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Controlling factors of heavy metal distributions in granitoid-derived soils and their environmental risks

Granitoyitten türeyen topraklarda ağır metal dağılımlarını kontrol eden faktörler ve çevresel riskleri

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Abstract

In this study, the weathering degrees of the outcropping magmatic rocks in the northeastern part of Aksaray province, as well as the heavy metal variations in the resulting granitoid-derived soils and their associated environmental risks, were evaluated. The calculated weathering indices vary as follows: Ruxton Ratio (RR) 5.88–8.51, Chemical Index of Alteration (CIA) 49.58–66.33, Chemical Index of Weathering (CIW) 60.45–80.18, Weathering of Parker Index (WIP) 48.32–76.79, and Plagioclase Index of Alteration (PIA) 64.33–83.79. These values indicate that the granites in the study area are moderately weathered. To assess the environmental risks of heavy metals (HMs) in the granitic soils, the Geo-accumulation Index (Igeo), Contamination Factor (CF), Pollution Load Index (PLI), and Potential Ecological Risk (PER) were calculated, ranging from -4.58 to 0.99, 0.06 to 2.98, 0.36 to 0.97, and 0.124 to 23.818, respectively. The ecological indices, which show similar distributions with increasing weathering degrees, indicate the absence of significant heavy metal pollution in the area and suggest that any minor contamination originates from the lithology, with no anthropogenic pollution observed.

Keywords: Environmental risks, Heavy metal, Granitoid-derived soil, Weathering.

Öz

Bu çalışmada, Aksaray ilinin kuzeydoğusunda yüzeyleyen magmatik kayaların ayrışma dereceleri ile ayrışmaya bağlı oluşan granitoyitten türeyen topraklardaki ağır metal değişimleri ve çevresel riskleri ortaya konulmuştur. Hesaplanan ayrışma indeksleri Ruxton oranı (RR) 5.88-8.51, Kimyasal değişim indeksi (CIA) 49.58-66.33, Kimyasal ayrışma indeksi (CIW) 60.45-80.18, Parker ayrışma indeksi (WIP) 48.32-76.79, Plajiyoklaz değişim indeksi (PIA) 64.33-83.79 aralığında değişmektedir. Bu değerler bölgedeki granitlerin orta derecede ayrışmış olduğuna işaret etmektedir. Granitik topraklardaki ağır metallerin (HM) çevresel risklerini belirlemek için hesaplanan jeo-birikim indeksi (Igeo), Kirlenme Faktörü (CF), Kirlilik Yükü İndeksi (PLI) ve Potansiyel Ekolojik Risk (PER) indeksleri sırasıyla -4.58-0.99; 0.06-2.98; 0.36-0.97 ve 0.124-23.818 aralığında değişmektedir. Artan ayrışma derecesi ile benzer dağılımlar sunan ekolojik indeksler bölgede ağır metal bakımından belirgin bir kirliliğin olmadığına var olan düşük derecedeki kirlenmenin ise litoloji kaynaklı olduğunu ve herhangi bir antropojenik kirlenmeden bahsedilemeyeceğini ortaya koymuştur.

Anahtar kelimeler: Çevresel risk, Ağır metal, Granitoitten türeyen toprak, ayrışma.

1 Introduction

The main material of soil, a natural entity formed through prolonged pedogenic processes, is continuously modified by the complex interactions of soil-forming factors. The main material may be of organic or mineral origin; it may have been transported by agents such as water and wind or developed in situ. Soil formation is governed by processes including atmospheric additions (e.g., water, CO_2, solar radiation), downward translocation of humus, clay, sesquioxides, salts, and basic cations, the decomposition and transformation of mineral and organic constituents, and material losses from surface and subsurface horizons. Under the influence of these processes, soil profiles develop, and distinct horizons are formed [1].

Weathering plays a crucial role in soil formation. Soils and sediments develop through various physical and chemical weathering processes of the Earth's crustal rocks. In some cases, soils are also derived from the weathering of crystalline rocks (e.g., granite, gabbro, and metamorphic rocks), thereby retaining mineralogical and geochemical signatures of the whole rock [2]-[5]. The heavy metal contents of soils and sediments, in particular, may pose significant environmental risk factors. There are two main pathways through which soils accumulate heavy metals: (i) natural inputs resulting from the weathering of continental rocks and (ii) anthropogenic sources such as traffic [6]-[10], industrial production, atmospheric deposition [11]-[14], and agricultural [15], [16] activities [17]-[20]. Although studies focusing specifically on heavy metal distributions in relation to the weathering processes of source rocks are relatively limited, several investigations have evaluated the extent of heavy metal contamination in soils using integrated pollution indices and multivariate statistical analyses [21]-[25].

Soils derived from granitic rocks are of particular importance, as their mineralogical composition and geochemical weathering processes can naturally enrich them with heavy metals (HMs). Such natural processes contribute to the

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background concentrations of elements such as lead (Pb), arsenic (As), cadmium (Cd), chromium (Cr), and mercury (Hg) in the environment. In addition to these geogenic sources, anthropogenic activities-including industrial emissions, mining, agrochemical application, waste disposal, and urban runoff-substantially increase heavy metal accumulation in soils [26]. These activities lead to persistently elevated concentrations of toxic elements, which may bioaccumulate and pose long-term ecological and human health risks. Because heavy metals are non-biodegradable and exhibit residence times in soils spanning thousands of years, they not only affect plant growth but also bioaccumulate in aquatic ecosystems, entering the food chain and posing hazards to both humans and animals [27]-[32]. Among these, Cr, Cu, Hg, and Pb are recognized as some of the most widespread soil contaminants [33]. In addition to their toxicological effects, HMs also alter soil physical properties. Their accumulation in surface horizons may reduce soil aggregate stability, thereby increasing susceptibility to wind and water erosion [34]. Moreover, elements such as nickel (Ni) and zinc (Zn) can influence soil texture by modifying the distribution of sand, silt, and clay fractions [35]. To assess the severity of heavy metal contamination and its ecological implications, many geochemical indices have been developed, including the Pollution Index (PI), Geo-accumulation Index (I_{geo}), and Potential Ecological Risk Index (PERI). These indices provide systematic tools to quantify contamination levels and estimate ecological risk [26].

Establishing accurate baselines for soil contamination assessment requires careful consideration of both natural and anthropogenic variables. At the regional scale, main material, soil type, elevation, slope [36], [37], and the intensity of bedrock weathering play a significant role in shaping the spatial distribution of heavy metals. In crystalline rocks, in situ weathering typically initiates along mineralogical and structural weaknesses, such as foliation planes, compositional discontinuities, and grain boundaries. This process represents a gradual but persistent transformation, where physical and chemical weathering mechanisms act in concert.

The present study investigates the relationship between ecological risk and weathering indices by focusing on regoliths developed in a granitic basin. In this regard, the present study is of considerable significance. Previous research has generally addressed either the assessment of weathering indices to characterize rock alteration or the evaluation of ecological risks associated with heavy metal accumulation in soils. However, studies integrating these two aspects remain scarce. This research, therefore, provides a comprehensive approach by specifically focusing on the relationship between the degree of weathering in magmatic rocks and the ecological risks associated with the mobilization and potential release of heavy metals during soil formation. Such an integrated perspective contributes to a better understanding of how geochemical weathering processes influence environmental risk development in granitoid-derived soils. Ecological indices, including the Geo-accumulation Index (I_{geo}), Contamination Factor (CF), Degree of Contamination (CD), Pollution Load Index (PLI), and Potential Ecological Risk (PER), were calculated alongside weathering proxies such as the Ruxton Ratio (RR), Chemical Index of Alteration (CIA), Chemical Index of Weathering (CIW), Weathering Index of Parker (WIP), and Plagioclase Index of Alteration (PIA). Spatial distributions of these indices were compared to evaluate the relationship between weathering intensity in granitic rocks and the distribution of heavy metals in granitoid-derived soils.

2 Study area

The study area is located in the northeast of Aksaray Province, covering an area of approximately 25 km^2 (Figure 1). The study area comprises magmatic units and their resulting arenas and soils, which crop out within the Central Anatolian Basement Units, between the settlements of Taptuk Emre, Borucu, Yanyurt, and Salmanlı. Weathering products can be traced in the region, from the fresh bedrock to the soilification stage. This area, which primarily consists of granite, granodiorite, and gabbro rocks, is important for the formation and development of granitoid-derived soils (Figure 2).

