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Research Article

ASSESSMENT OF ELEMENTAL COMPOSITION IN ULTRAMAFIC PARENT MATERIAL AND DERIVED SOILS USING POLLUTION INDICES

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ABSTRACT

The occurrence of heavy metals in agricultural areas, whether due to natural processes or human activities, poses significant risks to both the ecosystem and public health through their incorporation into the food chain *via* plants. This study aimed to evaluate the concentrations of metals and the pollution risk levels in ultramafic soils within Kahramanmaraş and its surrounding districts (Türkoğlu, Ekinözü, Afşin) in the Eastern Mediterranean region. A total of 56 samples, consisting of 28 surface soil samples (0 cm-30 cm) and 28 parent material samples (90+ cm), were collected from these areas. Various pollution indices, including the Enrichment Factor (EF), Geoaccumulation Index (Igeo), Pollution Load Index (PLI) and Contamination Factor (CF), were utilized to assess both natural and human-induced impacts on the ultramafic soils. The findings indicated that the concentrations of Ni, Cr and Co in the topsoil layer (0 cm-30 cm) exceeded the maximum limits established by the World Health Organization. Despite this, the pollution indices (EF, Igeo, PLI and CF) for these elements were relatively low, suggesting a similar composition between the parent material and the soil. This points to the natural occurrence of these heavy metals in the soil. On the other hand, the pollution indices for Pb and Cu indicated human-related influences on these elements. Additionally, there was no significant enrichment of Mn or Cd from either natural or human sources. Environmental hazards such as erosion and dusting are common in areas affected by pollution, whether natural or anthropogenic. To address these issues, specific management practices are necessary, such as reducing soil disturbance in polluted agricultural zones or maintaining permanent vegetation cover to stabilize the soil.

INTRODUCTION

Soil contamination by heavy metals poses a substantial risk to the environment and agricultural productivity. These metals can come from human activities or natural sources. In soils derived from ultramafic rocks, heavy metal pollution is generally of natural origin.

Ultramafic rocks consist of ferromagnesian-rich minerals associated with ophiolite suites, formed through the hydrothermal alteration of peridotites at tectonic convergent plate margins. These rocks, particularly serpentinites, are characterized by very high levels of magnesium (18%-24%) and iron (6%-9%), but very low levels of calcium (1%-4%) and aluminum (1%-2%) (Alexander 2004). Ultramafic rocks have a naturally elevated geochemical background, especially for chromium (Cr), Cobalt (Co) and Nickel (Ni), Brooks 1987.

The pedogenic processes and types of soil that form during the weathering of ultramafic rocks are largely influenced by climatic conditions Kierczak et al., 2007.

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Ultramafic soils, which develop on peridotite (such as dunite, harzburgite, lherzolite and werlite) or serpentinite (such as olivine, pyroxene and serpentine) parent materials are notably rich in Nickel (Ni), Cobalt (Co), Chromium (Cr), Manganese (Mn) and Iron (Fe), but are deficient in essential plant nutrients like Phosphorus (P), Potassium (K) and Calcium (Ca) Hseu et al., 2007. These soils also have low Ca/Mg ratios and are prone to erosion Bani et al. 2014.

High concentrations of heavy metals in ultramafic soils pose significant environmental risks and can adversely affect human health Galey et al., 2017. These elevated heavy metal levels can also harm certain plant species, animals, microorganisms and overall environmental quality Kara et al., 2018. Due to their unique physical and chemical properties, ultramafic soils can negatively impact agricultural productivity, product quality, the environment and human health Fernandez et al., 1999. Even at low concentrations, heavy metals in soils can have detrimental effects on humans, animals and plants Oze et al. 2008.

Identifying the levels of heavy metals in ultramafic soils and implementing suitable conservation strategies in these regions are significant for safeguarding both the environment and human well-being Kazakou et al. 2008.

There are several indices (such as the enrichment factor, pollution load index, contamination factor and geo-accumulation index) used to determine whether pollution in agricultural soils is of natural or anthropogenic origin Kumar et al., 2013. Typically, studies utilize reference background values for these indices Shah et al., 2013. However, soil exhibits a heterogeneous structure, with various properties that can change seasonally and different physical and chemical characteristics even within a small area Duivenvoorden et al., 2017. This variability has raised concerns among some scientists about the reliance on reference background values in pollution index calculations Yakupoğlu et al. 2018.

Considering these discussions, reference background values were not used to determine the heavy metal accumulation in ultramafic soils found in Kahramanmaraş and its districts, Kara 2019. Selecting background values from different regions or countries would not be appropriate Saltalı et al., 2022. Therefore, soil samples from both the upper depth (0 cm-30 cm) and lower depth (90+ cm) were collected from the study area Saltali et al., 2023. The lower depth samples were physically fragmented rock forms that visually resembled the upper depth soils, Kara et al. 2023.

