assessment, 194*, 126. https://doi.org/10.1007/s10661-022-09781-4

Shetty, B. R., Pai, B. J., Salmataj, S. A., & Naik, N. (2024). Assessment of carcinogenic and non-carcinogenic risk indices of heavy metal exposure in different age groups using Monte Carlo simulation approach. *Scientific Reports, 14*, 30319. https://doi.org/10.1038/s41598-024-81109-3

Soleimani, A., Toolabi, A., Mansour, S. N., Abdolahnejad, A., Akther, T., Fouladi Fard, R., Miri, M., & Mohammadi, A. (2024). Health risk assessment and spatial trend of metals in settled dust of surrounding areas of Lake Urmia, NW Iran. *International Journal of Environmental Analytical Chemistry, 104*(5), 1172–1185. https://doi.org/10.1080/03067319.2022.2032013

SPCR. (2005). *Soil pollution control regulation*, (p. 25831.) Republic of Türkiye Ministry of Environment and Forestry.

Su, H., Hu, Y., Wang, L., Yu, H., Li, B., & Liu, J. (2022). Source apportionment and geographic distribution of heavy metals and as in soils and vegetables using kriging interpolation and positive matrix factorization analysis. *International Journal of Environmental Research and Public Health, 19*(1), 485. https://doi.org/10.3390/ijerph19010485

Sun, H., Brocato, J., & Costa, M. (2015). Oral chromium exposure and toxicity. *Current Environmental Health Reports, 2*, 295–303. https://doi.org/10.1007/s40572-015-0054-z

Taghavi, M., Bakhshi, K., Zarei, A., Hoseinzadeh, E., & Gholizadeh, A. (2024). Soil pollution indices and health risk assessment of metal(loid)s in the agricultural soil of pistachio orchards. *Scientific Reports, 14*, 8971. https://doi.org/10.1038/s41598-024-59450-4

Taghavi, M., Darvishiyan, M., Momeni, M., Eslami, H., Fallahzadeh, R. A., & Zarei, A. (2023). Ecological risk assessment of trace elements (TEs) pollution and human health risk exposure in agricultural soils used for saffron cultivation. *Scientific Reports, 13*, Article 4556. https://doi.org/10.1038/s41598-023-31681-x

Taşpınar, K., Ateş, Ö., Pınar, M. Ö., Yalçın, G., Kızılaslan, F., & Fidantemiz, Y. F. (2022). Soil contamination assessment and potential sources of heavy metals of alpu plain Eskişehir Turkey. *International Journal of Environmental Health Research, 32*(6), 1282–1290. https://doi.org/10.1080/09603123.2021.1876218

USEPA. (2007). Method. 3051 A, Microwave assisted acid digestion of sediments, sludges, soils and oils. Retrived June 18, 2025 from https://www.epa.gov

USEPA. (2019). Regional screening levels (RSLs)–user's guide. Retrived June 18, 2025 from https://www.epa.gov

Varol, M., Gündüz, K., & Sünbül, M. R. (2021). Pollution status, potential sources and health risk assessment of arsenic and trace metals in agricultural soils: A case study in Malatya province, Turkey. *Environmental Research, 202*, Article 111806. https://doi.org/10.1016/j.envres.2021.111806

Wiggenhauser, M., Bigalke, M., Imseng, M., Keller, A., Rehkämper, M., Wilcke, W., & Frossard, E. (2019). Using isotopes to trace freshly applied cadmium through mineral phosphorus fertilization in soil-fertilizer-plant systems. *Science of the Total Environment, 648*, 779–786. https://doi.org/10.1016/j.scitotenv.2018.08.127

Yan, L., Franco, A. M., & Elio, P. (2021). Health risk assessment via ingestion and inhalation of soil PTE of an urban area. *Chemosphere, 271*, Article 130964. https://doi.org/10.1016/j.chemosphere.2021.130964

Yerli, C., Sahin, U., Oztas, T., & Ors, S. (2025). Fertility and heavy metal pollution in silage maize soil irrigated with different levels of recycled wastewater under conventional and no-tillage practices. *Irrigation Science, 43*, 221–238. https://doi.org/10.1007/s00271-024-00927-5

Yildiz, Ü., & Özkul, C. (2024). Heavy metal contamination and ecological risks in agricultural soils of Uşak, western Türkiye: A geostatistical and multivariate analysis. *Environmental Geochemistry and Health, 46*, 58. https://doi.org/10.1007/s10653-024-01856-0

Zhuang, Z., Mu, H., Fu, P., Wan, Y., Yu, Y., Wang, Q., & Li, H. (2020). Accumulation of potentially toxic elements in agricultural soil and scenario analysis of cadmium inputs by fertilization: A case study in Quzhou county. *Journal of Environmental Management, 269*, Article 110797. https://doi.org/10.1016/j.jenvman.2020.110797

Zuzolo, D., Cicchella, D., Lima, A., Guagliardi, I., Cerino, P., Pizzolante, A., Thiombane, M., De Vivo, B., & Albanese, S. (2020). Potentially toxic elements in soils of Campania region (Southern Italy): Combining raw and compositional data. *Journal of Geochemical Exploration, 213*, Article 106524. https://doi.org/10.1016/j.gexplo.2020.106524

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