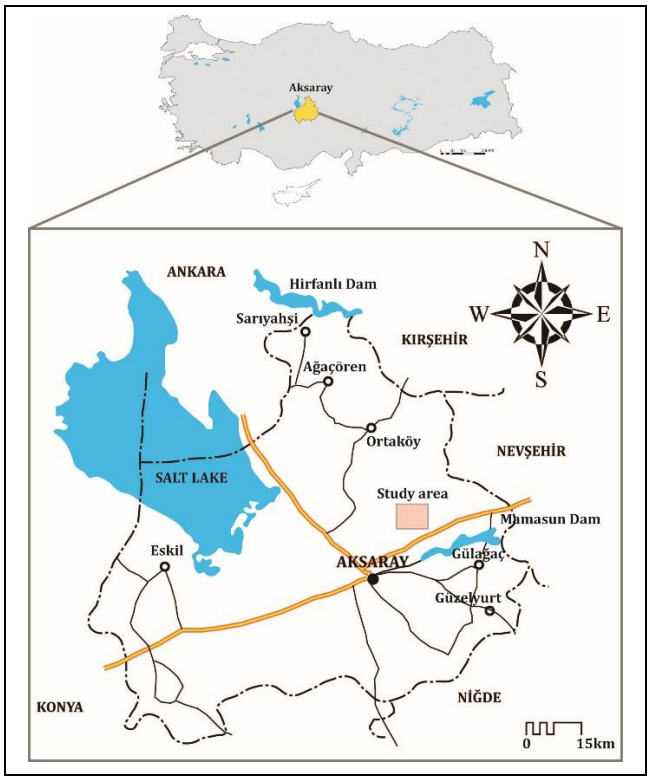
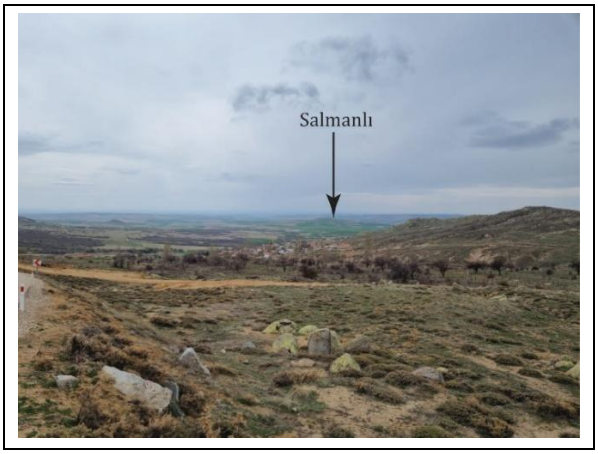


Figure 1. Location map of the study area.

2.1 Geology

The study area is composed of igneous rocks and their alteration products, which belong to the Central Anatolian Basement Units (CABU) [38]. These rocks mainly consist of granodiorite and gabbro, which display gradual transitions. Topographically, gabbro bodies form resistant outcrops and hills, whereas granodiorites exhibit a more widespread morphology due to extensive alteration. The granodiorites, particularly well exposed around the Borucu settlement, are mineralogically composed of quartz, plagioclase, orthoclase, hornblende, and biotite, with titanite, apatite, allanite (orthite), and opaque minerals occurring as accessory phases [39]. The occurrence of K-feldspar crystals measuring 1.5–2.5 cm within the granodiorites suggests a monzonitic affinity; however, towards the western part of the study area, the composition is entirely granodioritic (Figure 3).



(a)

(b)

Figure 2(a): A view from the study area. (b): Bedrock and arenization.

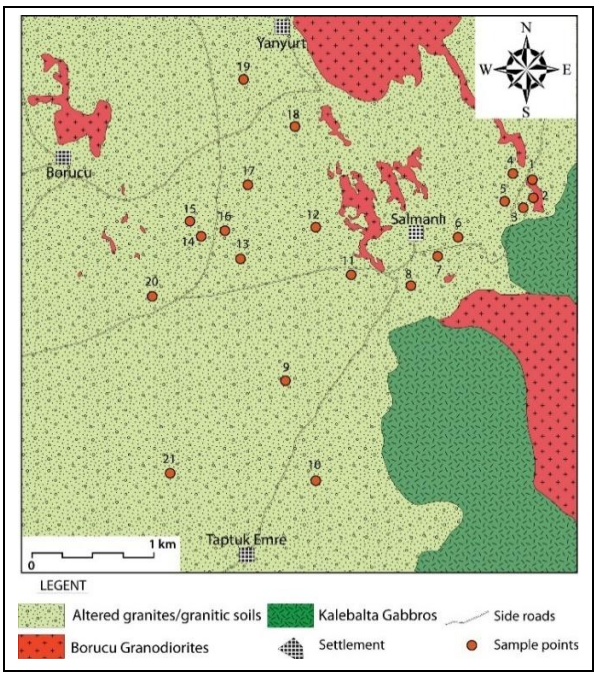


Figure 3. Simplified geological map of the study area.

Gabbros represent the dominant mafic lithologies cropping out in the southern part of the area. They are medium- to coarse-grained and are characterized by hornblende as the principal mafic mineral. Plagioclase, occurring in the andesine–labradorite compositional range, is the dominant feldspar phase [39].

A comparison of the gabbros and granodiorites in the study area reveals that the gabbros are more susceptible to physical disintegration, whereas granodiorites constitute the primary lithology subject to intense weathering.

2.2 Soil classification

With the progression of weathering in crystalline rocks, distinct weathering zones develop from the surface downward. At the top, a regolith or A horizon forms, influenced in part by the accumulation of organic matter. Beneath this layer, a granular and loose saprolite zone (grus, B horizon) is observed. At greater depths lies the saprock zone (C horizon), which partially preserves the characteristics of the parent rock but is mineralogically transformed. This zonal weathering model has been documented under various climatic and geological conditions and is of great significance for understanding the contribution of rocks to soil-forming processes [40]-[44].

In the study area, fresh bedrocks are observed as gray-colored, rounded, and weathered along fracture and joint surfaces. In zones where weathering is more pronounced, the main rock mass appears as isolated blocks within arenas. In the topographically higher parts of the area, particularly along stream beds, relatively fresh rocks with minor signs of weathering are present.

The rocks located mainly in the eastern and northeastern parts of the study area constitute the C-horizon (saprock). The C-horizon represents the transition between fresh bedrock and Zone IV in a complete regolith profile, as defined by Berry and Ruxton [45]. The saprock masses, which are rounded to sub-rounded and partially disintegrated, are locally overlain by the B-horizon (saprolite), which can reach thicknesses of up to 2–3 meters. The saprolite corresponds to the Zone III–Zone II transition in a complete regolith profile, where all minerals, except for residual quartz grains derived from the parent rock, are observed to be altered. In the lower-elevation, relatively flat parts of the study area, the A-horizon (regolith) occurs, representing Zone I of the complete regolith profile. Such a vertical succession indicates the presence of a fully developed regolith profile, as described by [45] (Figure 4).

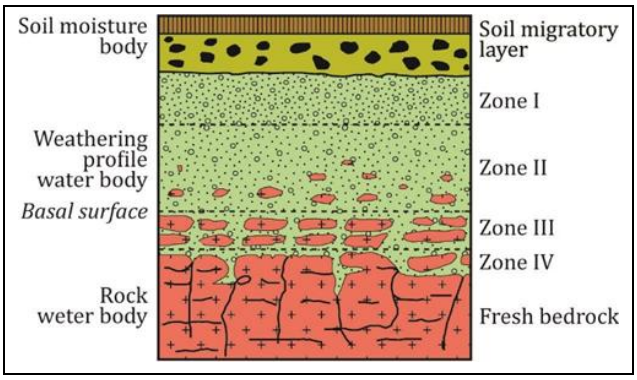


Figure 4. The complete regolith profile [45].

3 Materials and Methods

A total of 21 soil samples, ranging from fresh rock to variably altered granite soils, were collected from the study area. Samples were selected to represent the local geological conditions. Chemical analyses were carried out at the Geochemical Analysis Laboratory of the Central Research Laboratory, Aksaray University (ASUBTAM).

The soil samples were ground to a grain size of 20 µm using a Fritsch tungsten carbide ball mill. 6 g of the powdered sample were homogenized with 1 g of Micropulver Wachs. The mixture was pressed into pellets under a load of 13 kN. The pressing pellets were analyzed using a PANalytical Axios Max Minerals wavelength-dispersive X-ray fluorescence (WD-XRF) spectrometer. The instrument is equipped with an Rh-anode X-ray tube, five crystals (LiF200, PE002, LiF220, Ge111, and PX1), and a 4 kW X-ray generator. For geochemical analyses, the "Wholerock_asu_v3" method [46], [39] was applied, which employs certified reference materials including DTS-2b (dunite), IA-HGC / IA-MGC-A (high- and medium-sulphide concentrate), JA-2 (andesite), JGb-1 (gabbro), JSl-1 (slate), JSy-1 (syenite), NCS-DC-71303 (granodiorite), NCS-DC-73301 (granite), SDC-1 (mica schist), and SARM-44 (sillimanite schist). Loss on ignition (LOI) was determined by heating the samples at 900 °C for 12 hours in a muffle furnace.

Based on the analyses of all rock samples collected from the study area, major element oxides (K_2O, Na_2O, Al_2O_3, SiO_2, CaO, MgO, etc.) were used to calculate several weathering indices, including the Ruxton Ratio (RR), Chemical Index of Alteration (CIA), Chemical Index of Weathering (CIW), Weathering Index of Parker (WIP), and Plagioclase Index of Alteration (PIA). In addition, trace element data (Cu, Cr, Zn, Pb, Ni, and Fe) were used to compute ecological indices, including the Geo-accumulation Index (Igeo), Contamination Factor (CF), Degree of Contamination (CD), Pollution Load Index (PLI), and Potential Ecological Risk (PER). The obtained weathering and ecological risk indices were subsequently analyzed and interpreted, and their spatial distribution maps were generated using the Inverse Distance Weighting (IDW) interpolation method which offers a successful approach to the spatial distribution of groundwater and soil pollution [47].