The aim of this study was to determine the heavy metal concentrations in ultramafic parent materials and soils derived from these materials in Kahramanmaraş and its surrounding districts (Türkoğlu, Afşin, Ekinözü) in the Eastern Mediterranean region Kara et al., 2024. Additionally, an environmental risk assessment for these areas will be conducted using various pollution indices (EF, CF, Igeo and PLI) Vithanage et al. 2014.

MATERIALS AND METHODS

Study area

The study area includes Kahramanmaraş, which consists of nine districts: Andırın, Çağlayancerit, Ekinözü, Elbistan, Göksun, Nurhak, Pazarcık, Türkoğlu and Afşin Kaprara et al., 2015. Covering an area of 14,525 square kilometers and hosting a population of 1,089,038, it ranks as the 11th largest province in Turkey Kuppusamy et al., 2016. Kahramanmaraş is uniquely positioned at the convergence of three geographical regions: The Mediterranean Region, the Eastern Anatolia Region and the Southeastern Anatolia Region Antoniadis et al., 2017. This location influences its climate, which typically exhibits mediterranean characteristics, such as small temperature variations between day and night, mild and rainy winters and hot, dry summers McClain et al., 2017 and Vithanage et al., 2019. However, moving northward towards districts like Afşin and Ekinözü, the increase in elevation leads to a distinctly continental climate Robertson et al., 1980; Mertens et al., 2006 and Sagbara et al., 2020. In Kahramanmaraş, the diversity of climates (in terms of precipitation and temperature), parent materials and topographic forms results in a variety of soil types Elizabeth Rani et al., 2021 and Rajendran et al., 2022. These include red mediterranean soils, reddish-brown mediterranean soils, alluvial soils, basaltic soils, chestnut soils, decalcified brown forest soils, decalcified brown soils, colluvial soils, brown soils, reddish-brown soils, brown forest soils and hydromorphic and organic soils Hu et al. 2019.

This study focused on examining the ultramafic parent material and the soils derived from it in Kahramanmaraş and its surrounding districts (Türkoğlu, Afşin and Ekinözü) Zhang et al., 2012. Using a geological map, ultramafic rocks and the resulting soils were identified Cao et al., 2022 and Kafle et al., 2022. A total of 56 samples were collected from these specified areas, including 28 topsoil samples (0 cm-30 cm) and 28 parent material samples (90+ cm), selected through random sampling methods. The GPS coordinates of the sampling locations were recorded using a GPS device and are shown in Figure 1 on the Google Earth map Mavakala et al., 2022 and Yılmaz et al. 2022.

The geology of Kahramanmaraş and Districts (Türkoğlu, Ekinözü, Afşin)

The ophiolitic units in the Ekinözü and Afşin regions, located in the northern part of Kahramanmaraş and in the Türkoğlu region in the Southern part, which are the focus of this study, consist of facies that belong to different units compared to the typical Turkish ophiolitic rocks Soil Survey Staff 2014.

The northernmost ophiolitic units north of Afşin are primarily represented by serpentinized tectonites and are situated in the western part of the Southeastern Anatolian ophiolite belt (Reimann et al., 2005; Githaiga et al., 2021 and Aytop et al., 2023). These ophiolites are an extension of the Late Cretaceous Kömürhan ophiolite, which features a complete ophiolite sequence in the east (Gökmenoğlu et al., 2019). The ophiolitic units around the Ekinözü district are part of the Berit metaophiolite and are distinct from other ophiolites due to their intense metamorphism. In this area, ultramafic rocks include both cumulates and tectonites, with the tectonitic ultramafic rocks being notable for their significant serpentinization and alteration (Perinçek et al., 1984). In the Türkoğlu district in Southern Kahramanmaraş, the ophiolitic rocks are mostly serpentinized tectonites containing podiform chromite mineralization and, at times, ultramafic cumulates. These ophiolitic rocks, located at the forefront of the Arabian continent ophiolites, are correlated with the Koçali complex in the east and the Kizildag and Troodos ophiolites in the southeast (Tanirli et al., 2016). In the Türkoğlu area, where crustal rocks are also present, mantle rocks are generally predominant.

Assessment of pollution risk

Currently, several methodologies are used to evaluate soil pollution levels. In this study, the Enrichment Factor (EF), Geoaccumulation Index (Igeo), Pollution Load Index (PLI) and Contamination Factor (CF) were applied to measure the extent of soil pollution. These indices are commonly used to assess the presence and intensity of anthropogenic pollutant accumulation in surface soils. The elemental compositions of both the upper soil layer (0 cm-30 cm) and the parent material (90+ cm) were used to calculate these pollution indices as shown in Table 1.

Enrichment Factor (EF): The enrichment factor serves as an indicator of the natural and/or anthropogenic origins of metal pollution in soils (Wu et al., 2018). Iron (Fe) was utilized as the reference metal in this analysis. The enrichment factor was computed using the following formula (Sutherland et al. 2000).

$$ET = \frac{\left(\frac{Metal}{Fe}\right)Soil}{\left(\frac{Metal}{Fe}\right)\text{ParentMaterial}} \quad ....(1)$$

Geoaccumulation Index (Igeo): The geoaccumulation index, a pollution index, was used to evaluate the soil pollution level. The geoaccumulation index of the soils was calculated with the formula stated below (Müller et al. 1969).

$$Igeo = \frac{log2(Cn)}{(1,5*Bn)} \quad ....(2)$$

- Cn: Concentration of the metal in the soil samples.
- Bn: Concentration of metal in parent material samples.

Contamination Factor (CF): The CF value of each metal was calculated according to equation 3 (Hakanson et al. 1980).

$$CF = \frac{(Metal)\,Soil}{(Metal)\,ParentMaterial} \quad ....(3)$$

Pollution Load Index (PLI): The Pollution Load Index (PLI) of the soils was calculated according to equation 4 (Tomlinson et al., 1980). This index is an important factor in proving that soil conditions deteriorate as a result of the accumulation of heavy metals (Varol et al. 2011).

$$PLI = \sqrt[n]{CF1*CF2*CF3*........CFn} \quad ....(4)$$

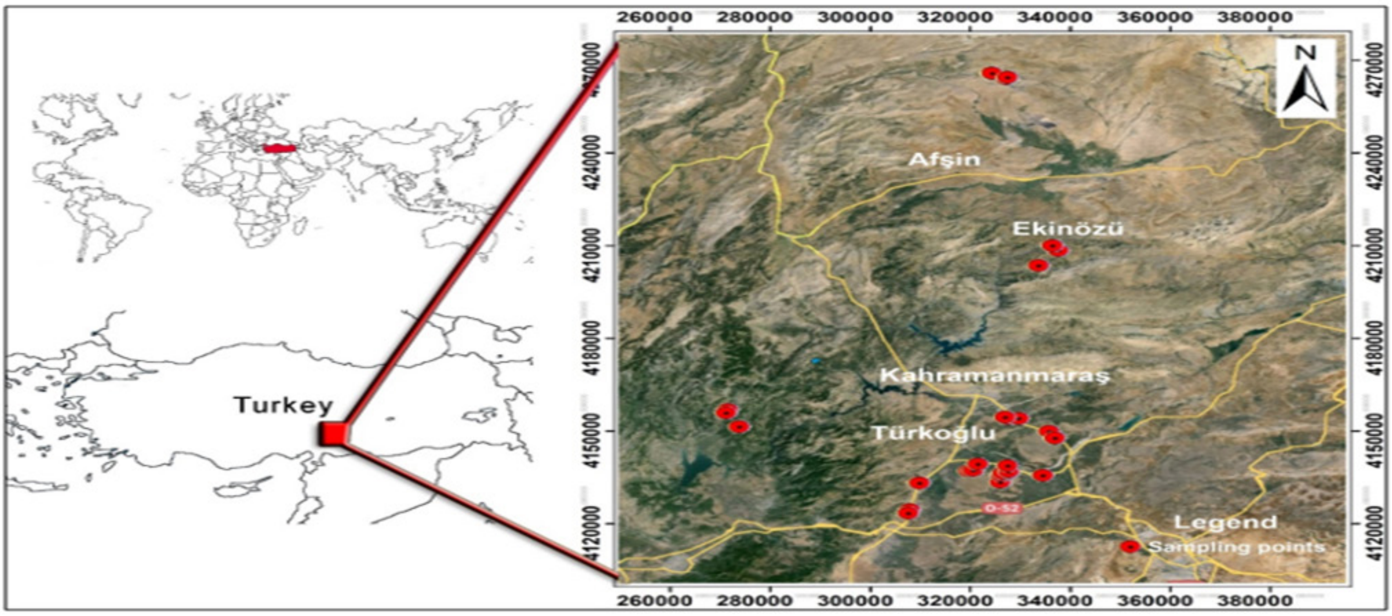

Fig. 1 View of the study area in Google Earth.