4 Results

Whole-rock geochemical compositions and heavy metal concentrations of the magmatic units, weathering products, and granitoid-derived soils in the study area are presented in Table 1 and 2. Based on these analyses, alteration indices (Table 1) and pollution indices (Table 3) were calculated to evaluate the degree of weathering in the granitic rocks and to assess the environmental risks associated with weathering-related heavy metal contents.

4.1 Field observations

The upper topographic levels of the study area are mainly underlain by fresh to slightly altered granitic and gabbroic lithologies. Towards the lower morphologic, these crystalline units are extensively weathered, producing characteristic weathering profiles that include arenas, grus, saprolitic sand accumulations, and granitoid-derived soils. Along fracture zones within the granitic bodies, in-situ weathering commonly results in relict granite in forms spheroidal to ellipsoidal (Figure 5a, b). Geochemically, the soils formed at the incipient stages of weathering retain the primary compositional characteristics of the parent lithologies. With increasing distance basinward, however, soil chemistry progressively deviates from the bedrock signature, reflecting superimposed pedogenic modification, particularly under the influence of climatic conditions. This differentiation, with the increase of alteration processes, may lead to the redistribution of initially existing elements within the soil profile and the differentiation of the resulting soils [48], [49]. Field studies indicate that the soil profiles (regolith) within the basin develop over bedrock (saprok) or partially weathered (saprolite) layers with a thickness of 20-30 cm (Figure 5c, d).

(a)

(b)

(c) (d)

Figure 5. (a): Compact saprock (C-horizon). (b): Friable saprolite (B-horizon). (c): Regolith (A-horizon) developed over saprolite, and (d): Internal structure.

Color variations associated with differing degrees of weathering are particularly evident in areas utilized for agriculture. The regolith, ranging in color from light to dark brown, is 20–50 cm thick along the basin margins, whereas in the central basin, where weathering intensity is greater, its thickness reaches up to 1 m.

Table 1. Major element oxide and calculated weathering indices values of granitoid-derived soil.

Sample	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	Cr_2O_3	MnO	Fe_2O_3	LOI	TOTAL		RR	CIA	CIW	WIP	PIA
1	1.76	1.59	14.10	68.73	0.10	5.75	2.87	0.29	0.001	0.09	3.86	0.80	99.94		8.27	49.58	63.48	76.79	64.33
2	1.30	2.10	17.17	62.67	0.09	3.61	3.47	0.61	0.016	0.10	5.24	3.48	99.86		6.19	58.14	67.01	57.29	73.96
3	1.41	2.40	15.50	65.20	0.09	3.86	3.16	0.62	0.003	0.10	5.03	2.54	99.93		7.14	55.88	65.81	60.45	71.83
4	1.66	1.21	16.51	68.06	0.04	4.58	1.98	0.24	0.001	0.07	3.10	2.46	99.92		6.99	59.39	72.28	62.64	76.61
5	1.48	2.23	15.45	65.57	0.09	4.38	3.04	0.57	0.003	0.10	4.64	2.34	99.90		7.20	54.90	66.02	64.70	71.03
6	1.45	2.55	14.71	63.71	0.14	4.21	3.99	0.80	0.006	0.13	6.27	1.77	99.73		7.35	50.92	60.45	66.24	65.91
7	1.48	2.41	14.69	65.52	0.11	4.23	3.21	0.64	0.006	0.11	5.23	2.29	99.93		7.57	53.35	63.99	64.38	69.06
8	1.32	1.04	17.73	67.09	0.08	4.62	1.22	0.19	0.004	0.08	2.70	3.91	99.99		6.42	65.39	80.18	57.40	83.79
9	0.64	1.72	16.22	64.30	0.14	4.20	1.89	0.52	0.012	0.11	4.47	5.58	99.80		6.73	64.23	78.34	51.13	82.62
10	0.93	1.58	15.36	65.56	0.18	4.45	2.28	0.42	0.011	0.10	3.75	5.15	99.76		7.25	59.42	73.03	56.49	77.28
11	0.70	2.14	16.39	61.48	0.28	4.26	2.47	0.72	0.009	0.12	5.43	5.81	99.79		6.37	61.50	74.37	54.86	79.26
12	1.50	1.04	14.20	71.24	0.13	4.66	2.14	0.27	0.003	0.08	2.38	2.27	99.90		8.51	55.47	69.08	61.70	72.39
13	1.06	2.19	15.83	63.51	0.14	4.01	2.99	0.65	0.008	0.11	5.26	4.10	99.85		6.81	57.88	68.80	57.50	74.48
14	1.56	2.22	15.46	64.21	0.12	4.70	3.62	0.68	0.013	0.10	5.26	1.87	99.82		7.05	52.07	62.85	69.63	67.52
15	1.30	2.23	16.14	63.11	0.12	3.92	3.41	0.69	0.010	0.11	5.57	3.19	99.81		6.63	56.19	65.91	60.11	72.17
16	1.74	1.65	14.94	68.06	0.11	4.29	3.05	0.32	0.003	0.09	3.77	1.90	99.91		7.73	53.38	64.00	64.77	68.99
17	0.64	1.82	17.76	61.54	0.10	3.76	2.14	0.69	0.011	0.11	5.70	5.47	99.74		5.88	66.33	78.21	48.32	83.42
18	1.12	1.95	16.48	63.46	0.13	4.10	2.71	0.61	0.009	0.10	4.76	4.38	99.81		6.54	59.50	70.86	57.47	76.35
19	1.08	1.66	17.06	64.94	0.09	4.38	2.17	0.50	0.008	0.09	4.19	3.67	99.85		6.46	61.99	74.90	57.30	79.61
20	1.05	1.73	16.19	64.93	0.14	4.39	2.46	0.55	0.029	0.10	4.51	3.77	99.85		6.81	59.65	72.32	58.01	77.08
21	1.06	1.57	15.42	65.96	0.11	4.58	1.99	0.47	0.010	0.10	3.85	4.78	99.90		7.26	59.90	74.17	58.07	78.02
													Average	**Calculated Weathering Indices**	**7.01**	**65.40**	**69.81**	**60,25**	**74.56**

Table 2. Trace element results of granitoid-derived soil.

Sample	Cl	Sc	Co	Ni	Cu	Zn	Ga	As	Rb	Sr	Y	Zr	Nb	Mo	Cd	Sn	Ba	Nd	Sm	Gd	Yb	Hf	Pb
1	175.1	7.0	13.5	7.6	13.0	42.4	16.4	5.9	200.6	124.0	44.6	112.6	9.7	8.1	0.06	5.7	518.2	27.5	6.8	3.0	7.4	4.0	25.8
2	217.5	3.6	21.0	13.2	11.5	59.2	21.0	5.6	166.0	158.8	47.5	135.3	10.3	6.7	0.07	2.5	479.3	29.4	9.0	5.4	8.7	5.1	28.9
3	228.4	2.7	21.5	10.4	13.2	53.7	17.5	4.0	185.0	155.0	46.1	122.0	10.1	7.7	0.07	2.0	502.6	28.5	9.2	5.2	5.9	5.0	23.1
4	354.5	2.2	10.0	9.8	15.8	30.5	15.4	7.8	180.9	97.4	38.7	98.0	9.1	10.3	0.06	3.5	383.5	21.0	7.5	3.1	5.6	3.7	26.3
5	257.8	7.6	18.3	10.5	9.5	56.6	18.4	5.7	187.0	143.4	51.4	109.7	8.1	7.2	0.07	4.6	415.1	31.0	8.3	3.6	6.5	3.6	24.9
6	278.9	5.8	22.3	10.2	13.5	70.0	19.8	5.2	195.0	158.7	50.7	118.6	10.1	7.7	0.08	5.3	497.7	41.3	7.2	4.8	5.9	4.3	27.5
7	293.1	8.3	22.6	12.3	14.4	64.9	17.2	4.7	191.6	139.6	49.0	124.7	11.0	6.4	0.07	2.7	512.9	32.0	7.8	4.4	7.1	4.3	25.0
8	97.0	4.8	9.5	23.9	16.5	35.6	17.2	17.8	272.3	59.8	60.1	102.7	11.7	8.7	0.04	3.6	331.7	11.2	9.3	4.0	8.6	4.0	44.3
9	121.1	7.1	20.2	36.5	19.8	59.2	19.0	12.9	204.3	108.0	49.6	123.8	12.8	9.5	0.07	3.7	490.1	30.7	7.6	3.6	10.0	4.9	39.5
10	84.2	6.7	15.7	31.7	20.2	47.7	15.7	13.7	227.5	95.3	55.0	121.7	11.5	9.3	0.07	6.0	429.8	26.3	8.3	3.4	9.3	4.8	39.9
11	224.9	10.2	22.0	28.0	23.7	76.7	20.2	9.9	212.3	139.4	57.5	143.1	13.5	8.2	0.07	5.8	551.1	33.7	9.5	4.7	9.1	5.2	37.1
12	114.7	4.6	8.1	14.8	12.0	33.0	12.6	6.9	148.1	149.1	35.8	145.3	10.0	9.6	0.06	3.2	756.0	24.3	7.7	2.6	10.8	6.0	27.2
13	166.0	8.7	23.3	19.5	18.0	63.2	19.6	8.2	171.0	147.5	45.1	138.5	11.5	7.3	0.07	1.3	570.2	35.6	7.3	4.8	6.3	5.1	30.8
14	412.8	7.0	20.0	9.8	16.7	51.2	18.2	4.9	194.6	176.3	44.2	116.1	9.8	7.4	0.07	2.6	841.5	36.7	7.6	3.5	3.6	4.6	25.2
15	283.7	7.7	21.6	15.0	24.4	59.0	20.7	5.7	182.1	158.9	47.0	142.5	11.0	7.0	0.07	4.6	517.9	34.4	6.4	3.4	5.8	5.7	28.4
16	208.6	4.4	13.9	8.9	16.4	42.0	16.7	7.9	154.1	142.0	37.6	134.9	8.3	8.1	0.06	4.3	497.7	25.7	7.5	3.7	7.3	4.7	26.6
17	107.4	8.8	23.6	26.8	20.8	65.9	19.6	9.6	172.3	125.6	43.4	135.7	11.7	7.6	0.08	6.5	587.4	35.2	6.7	5.2	6.9	5.2	35.1
18	239.0	7.1	20.3	17.3	15.0	56.7	18.5	7.1	182.1	134.0	47.2	134.0	10.5	8.3	0.07	7.8	493.4	27.8	9.3	3.6	7.5	4.8	29.5
19	160.0	6.9	16.6	18.3	17.5	47.0	17.1	8.1	182.1	118.5	43.9	139.9	10.6	7.9	0.06	3.5	596.3	24.7	7.5	4.7	8.7	5.1	29.4
20	120.1	4.5	17.6	21.1	29.4	55.6	17.6	10.6	160.5	144.1	38.3	153.6	10.4	8.1	0.07	7.5	677.0	34.4	7.6	2.8	5.7	5.9	35.6
21	72.5	8.8	16.7	28.9	17.9	51.2	15.7	9.7	176.8	128.7	40.5	132.3	10.9	8.1	0.06	nd	725.7	30.3	7.6	3.2	9.8	4.9	34.8

Table 3. Calculated ecological risk index values of granitoid-derived soil.

Sample	$I_{geo}Cu$	$I_{geo}Cr$	$I_{geo}Zn$	$I_{geo}Pb$	$I_{geo}Ni$	$I_{geo}Fe$	CFCu	CFCr	CFZn	CFPb	CFNi	CFFe	Cd	PLI	EriCu	EriCr	EriZn	EriPb	EriNi	PERI
1	-1.53	-4.57	-1.20	0.22	-3.46	-1.59	0.52	0.06	0.65	1.74	0.14	26995.05	3.61	0.37	2.59	0.13	0.65	8.71	0.68	12.76
2	-1.70	-0.76	-0.72	0.38	-2.67	-1.14	0.46	0.88	0.91	1.95	0.24	36646.92	5.12	0.70	2.30	1.77	0.91	9.75	1.18	15.92
3	-1.50	-3.02	-0.86	0.05	-3.01	-1.20	0.53	0.19	0.83	1.56	0.19	35213.72	3.94	0.50	2.64	0.37	0.83	7.79	0.93	12.56
4	-1.25	-4.59	-1.68	0.24	-3.09	-1.90	0.63	0.06	0.47	1.77	0.18	21669.98	3.51	0.36	3.16	0.12	0.47	8.87	0.88	13.50
5	-1.98	-2.98	-0.78	0.16	-3.00	-1.32	0.38	0.19	0.87	1.68	0.19	32489.88	3.91	0.48	1.90	0.38	0.87	8.40	0.94	12.48
6	-1.47	-2.14	-0.48	0.31	-3.04	-0.88	0.54	0.34	1.08	1.86	0.18	43895.23	4.81	0.62	2.71	0.68	1.08	9.30	0.91	14.68
7	-1.38	-2.27	-0.59	0.17	-2.77	-1.15	0.58	0.31	1.00	1.69	0.22	36591.08	4.47	0.60	2.88	0.62	1.00	8.45	1.10	14.05
8	-1.19	-2.73	-1.45	1.00	-1.81	-2.10	0.66	0.23	0.55	2.99	0.43	18889.43	5.20	0.58	3.29	0.45	0.55	14.95	2.14	21.38
9	-0.92	-1.25	-0.72	0.83	-1.20	-1.37	0.79	0.63	0.91	2.67	0.65	31263.71	6.23	0.88	3.96	1.26	0.91	13.35	3.26	22.74
10	-0.89	-1.38	-1.03	0.85	-1.41	-1.62	0.81	0.58	0.73	2.70	0.57	26274.76	5.87	0.80	4.04	1.15	0.73	13.48	2.83	22.23
11	-0.66	-1.57	-0.35	0.74	-1.58	-1.09	0.95	0.50	1.18	2.51	0.50	38011.64	6.34	0.89	4.74	1.01	1.18	12.54	2.50	21.97
12	-1.64	-2.98	-1.56	0.29	-2.50	-2.28	0.48	0.19	0.51	1.84	0.26	16631.59	3.59	0.44	2.41	0.38	0.51	9.18	1.32	13.80
13	-1.06	-1.77	-0.63	0.47	-2.11	-1.14	0.72	0.44	0.97	2.08	0.35	36798.69	5.24	0.73	3.60	0.88	0.97	10.41	1.74	17.60
14	-1.17	-1.05	-0.93	0.18	-3.10	-1.14	0.67	0.73	0.79	1.70	0.18	36834.37	4.74	0.65	3.33	1.45	0.79	8.51	0.88	14.95
15	-0.62	-1.53	-0.72	0.36	-2.49	-1.05	0.97	0.52	0.91	1.92	0.27	39020.38	5.31	0.74	4.87	1.04	0.91	9.61	1.34	17.76
16	-1.19	-2.99	-1.22	0.26	-3.24	-1.62	0.66	0.19	0.65	1.80	0.16	26381.31	3.94	0.47	3.28	0.38	0.65	8.98	0.79	14.08
17	-0.85	-1.38	-0.56	0.66	-1.65	-1.02	0.83	0.58	1.01	2.37	0.48	39900.44	6.01	0.86	4.17	1.16	1.01	11.85	2.39	20.58
18	-1.32	-1.56	-0.78	0.41	-2.28	-1.28	0.60	0.51	0.87	2.00	0.31	33333.16	4.91	0.68	3.01	1.02	0.87	9.98	1.55	16.43
19	-1.10	-1.76	-1.05	0.40	-2.20	-1.47	0.70	0.44	0.72	1.98	0.33	29326.13	4.72	0.65	3.49	0.89	0.72	9.92	1.63	16.66
20	-0.35	0.08	-0.81	0.68	-1.99	-1.36	1.17	1.58	0.86	2.41	0.38	31548.99	6.98	0.97	5.87	3.17	0.86	12.04	1.88	23.82
21	-1.07	-1.45	-0.93	0.65	-1.54	-1.59	0.71	0.55	0.79	2.35	0.52	26956.25	5.42	0.76	3.57	1.10	0.79	11.75	2.58	19.79

Note: In the CF calculations, the reference values for the elements are based on [68] (Cu: 25 ppm, Cr: 126 ppm, Zn: 65 ppm, Pb: 14.80 ppm, Ni: 56 ppm, and Fe: 54000 ppm).

4.2 Indices of weathering

In geogenic processes, weathering and/or alteration are the primary factors influencing the physical and chemical properties of soils, as well as the accumulation of heavy metals within them. The mobility of heavy metals in soils generally occurs under oxygen-deficient (reducing) conditions, during which redox reactions control the release, transport, and redistribution of metals. Furthermore, the accumulation of heavy metals in soils is largely governed by their ability to bind with organic matter and by the degree of weathering or decomposition of the parent material [50]. Soils with higher organic content tend to retain metals through adsorption and complexation processes, whereas in more intensely weathered soils, the breakdown of mineral structures may enhance metal mobility and bioavailability [51].

A variety of weathering indices have been proposed by different researchers [52]-[56] to quantify the degree of rock weathering based on chemical analyses. These calculations generally rely on ratios among major cations such as Ca, Mg, K, Na, Al, and Si. As outlined in the geological framework, the study area is composed entirely of igneous rocks and their weathering products. In addition to the commonly applied weathering indices for granitic rocks, loss on ignition (LOI) has also been considered a reliable indicator of weathering intensity [57]. LOI reflects the abundance of weathering products containing volatile components such as OH^-, H_2O, and CO_3 in the bulk rock [57]-[59].

The excess of these weathering products indicates an increase in the degree of weathering of the bedrock. The LOI values of weathering products in the study area (LOI_{avg}: 3.41) vary between 0.80 and 5.81. This value can be considered as the degradation limit, especially for granitic rocks. The binary variation diagram of other weathering indices and heavy metals with increasing degree of weathering with reference to LOI is given in Figure 6. In the diagram, the LOI value is negatively correlated with RR and WIP and positively correlated with CIA, CIW, and PIA.

4.2.1 Ruxton ratio (RR)

The Ruxton Ratio (RR) is a simple weathering index proposed by Ruxton [52] to determine the degree of weathering of igneous rocks, particularly those with acidic and intermediate compositions. This ratio is based on the relationship between silica loss and total element loss within the rock and is based on the assumption that Al is immobile during the weathering process [60]. Mathematically,

$$RR = mol\ SiO_2/mol\ Al_2O_3 \quad (1)$$

While RR is expected to be >10 in undifferentiated rocks, it is observed that this value decreases gradually as the degree of weathering increases. Although weak, a negative correlation with LOI (R^2: 0.4448) is observed (Figure 6a), with RR values ranging between 5.88 and 8.51. The average RR value of 7.01 in the soils indicates moderate weathering in the study area. The RR values tend to be lower, particularly in areas with a relatively thicker soil horizon.