Table 1. Classification of pollution indices (EF, Igeo, PLI, CF).

Index	Range of indices	Soil conditions	References
Enrichment Factor (EF)	EF<2	Deficiency to minimal enrichment	Sutherland et al. (2000)
	2<EF<5	Moderate enrichment	
	5<EF<20	Significant enrichment	
	20<EF<40	Very high enrichment	
	EF>40	Extremely high enrichment	
Geoaccumulation Index (Igeo)	Igeo<0	Unpolluted	Müller et al. (1969)
	0<Igeo<1	Unpolluted to moderately polluted	
	1<Igeo<2	Moderately polluted	
	2<Igeo<3	Moderately to strongly polluted	
	3<Igeo<4	Strongly polluted	
	4<Igeo<5	Strongly to extremely polluted	
	5>Igeo	Extremely high polluted	
Pollution Load Index (PLI)	PLI<1	There is no pollution	Varol et al. (2011)
	PLI>1	There is pollution	
Contamination Factor (CF)	CF<1	Low contamination factor	Hakanson et al. (1980)
	1<CF<3	Moderately contaminated factor	
	3<CF<6	Considerably contaminated factor	
	CF>6	Very high contaminated factor	

Soil chemical characterization

The total major elemental (SiO_2, Al_2O_3, MgO, CaO, P_2O_5, K_2O and Na_2O) analysis of samples (both soil and parent material) collected from the study area were conducted at the Ankara University Earth Sciences Application and Research Center (YEBİM). Initially, the samples were pulverized and then 4 g of the ground samples along with 0.9 g of binder material were weighed and thoroughly mixed. Subsequently, they were compressed using a hydraulic press to form press lozenges. Once prepared, the major elemental content of the samples was determined utilizing an X-Ray Fluorescence Spectrometer (XRF) device. Certified reference material (LGC6187) was used when determining the major element contents of the samples.

Minor element (Fe, Cr, Mn, Co, Ni, Cu, Cd and Pb) concentrations of the samples were determined in YEBİM. Soil and parent material samples were placed in a mortar and pulverized. The powdered samples were passed through a 0.05 mm sieve and 0.1 g of each sample was placed in a microwave tube. Ten milliliters of royal water solution obtained from a mixture of HCl and HNO_3 in a 1:1 ratio was added and burned in a microwave oven (CEM MARS-6). These processes were carried out in 3 replicates for each soil and parent material sample. The clear liquids obtained after the wet digestion process were filtered through 50 ml volumetric flasks with Whatman filter paper. Then, the volumetric flasks were filled to the required volume with ultrapure water. Minor element concentrations of the samples were determined on an Agilent 5100 ICP-OES device Certified reference material (LGC6187) was used when determining the minor element contents of the samples. Certified reference material was obtained from Kahramanmaraş Agricultural Research Institute Directorate. In addition, pollution index values were calculated by averaging the results obtained for each element (Cr, Mn, Co, Ni, Cu, Cd and Pb).

Statistical evaluation

Descriptive statistics and Pearson correlation analysis were applied to the data from both parent material and soil samples. Additionally, Principal Component Analysis (PCA), a multivariate statistical method, was used to illustrate relationships among the data from the upper soil layer. IBM SPSS Statistics 22.0 software was employed for the statistical evaluation of the data.

RESULTS AND DISCUSSION

Table 2 presents the total elemental compositions of the ultramafic soil (0 cm-30 cm depth) and the parent material (90+ cm depth). The bedrock composition is typical of serpentinite, consisting of 40% SiO_2, 33.6% MgO, 5.99% Fe, 0.24% Ni, 0.86% CaO and 0.17% Al_2O_3. The Ni concentration in the bedrock was 0.27%, showing no significant variation among the soils but a notable difference compared to the serpentine in the bedrock, which had 0.3% Ni, indicating signs of weathering.

The Silicon Oxide (SiO_2) content in the soil ranged from 23.31% to 51.07%, averaging 40.024%. Typically, SiO_2 content in ultramafic soils is less than 45% (Vithanage et al., 2014), aligning with the characteristics observed in the study area. The average concentrations of Aluminum Oxide (Al_2O_3), Magnesium Oxide (MgO), Calcium Oxide (CaO), Phosphorus Pentoxide (P_2O_5), Potassium Oxide (K_2O) and Sodium Oxide (Na_2O) in the ultramafic soil (0 cm-30 cm depth) were 4.869%, 15.320%, 3.969%, 0.078%, 0.574% and 0.042%, respectively (Table 2). Calcium oxide content was generally low across the soils, with some samples showing a significant deficiency, dropping to less than 0.3%.