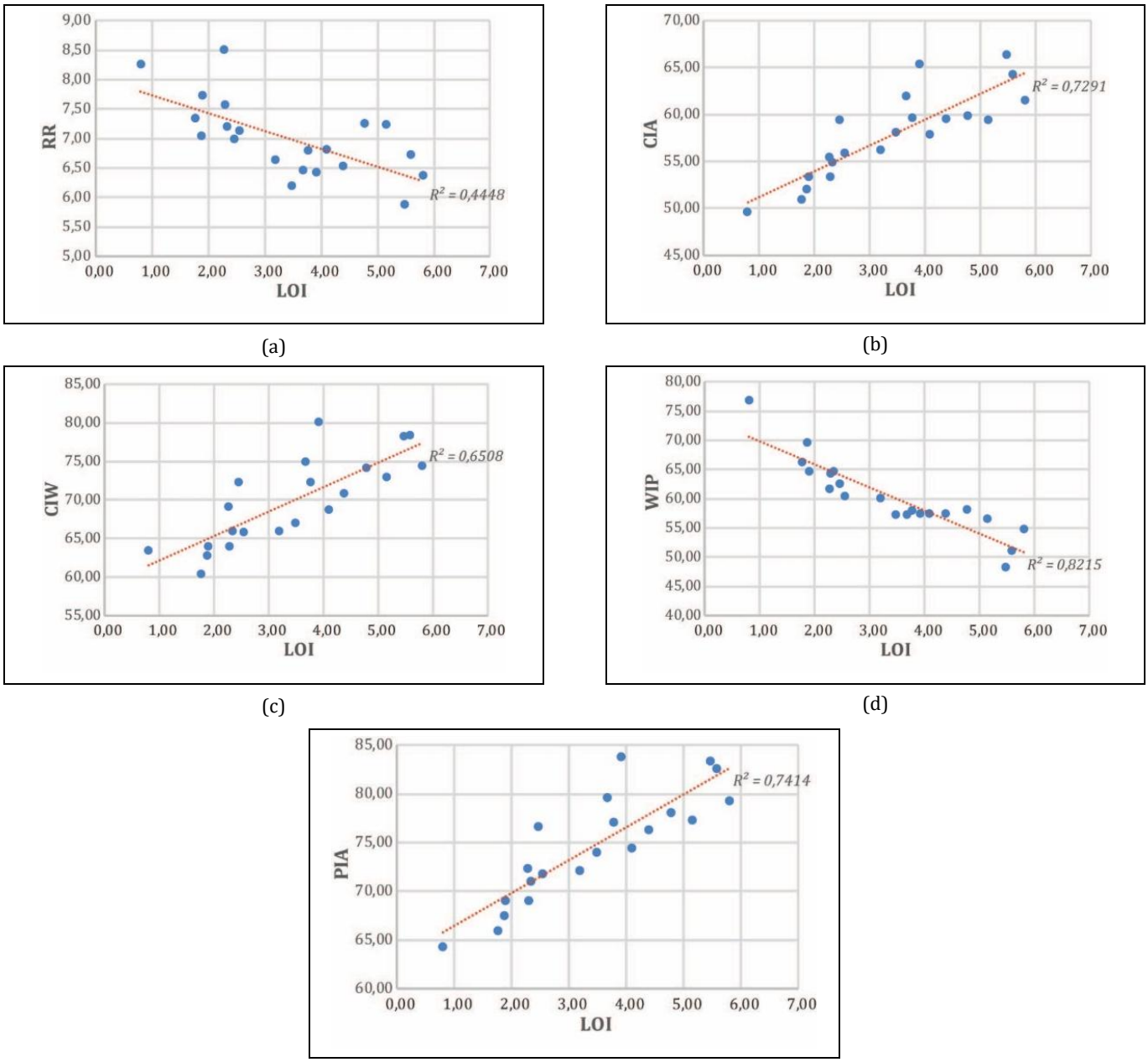


Figure 6. Variation diagrams of weathering indexes vs LOI.

4.2.2 Chemical index of alteration (CIA)

The chemical alteration index [54] is an index based on the changes in chemical composition associated with the weathering of feldspar, a major component of the continental crust, and the formation of clay minerals [61]. It is a potentially useful index for evaluating the degree of chemical weathering. High CIA values reflect the removal of mobile cations (e.g., Ca^{2+}, Na^{+}, K^{+}) relative to immobile components (Al^{3+}, Ti^{4+}) during weathering [53]. In contrast, low CIA values indicate an almost absence of chemical weathering and thus may reflect cool and/or arid conditions [56]. The general formula is;

$$CIA = 100x[Al_2O_3/(Al_2O_3 + CaO + Na_2O + K_2O)] \quad (2)$$

CIA (where the variables represent the molecular proportions of each major element oxide and CaO* denotes the silicate-bound CaO) varies between 45 and 55 in silicic igneous rocks, while these values vary between 25 and 45 in mafic igneous rocks. CIA, which is positively correlated with LOI (R^2: 0.7291) in the study area (Figure 6b), ranges from 49.58 to 66.33 (avg: 57.86). Changes in saproch and saprolites, where decomposition is less than in granitoid-derived soils, can be easily followed using CIA [62].

4.2.3 Chemical index of weathering (CIW)

The Chemical Weathering Index (CIW), proposed by Harnois [55], is quite useful in determining the degree of weathering of granites and basalts. CIW, which is very similar to CIA, tends to adsorb more K+ than Na+ and Ca^{2+} by clay particles due to its high exchange capacity. This indicates that K_2O should not be used in rocks rich in K-feldspar, whether weathered or not, because the Al_2O_3 values associated with K-feldspars may be high [63]. In this case, CIW;

$$CIW = 100x[Al_2O_3/(Al_2O_3 + CaO + Na_2O)] \quad (3)$$

(where the variables represent the molecular proportions of each major element). CIW is ≤50 in igneous rocks where no weathering or partial weathering is observed [64]. This value increases with increasing weathering [60]. The CIW ranges between 60.45 and 80.18 in the study area with an average value of 69.81, indicating a medium-high degree of weathering. The CIW, which presents a positive correlation (R^2: 0.6508) with LOI (Figure 6c), more clearly demonstrates the difference between the degrees of segregation in the region.

4.2.4 Weathering index of Parker (WIP)

Based on the abundances of alkali and alkaline earth elements within the rock [60], the Weathering Index of Parker (WIP) is used to evaluate the intensity of weathering in magmatic and metamorphic rocks. Formulated by Parker [53];

$$WIP = 100[(2Na_2O/0.35) + (MgO/0.9 + (2K_2O/0.25) + (CaO/0.7)] \quad (4)$$

The WIP essentially represents an approach based on the mass transfer of mobile elements. In magmatic rocks, WIP values typically range from 0 to 100 [64]. Low WIP values indicate intense chemical weathering, whereas high values reflect relatively unweathered bedrock [65]. Consequently, WIP exhibits a strong negative correlation with LOI (R^2: 0.8215) (Figure 6d). In the study area, the average WIP is 60.25; while WIP values are calculated as 48.32 in granitoid-derived soils, they increase up to 76.79 in fresh bedrock.

4.2.5 Plagioclase index of alteration (PIA)

Plagioclase, a major component of crystalline rocks, can dissolve relatively quickly during weathering processes and transform into clay minerals. Therefore, it can be effectively used to assess the degree of weathering in magmatic and metamorphic rocks. Fedo et al. [56] noted that the exclusion of K_2O in some weathering indices may be insufficient to reveal metasomatic effects and proposed the following formulation to more accurately track weathering:

$$PIA = 100(Al_2O_3 - K_2O)/(Al_2O_3 + CaO + Na_2O - K_2O) \quad (5)$$

In unweathered magmatic and metamorphic rocks, PIA values are ≤50, and they increase with progressive weathering [64]. In the study area, PIA exhibits a positive correlation with LOI (R^2: 0.7414) (Figure 6e), ranging from 64.33 in fresh bedrock to 83.79 in granitoid-derived soils.

4.3 Environmental risk assessment

Environmental Risk Assessment is a process that evaluates the likelihood or probability of adverse impacts on environmental values resulting from human activities. Environmental risk assessment is based on comparing changes in environmental indicators over time. Heavy metals, one of the environmental risk factors, pose a risk to both environmental quality and public health when present in high concentrations in soil. Therefore, various researchers have developed various methods to assess heavy metal risk in soil to identify these risks and take necessary precautions.

The objectives of this study are to determine the concentration and distribution of heavy metals in soil samples, to identify heavy metal sources using multivariate analyses, and to assess the potential ecological risk levels of heavy metals using ecological risk indices. To determine the risks within the scope of the study, the following indices were calculated and evaluated: Geo-accumulation index (I_{geo}), Contamination factor (CF), degree of contamination (Cd), Pollution Load index (PLI), Ecological risk index (ERi), and potential ecological risk (PERI). These risk indices have also been widely applied in evaluating temporal variations in environmental conditions and in quantifying the extent of anthropogenic contributions to metal contamination.