Comparing the total chemical content of the parent material (SiO_2, $Al2O_3$, MgO and CaO) with that of the soil, it is clear that the SiO_2 content is indicative of the surface soil. The concentrations of $Al2O_3$ and CaO are higher than in the bedrock, indicating some degree of weathering. In contrast, the parent material has a higher MgO concentration. The increased MgO content at a depth of more than 90 cm compared to the upper layer suggests the parent material is rich in magnesium, whereas iron is relatively more abundant in the soil. Previous research has reported low Al_2O_3 and CaO (Tashakor et al., 2014) concentrations and high MgO concentrations in ultramafic soils.

The initial Mg:Si ratio in the bedrock is 2.6, whereas in the soil it is 1.2. This indicates a consistent decrease in the Mg:Si ratio from the bedrock to the soil, corresponding to a loss of magnesium that is more than twice the loss of silicon. This regular decrease in the Mg:Si ratio signifies a substantial loss of magnesium, confirming the degree of soil evolution.

As far as the Fe:Si ratio is concerned, the trend towards Fe enrichment is present in soils. It is much more pronounced in soils 0.18 in the 0 cm-30 cm horizon of soil I as compared with 0.14 in the bedrock.

The soils are rich in metals typical of serpentines, such as Ni, Co and Cr, are relatively infertile in terms of P_2O_5 and K_2O content (Bonifacio et al., 1999). Variations in the percentages of P_2O_5 and K_2O between the lower and upper soil layers may be due to increased mineral decomposition in surface soils. The total phosphorus content of ultramafic soils (0 cm-30 cm) was found to be 0.018% (Xhaferri et al., 2017), aligning with findings from other studies. The total Ni content was high in both the parent material and all soil samples examined as shown in Table 2.

The average concentrations of minor elements in ultramafic soils (0 cm-30 cm) were as follows: Cr, 2606.57 µg/g; Mn, 1139.18 µg/g; Co, 120.99 µg/g; Ni, 1726.71 µg/g; Cu, 27.76 µg/g; Cd, 0.82 µg/g; and Pb, 5.44 µg/g. These levels generally matched those of the parent material, except for Pb, which was about seven times higher in the topsoil compared to the parent material (90+ cm) (Table 2). Numerous studies have highlighted the high concentrations of Ni, Cr, Co and Mn in ultramafic soils (Reeves et al., 1999; Fantoni et al., 2002; Shanker et al., 2005; Hseu et al., 2007; Susaya et al., 2010; Bani et al., 2009; 2010; 2013; 2014; Butt et al., 2013; Vithanage et al., 2014; Pal et al., 2014 and Kara et al. 2023.

The World Health Organization (WHO) sets soil standards for Cr, Mn, Co, Ni, Cu, Cd and Pb at 100, 2000, 50, 50, 100, 30 and 100 µg/g, respectively (Zondo et al., 2021). Comparing the ultramafic soil results with these standards reveals significantly high levels of Cr and Ni, both exceeding the recommended limits by more than twice. However, the concentrations of Mn, Cu, Cd and Pb were below the critical thresholds. The elevated levels of Cr, Ni and Co in the ultramafic soils are attributed to the parent material, which reflects the typical chemical composition of naturally occurring soils, particularly those derived from mafic-ultramafic rocks (ophiolites) (Muhammad et al., 2019 and Kara et al., 2019). Compared to WHO standards, the ultramafic soils exhibit particularly high levels of Cr and Ni, both exceeding the recommended limits by more than twofold, while Mn, Cu, Cd and Pb remain below critical levels. The high concentrations of Cr, Ni and Co in these soils are due to the parent material, as the chemical composition of soils generally mirrors that of their parent rocks. Soils derived from mafic-ultramafic rocks, such as ophiolites, typically contain elevated levels of heavy metals like Cr, Ni and Co (Muhammad et al., 2019 and Kara et al. 2019).

The correlation and principal component analyses of the ultramafic soils are outlined in Tables 3 and 4. As indicated in Table 3, Cr shows a negative correlation with CaO and a positive correlation with Ni, Co and Pb. Similarly, Mn is positively correlated with Fe and Co (Table 3). Additionally, Co has consistent directional relationships with Fe, Cr, Mn and Ni but shows a negative correlation with CaO (Table 3). These relationships are typical of ultramafic substrates (soils and rocks). Ni content is inversely correlated with CaO, Al_2O_3 and Cu but positively correlated with MgO, Fe, Cr and Co (Table 3). This supports findings that ultramafic soils are rich in Ni, MgO, Fe, Cr and Co but deficient in Ca (Bani et al., 2009; 2013 and 2014). Regarding other variables, Cu has a negative correlation with MgO and Ni but a positive correlation with Al_2O_3. In ultramafic soils, Pb shows similar relationships with Al_2O_3, SiO_2 and Cr and an inverse relationship with MgO. Overall, the total elemental content findings of this study are consistent with previous research (Raisanen et al., 1992; Robinson et al., 1997; Cheng et al., 2009; Duplay et al., 2014; Bani et al., 2014 and Tashakor et al. 2017).