By distinguishing between natural (geogenic) and human-induced (anthropogenic) sources, the indices provide an useful tool for assessing the degree of metal enrichment in different environmental media, such as soils, sediments, and atmospheric particulates, thereby offering valuable insights into the dynamics and evolution of pollution over time [66], [67].

4.3.1 Geo-accumulation index (I_{geo})

The calculation of Igeo, introduced by Müller [69], is based on the concentration of elements in the Earth's crust [24]. Thus, not only the effects of anthropogenic factors on metals but also the effects of natural geological processes are taken into account [25], [70], [71]. I_{geo} is used to quantitatively assess heavy metal pollution in sediments and other environments [72], [73]. In recent years, it has also been widely applied to assess heavy metal pollution in soils [74]. Its general formula;

$$I_{geo} = log_2(C_n/\mathrm{k}\, C_0) \quad (6)$$

Where Cn: the concentration of heavy metal element n in the soil sample, k represents the lithogenic effect factor (k=1.5 was taken by Ruiz [75] to account for possible changes in the earth's crust due to lithological differences), Co: the reference value for heavy metal elements in the soil [24], [75].

According to the Igeo values calculated for the study area, most of the samples are in the "Practically uncontaminated" classification. According to the lead, it is in the "Uncontaminated to moderately contaminated" class (Figure 7). Typically, the geo-accumulation index shows the heavy metal pollution status of the soil.

In the study area, the average Igeo values calculated based on heavy metal contents decrease in the order of Pb, Zn, Cu, Fe, Cr, and Ni. The lowest calculated Igeo value is observed for Cr (-4.59), while the highest is for Pb (1.00). The dominance of magmatic rocks and the soils derived from them within the study area supports this variation.

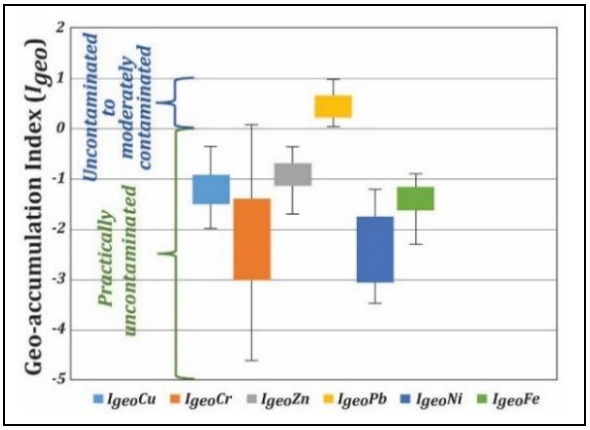


Figure 7. The box-plot graphic of the Geo-accumulation index.

All elements except Pb show negative values. The I_{geo} values indicate that the area is not contaminated with respect to all measured elements, except for Pb, which shows an uncontaminated to moderately contaminated level.

Negative I_{geo} values of the samples in the study area may indicate that there is no pollution in the area, or even that the environment is cleaner than the natural background value. This usually means that there is no or very low anthropogenic pollution impact.

4.3.2 Contamination factor (C_f) and degree of contamination (C_d)

The pollution factor is defined as the ratio of the concentration of each metal in the soil to the reference value [76]. CF was used to understand how much heavy metals were present in soil samples.

$$C_f^i = (C_n^i / B_n^i) \quad (7)$$

$$C_d = \sum_{i=1}^{n} C_f^i = (C_n^i / B_n^i) \quad (8)$$

Where, C_f^i represents the contamination factor for element i, C_n^i represents the concentration of metal i in the soil sample, and B_n^i represents the geochemical reference value or average crustal values. The degree of contamination (Cd) is the sum of all contamination factors. The calculated Cf values for samples in the study area range from 0.06 (for Cr) to 2.98 (for Pb) (Table 3 and Figure 8).

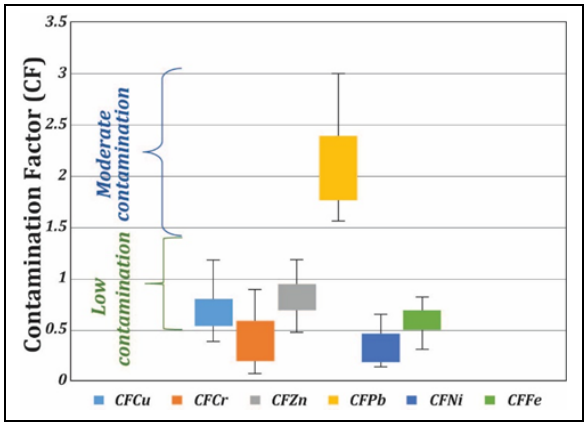


Figure 8. The CF Values of samples in the study area.

An examination of the contamination factor values reveals that only CFPb values fall into the "Moderate contamination" class. Cd values range between 3.51 and 6.98 (Table 3). It shows that the Cd values of all samples are less than 8 and fall into the "Low degree contamination" class (Table 4).

Table 4. The ecological risks index classification.

Index	Range	Classification
Geoaccumulation Index (I_{geo}) [39]	I_{geo}<0	Practically uncontaminated
	0≤ I_{geo} ≤1	Uncontaminated to moderately contaminated
	1≤ I_{geo} ≤2	Moderately contaminated
	2≤ I_{geo} ≤3	Moderately to heavily contaminated
	3≤ I_{geo} ≤4	Heavily contaminated
	4≤ I_{geo} ≤5	Heavily to extremely contaminated
	5≤ I_{geo}	Extremely contaminated
Contamination Factor (C_f^i) [51]	C_f^i<1	Low contamination
	1 ≤ C_f^i<3	Moderate contamination
	3 ≤ C_f^i<6	Considerable contamination
	6 ≤ C_f^i	Very high contamination
Degree of Contamination (Cd) [51]	C_d<8	Low degree contamination
	8≤ C_d <16	Moderate degree of contamination
	16≤ C_d <32	Considerable degree of contamination
	32≤ C_d	Very high degree of contamination
Pollution Load Index (PLI) [56]	PLI≤0	Background concentration
	0<PLI≤1	Unpolluted
	1<PLI≤2	Unpolluted to moderately polluted
	2<PLI≤3	Moderately polluted
	3<PLI≤4	Moderately to high polluted
	4<PLI≤5	Highly polluted
	PLI>5	Very highly polluted

4.3.3 Pollution load index (PLI)

The pollution load index (PLI) is an index calculated to assess water, soil, and sediment quality [24], [76]-[78]. It was introduced by Hakanson [79] in 1980 to assess the pollution levels of various pollutants. The formula is based on calculating the product of the nth root of the pollution factor (Cfx) of each pollutant.

$$PLI = (CF_1 \text{ x } CF_2 \text{ x } \dots \text{ x } CF_n)^{1/n} \quad (9)$$

Where, CF1, CF2, and CFn are the elemental concentration factors. PLI>1 indicates polluted, PLI =1 indicates basic pollution, and PLI<1 indicates unpolluted [78], [80]. PLI values in the study area range from 0.36 to 0.97. As all values were < 1, the area is classified as unpolluted according to the PLI [81]. The values close to zero mean that no contamination is detected in the sediment according to PLI. While CF assesses each element individually, PLI combines all these CF values to provide an overall environmental quality indicator (Figure 9).

4.3.4 Ecological risk index (ERI) and potential ecological risk (PERI)

ERI and PERI are used to assess the degree of environmental and ecological sensitivity caused by the presence of hazardous heavy metals in soil and the potential toxicity risk of all measured heavy metals [24], [79], [82], [83].

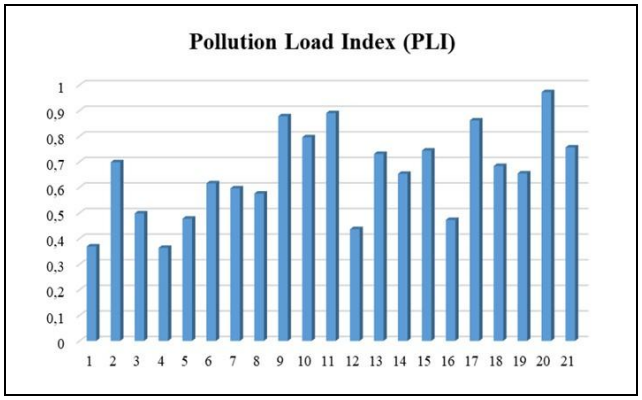


Figure 9. The Pollution Load Index (PLI) graph of samples.

It evaluates not only the pollution level but also potential ecotoxicological effects. It is a highly meaningful indicator, especially for ecosystem health and risk management. It gives an overall risk status by combining the effects of many metals.

The ERI is a comprehensive ecological risk assessment tool that takes into account both the amount of the metal in the environment and the toxic effect of that metal.

$$ERI = TR_x \text{ x } CF_{2x} \quad (10)$$

$$PERI = \sum_{x=1}^{n} EI_x \quad (11)$$

Trx and Cfx correspond to the toxic response factor and contamination factor for element x, respectively. The toxic response factors for each element can be found in Table 5.

Table 5. Factors of metal toxicity [79].

Element	Factor
Hg	40
Pb	5
Zn	1
As	10
Cr	2
Co	5
Ni	5
Cu	5

The PERI index is defined as the sum of the environmental risks associated with all elements and the individual environmental risks of these elements [78], [84].

$$PERI = \sum Er \quad (12)$$

The ERI values vary between 0.13 (for Cr) and 14.95 (for Pb) in the study area (Table 3). The PERI values range from 12.48 to 23.82 in the study area (Table 3).