Table 2. Descriptive statistics of the total major and minor element contents of ultramafic soils.

Soil depth	Soil properties	Min.	Max.	Mean
Soil (0 cm-30 cm)	SiO_2 (%)	23.31	51.07	**40.024**
	Al_2O_3 (%)	0.02	13.96	**4.869**
	MgO (%)	4.73	28.8	**15.32**
	CaO (%)	0.25	22.32	**3.969**
	P_2O_5 (%)	0.01	0.19	**0.078**
	K_2O (%)	0.11	1.23	**0.574**
	Na_2O (%)	0.04	0.05	**0.042**
	Fe (µg/g)	42273.9	110720.8	**7.33**
	Cr (µg/g)	450.2	5644.1	**2606.57**
	Mn (µg/g)	659.2	1680.2	**1139.18**
	Co (µg/g)	38.2	187	**120.99**
	Ni (µg/g)	254.8	2833	**0.17 (%)**
	Cu (µg/g)	4.2	130.8	**27.76**
	Cd (µg/g)	0.4	1	**0.82**
	Pb (µg/g)	0.6	14.4	**5.44**
Parent material	SiO_2 (%)	32.8	45.25	**40.29**
	Al_2O_3 (%)	0.006	1.872	**0.17**
	MgO (%)	28.39	36.61	**33.617**
	CaO (%)	0.152	11.63	**0.86**
	P_2O_5 (%)	0.001	0.007	**0.002**
	K_2O (%)	0.123	0.168	**0.142**
	Na_2O (%)	0.033	0.041	**0.036**
	Fe (µg/g)	50135.6	72042	**5.99**
	Cr (µg/g)	1488.2	4175.1	**2282.48**
	Mn (µg/g)	545.4	1043.5	**827.37**
	Co (µg/g)	71	163	**117.15**
	Ni (µg/g)	1437	3127	**0.24 (%)**
	Cu (µg/g)	2	146.7	**15.28**
	Cd (µg/g)	0.6	1.3	**0.79**
	Pb (µg/g)	0.4	1.2	**0.71**

Note: Bold values: Emphasizing their geochemical connectivity.

Table 3. Correlation analysis of ultramafic parent material and soils.

Parent Material (90+ cm) / Soil (0-30 cm)

	SiO_2	Al_2O_3	MgO	CaO	Fe	Cr	Mn	Co	Ni	Cu	Cd	Pb	
SiO_2	1	0.274	-0.28	**-.578****	**.412***	0.355	**.397***	0.322	0.087	0.056	-0.154	**.554****	SiO_2
Al_2O_3	-0.225	1	**-.750****	0.066	0.019	-0.154	0.17	-0.295	**-.572****	**.760****	-0.074	**.426***	Al_2O_3
MgO	0.049	0.123	1	-0.346	-0.008	0.081	-0.28	0.345	**.624****	**-.441***	-0.138	**-.533****	MgO
CaO	**-.383***	-0.004	**-.538****	1	**-.434***	**-.557****	-0.28	**-.712****	**-.674****	0.046	0.304	-0.226	CaO
Fe	0.293	-0.14	**-.400***	-0.03	1	0.31	**.706****	**.603****	**.493****	-0.003	0.163	0.051	Fe
Cr	-0.054	0.248	-0.141	0.118	0.327	1	0.335	**.643****	**.660****	-0.24	0.055	**.392***	Cr
Mn	0.113	-0.047	0.077	-0.088	**.626****	**.379***	1	.470*	0.225	0.15	0.01	0.208	Mn
Co	-0.256	0.13	-0.083	0.095	0.364	**.520****	**.414***	1	**.821****	-0.163	-0.065	0.066	Co
Ni	0.075	**-.456***	-0.198	-0.117	**.613****	0.086	0.22	**.375***	1	**-.455***	-0.04	-0.091	Ni
Cu	-0.066	**.633****	-0.121	0.053	0.012	**.657****	0	0.324	**-.390***	1	-0.089	0.078	Cu
Cd	0.188	0.093	0.055	0.054	-0.216	0.089	-0.027	-0.337	-0.373	0.083	1	-0.129	Cd
Pb	0.153	-0.115	-0.151	-0.01	0.338	0.31	0.14	0.068	0.318	0.001	0.001	1	Pb

Note: *: Correlations that are significant at the 0.05 level; **: Indicate a stronger significance at the 0.01 level; bold values emphasizing their geochemical connectivity; The color coding further helps to differentiate correlation strength.