PERI classifies soils and sediments into four categories: low ecological risk (PERI<150), moderate ecological risk (150<PERI<300), high potential ecological risk (300<PERI<600), and significantly high ecological risk (PERI>600) [24]. All samples are <150, so they are reflected in the low ecological risk class.

5 Discussion

When the geochemical analysis results of the soils in the study area, given in Table 1, are analysed, a significant decrease in Na_2O is observed, especially due to the increasing weathering degree, while a partial increase in Al_2O_3 value is observed. This situation shows that the Na released by the weathering of plagioclase type feldspars in the weathering/alteration process may have been rapidly removed from the environment. When the change of K_2O during the weathering process is analysed, it is observed that K_2O concentrations in granitoid-derived soils are lower than the concentrations in the bedrock. This indicates both that K is leached during soil formation [55] and that no diagenetic process [85] is effective in the formation of soils in the region.

In order to classify the weathering degree of weathering products in the study area, the ACNK triangle diagram [54] drawn according to the chemical alteration results was transferred (Figure 10). According to the diagram, the weathering degree in the region is seen as low to medium weathered units.

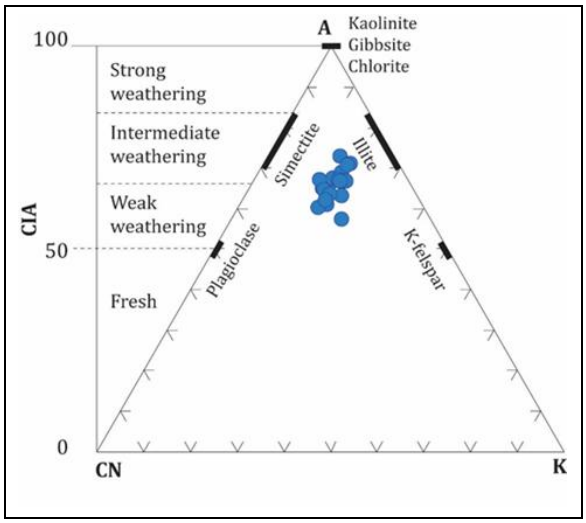


Figure 10. Distribution of granitoid-derived soil in the ACNK diagram and classification according to CIA value [54].

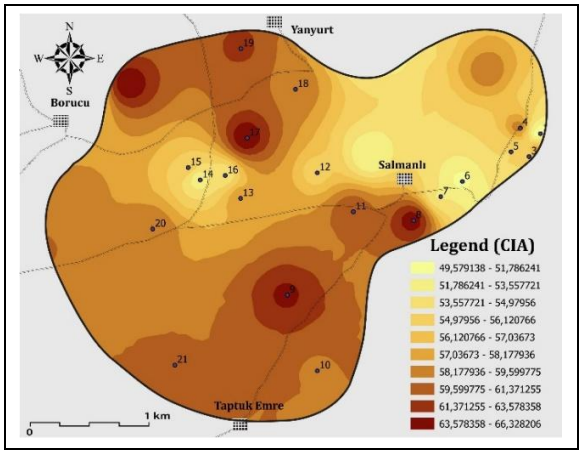
While the calculated CIA value was 49.5 in fresh rock, it was observed that this value increased up to 66.3 with increasing weathering.

The spatial distribution maps prepared by the Inverse Distance Weighting (IDW) interpolation method according to the weathering indices whose calculated values are given in Table 1 are given in Figure 11 and Figure 12. In the maps presenting similar distributions, an increase is observed in the other indices except the Ruxton ratio, especially in the areas where soilisation is intense and even in the areas used as agricultural land. The approach of the Ruxton ratio toward zero is considered an indicator of intense weathering. In this regard, the Ruxton ratio also indicates similar degrees of weathering to those suggested by the other weathering indices.

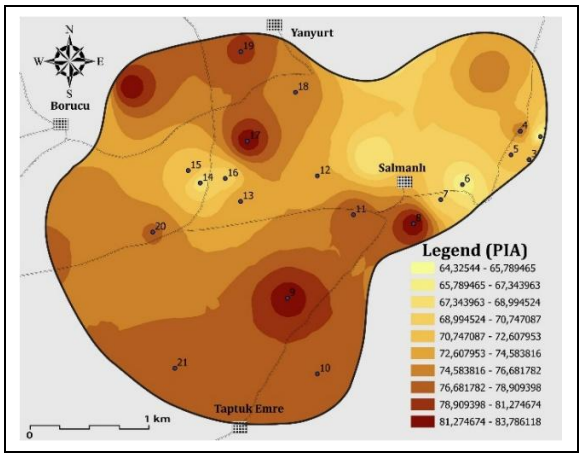
5.1 Assessment of heavy metal distribution in granitoid-derived soils

Various natural and anthropogenic factors influence the concentration of heavy metals in soils. Among the natural factors are parent material, elevation, soil type, slope, soil pH, organic matter content, and cation exchange capacity [86]. In contrast, anthropogenic factors include land use practices, traffic intensity, mining activities, and industrial density [87],

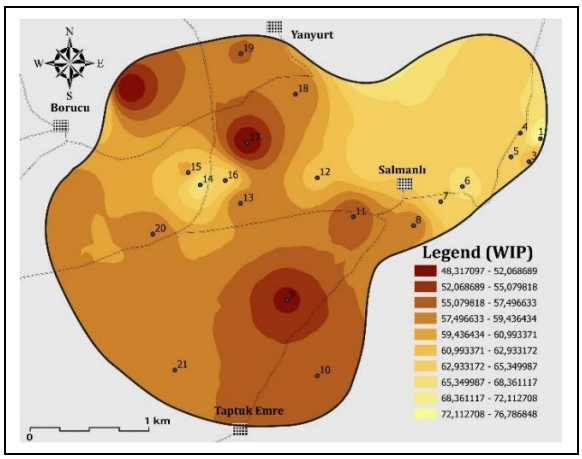
[88]. The spatial variability of heavy metal concentrations and associated risks underscores the need for geographically targeted interventions. Regulating agricultural practices, particularly the use of fertilizers and pesticides, is crucial to preventing further anthropogenic contamination. Moreover, raising public awareness of soil pollution, exposure risks, and safe agricultural practices plays a vital role in safeguarding community health [89], [90].



(a)

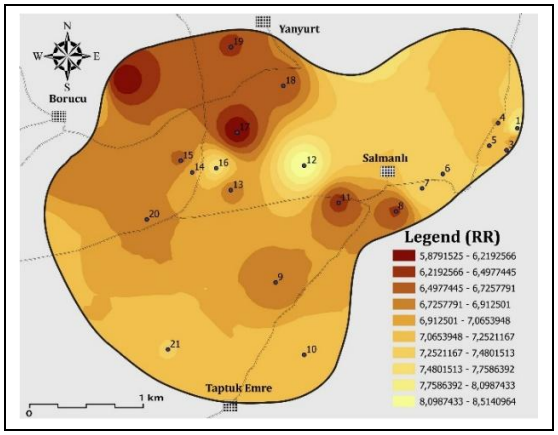


(b)

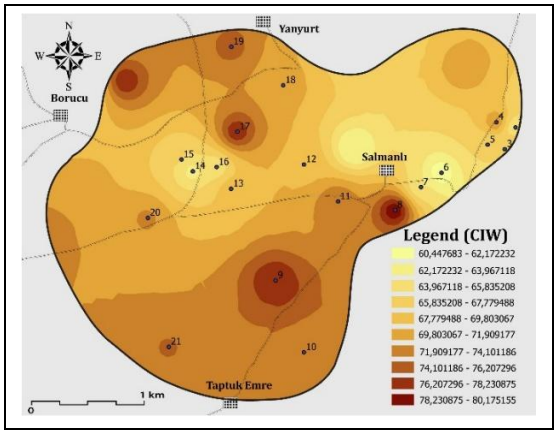


(c)

Figure 11. The spatial distribution maps of weathering indexes (a): CIA, (b): PIA, (c): WIP.



(a)



(b)

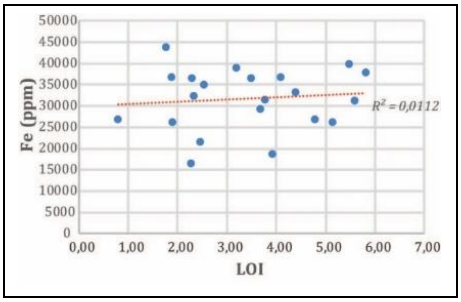
Figure 12. The spatial distribution maps of weathering indexes (a): RR, (b): CIW

In the study area, soils developed through the alteration of granitic rocks generally exhibit elemental compositions comparable to those of their parent material. The freshest representative granitoid sample (sample no. 1) reveals concentrations of Fe (26,995.1 ppm), Cu (13 ppm), Cr (8 ppm), Pb (25.8 ppm), Ni (7.6 ppm), and Zn (42.4 ppm).