In Table 4, the principal component analysis of ultramafic soils identified four components with eigenvalues of 1 or higher. These components explained 25.97% of the variance in PC-1, 25.95% in PC-2, 17.72% in PC-3 and 12.52% in PC-4, together accounting for 82.16% of the total variance (Table 4). For PC-1, which accounted for 25.97% of the variance in soil chemical element contents, MgO, Ni, Cu and Al_2O_3 were grouped together. Among these, Cu and Al_2O_3 had positive loadings, while MgO and Ni had negative loadings relative to the other parameters (Table 4). PC-2, which explained 25.95% of the variance, showed consistent directional loadings for Fe, Mn, Co and Ni, with an inverse relationship to CaO. Ni served as a linking variable between PC-1 and PC-2, while CaO linked PC-2 and PC-4. Several soil variables, including MgO, Al_2O_3, CaO, Fe, Mn, Co, Cd, Cu and Ni, likely share a common source. In PC-3, SiO_2, Cr and Pb formed a cluster with positive loadings among them. CaO and Cd were grouped in PC-4 (Table 4).

The pollution index values (EF, Igeo, PLI, CF) of the ultramafic soils are shown in Table 5. Based on the average EF values, Pb had the highest value (6.35), followed by Cu (2.33), Mn (0.98), Cd (0.90), Cr (0.89), Co (0.86) and Ni (0.59). According to the EF classification system, Pb (5<EF<20) is categorized as high enrichment, Cu (2<EF<5) as medium enrichment and the other metals as low enrichment since their EF values are below 2 (Sutherland et al. 2000).

Based on the Geoaccumulation Index (Igeo) results for the ultramafic soils, Pb (2.131) exhibited the highest value, followed by Cu (0.446), while the other metals had values close to zero. Accordingly, Pb (2<Igeo<3) was categorized as moderately severely contaminated, whereas other metals (Mn, Cu, Ni, Co and Cr) fell into the uncontaminated-moderately contaminated range (0<Igeo<1) and Cd (0<Igeo) was classified as uncontaminated (Müller et al. 1969).

Based on the Pollution Load Index (PLI) values of the ultramafic soils, the concentrations of Pb and Cu were greater than 1, indicating pollution, while the PLI values of Mn, Cd, Cr, Co and Ni were less than 1 (Table 5). According to Varol et al., (2011), a PLI greater than 1 signifies pollution caused by the metals present, thus categorizing Pb and Cu as pollutants (Ndiokwere (70), 1984; Carlosena (71) et al., 1998; Imperato (72) et al., 2003; Çelik (73) et al. 2005).

Examining the CF values of the soils, Mn, Cr, Co and Ni exhibited CF values of 1 or less for heavy metals. Among the other elements, Cu had a CF value of 2.27, while Pb had a CF value of 5.08 (Table 5) (Ho et al., 1988). According to the evaluation system reported by Hakanson et al., 1980, Pb (3<CF<6) was classified as a significant contaminant, Cu (1<CF<3) as a moderate contaminant and Mn, Cr, Co and Ni as minor contaminants.

Based on the pollution index results (EF, Igeo, PLI and CF), the index values for Pb and Cu were higher than those for other analyzed elements. Analysis of areas with elevated Pb and Cu levels in the research zone showed their proximity to roads or agricultural lands, Blake et al., 2002; Lia et al., 2007. The high Pb and Cu pollution indices in soils derived from serpentine parent material in the study area may be associated with their proximity to highways and the use of Cu-containing agricultural chemicals (Figure 1) (Zehetner et al., 2009 and Zhang et al. 2012).

Traffic-related pollution from vehicle emissions and mechanical wear leads to the buildup of heavy metals (Pb and Cu) in agricultural lands. Significant increases in heavy metal levels, including Pb, Cu, Al, Mo, Hg and Se, have been observed in agricultural soils near highways. Similarly, elevated Cu concentrations have been reported in agricultural soils close to heavily trafficked highways (Davis et al. 2001).

Additionally, the friction between brakes, moving engine parts and other vehicle components can contribute to the release of Cu. While the concentrations of Ni, Cr and Co in the ultramafic soils of the research area exceeded the maximum critical values recommended by the World Health Organization, their pollution indices were lower than those of Pb and Cu. Therefore, Ni, Cr and Co mainly accumulate in ultramafic soils from parent material sources (Blaser et al., 2000; Githaiga et al., 2001; Aytop et al., 2023; Bonifacio 1997 and Brady 2005. This study highlights the importance of considering both lower-depth and upper-depth soils when assessing the origin of pollutants. The significance of including the parent material (90+ cm depth) in soil heavy metal calculations has been noted. Other researchers have also indicated that inaccuracies can arise from the choice of reference material in calculations Caillaud et al., 2009; Echevarria et al., 2020; Hewawasam et al., 2014 and Šeda et al. 2017).

Table 4. Principal component analysis of ultramafic soils.

	PC-1	PC-2	PC-3	PC-4
SiO_2	-	-	0.68	-
$Al2O_3$	0.882	-	-	-
MgO	-0.721	-	-	-
CaO	-	-0.565	-	0.607
Fe	-	0.909	-	-
Cr	-		0.574	-
Mn	-	0.799	-	-
Co	-	0.772	-	-

Ni	-0.726	0.588	-	-
Cu	0.849	-	-	-
Cd	-	-	-	0.866
Pb	-	-	0.918	-
EV	4.19	3.12	1.38	1.16
CR (%)	25.97	25.95	17.72	12.52
CCR (%)	25.97	51.93	69.64	82.16
Note: **EV: Eigenvalues; CR: Contribution Rate (%); CCR: Cumulative Contribution Rate (%).				

Table 5. Pollution index values of ultramafic soils.

Pollution indices	**Function**	**Cr**	**Mn**	**Co**	**Ni**	**Cu**	**Cd**	**Pb**
Enrichment Factor (EF)	Minimum	0.16	0.76	0.34	0.07	0.62	0.4	0.92
	Maximum	1.69	1.24	1.47	0.82	8.2	1.48	15.2
	Mean	**0.89**	**0.98**	**0.86**	**0.59**	**2.33**	**0.9**	**6.35**
Geoaccumulation Index (Igeo)	Minimum	0.002	0.006	0.028	0.002	0.032	-1.102	0.067
	Maximum	0.005	0.013	0.069	0.005	1.36	-0.062	4.01
	Mean	**0.003**	**0.008**	**0.04**	**0.003**	**0.446**	**-0.266**	**2.131**
Pollution Load Index (PLI)	Minimum	0.4	0.89	0.58	0.26	0.79	0.63	0.96
	Maximum	1.38	1.09	1.21	0.9	2.37	1.21	2.85
	Mean	**0.93**	**0.99**	**0.92**	**0.75**	**1.45**	**0.94**	**2.2**
Contamination Factor (CF)	Minimum	0.16	0.79	0.34	0.07	0.62	0.4	0.92
	Maximum	1.9	1.46	1.47	0.82	5.6	1.48	8.14
	Mean	**0.92**	**1**	**0.86**	**0.59**	**2.27**	**0.9**	**5.08**
Note: Bold values: Emphasizing their geochemical connectivity.								

CONCLUSION

This study examined the elemental composition of ultramafic parent material and the derived soils using various pollution indices (EF, Igeo, PLI and CF). A typical ultramafic soil from the Kahramanmaraş region was analyzed as a representative sample of Turkish ultramafic landscapes. The weathering of ultramafic minerals in these soils was identified as a process involving the release of CaO and Fe.

The heavy metal concentrations in ultramafic soils reflected those in the parent material and followed the order Cr>Ni>Mn>Co>Cu>Pb>Cd, with Cr, Ni and Co levels exceeding the World Health Organization's critical limits. Among the elements studied, Pb had the highest pollution index value, followed by Cu, indicating an anthropogenic source of pollution in agricultural soils. The weathered soils contained less Ni than the primary minerals in the bedrock, demonstrating that the initial stages of weathering are slow. In Cambisols, the dominant minerals are serpentine, followed by Fe-rich smectites and well-crystallized goethite. In Vertisols, the dominant minerals are Mg-rich smectites, likely resulting from Mg leaching downslope.

Despite the high concentrations of Cr, Ni and Co in ultramafic soils in the research area, their low EF, Igeo, PLI and CF values suggest a natural source of pollution. The high heavy metal content in ultramafic rocks and soils poses environmental risks. To mitigate these risks, it is recommended to practice minimum tillage, maintain continuous green cover (such as pasture, forest, or agroforestry), or apply technologies like phytostabilization and phytomining in areas with ultramafic material. Further research is needed to better understand pedogenesis and nickel biogeochemistry in the ultramafic regions of Turkey.

ETHICS STATEMENT

The authors confirm that they have adhered to the ethical policies of the journal.

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