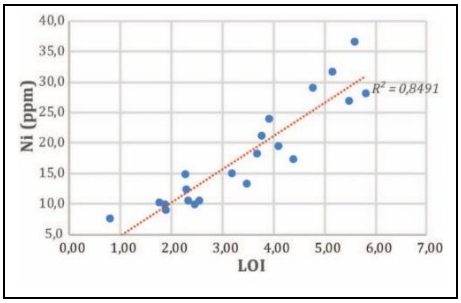
When compared with the average concentrations in soils, the relative enrichment with respect to the bedrock is most pronounced in Ni (avg: 18.3 ppm)140.9%, followed by Cu (avg: 17.3 ppm) 33.5%, Zn (avg: 53.9 ppm) 27.2%, Pb (avg: 30.9 ppm) 20% and Fe (avg: 31883.9 ppm) 18%.

The overall mean enrichment of heavy metals in soils is calculated at 47.9%. These results indicate that, although the degree of enrichment varies among elements, the soils have generally undergone geochemical modification influenced by the weathering of magmatic parent materials. Although such an increase may suggest a high degree of contamination in the derived soils, ecological risk factors based on average upper continental crust values indicate only a low degree of pollution, specifically with respect to Pb.

To further elucidate the relationship between heavy metal distribution and the degree of weathering, bivariation diagrams of heavy metals versus loss on ignition (LOI) were constructed (Figure 13 and Figure 14).

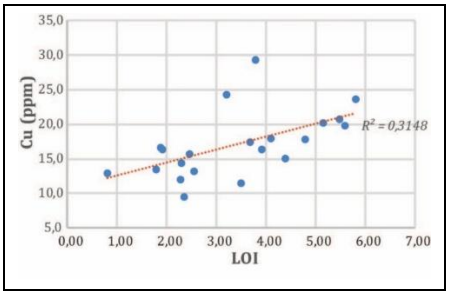


(a)

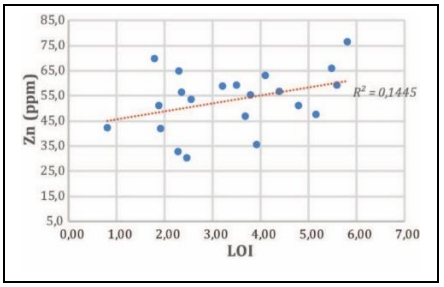


(b)

Figure 13. Variation diagrams of LOI vs (a): Fe and (b): Ni.



(a)



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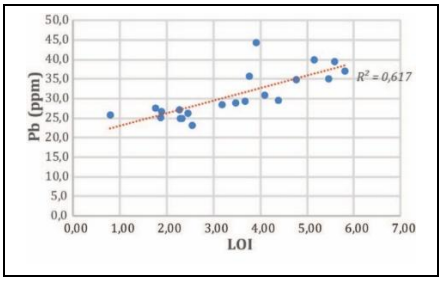
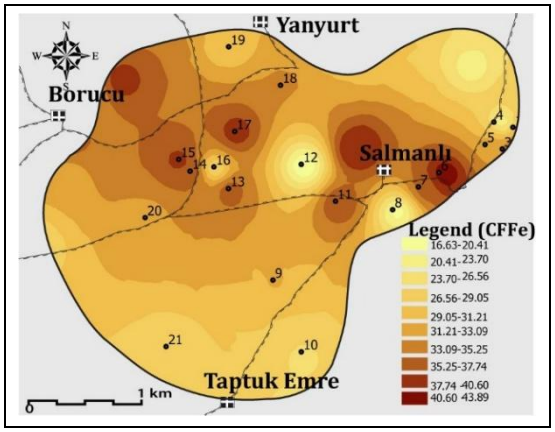


(c)

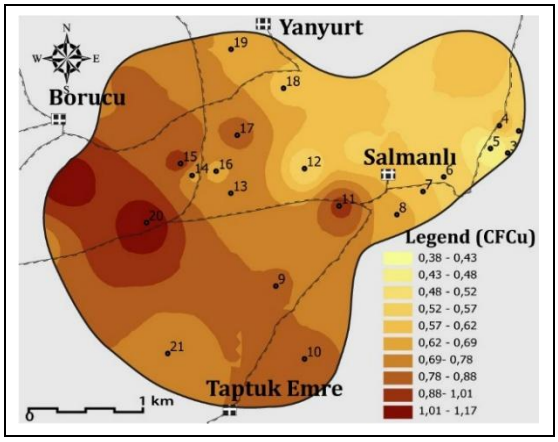
Figure 14. Variation diagrams of LOI vs (a): Cu, (b): Zn, and (c): Pb.

These diagrams provide insights into how the intensity of chemical weathering influences the redistribution of heavy metals within granitoid-derived soils.

In the variation diagrams, all heavy metals exhibit a general tendency to increase with progressive degrees of weathering. However, the magnitude of these increases does not reach concentrations that would indicate a distinct or localized point-source contamination. Among the analyzed elements, Pb displays a comparatively stronger enrichment. Environmental risk indices calculated from the geochemical composition of granitoid-derived soils support the interpretation that this enrichment is not associated with a dominant anthropogenic pollution source. In particular, the CF index for Pb exhibits a distinct spatial concentration in areas where gabbroic rocks are exposed, indicating that Pb is preferentially enriched in these zones. This enrichment likely reflects the geochemical behavior of Pb during the weathering and alteration of gabbroic rocks, suggesting that the separation and subsequent breakdown of gabbroic rocks may have played a significant role in the localized accumulation of Pb (Figure 15 and Figure 16). Although the calculated environmental risk assessment indices generally present similar spatial distribution patterns, distribution maps in this study were generated based on the CF (Contamination Factor) values (Figure 15 and Figure 16).

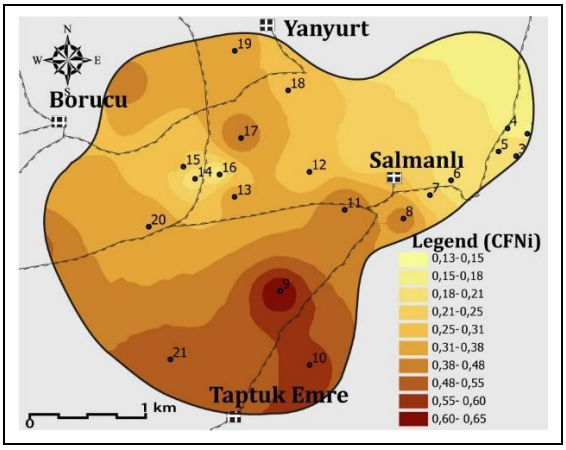


(a)

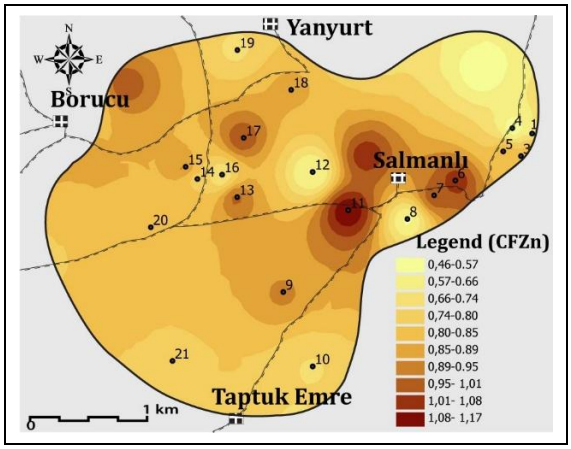


(b)

Figure 15. The spatial distribution maps of (a): CFFe and (b): CFCu index values.



(a)



(b)

Figure 16. The spatial distribution maps of (a): CFNi and (b): CFZn index values.

This parameter was selected particularly because, according to the calculated index values, it indicates an unpolluted status for the area, thereby providing a more reliable basis for evaluating the elemental distribution and potential sources of heavy metals in the region.

The low levels of contamination observed for certain elements are more plausibly attributed to geogenic origins, specifically the weathering of pre-existing magmatic rocks. This finding highlights that within a granitic basin, areas experiencing higher degrees of weathering represent zones of increased sensitivity with respect to potential contamination.

From an environmental management perspective, these results emphasize the necessity of distinguishing between natural geochemical background levels and anthropogenic contributions when evaluating heavy metal distributions. Recognizing the geogenic origin of the observed enrichments is crucial to avoid misinterpretations that could lead to unnecessary remediation measures.

Nevertheless, the identification of weathering-intensified zones as more vulnerable to contamination underlines the importance of implementing site-specific land-use planning, sustainable agricultural practices, and continuous soil monitoring. Such measures will not only help to prevent future anthropogenic inputs but also ensure the long-term protection of soil and water resources in granitic landscapes.

6 Conclusion

The present study highlights the relationships between chemical weathering, heavy metal enrichment, and potential environmental risks in the granitoid-derived soils area. Binary variation diagrams indicate that heavy metal concentrations tend to rise with increasing intensity of weathering, with Pb exhibiting the most significant enrichment. The Chemical Index of Alteration (CIA) further confirms progressive alteration, increasing from 49.5 in fresh rocks to 66.3 in weathered soils.

The enrichment of heavy metals, including Ni, Cu, Zn, Pb, and Fe, does not indicate significant anthropogenic pollution. Spatial patterns of HMs enrichment coincide with outcrops of gabbroic rocks, suggesting that the observed concentrations are primarily geogenic in origin and may be associated with the weathering of mafic lithologies rather than human activities. Environmental risk assessment indicates that the overall average enrichment of heavy metals in soils is, with the contamination factor (CF) effectively representing elemental distributions. The area is generally considered unpolluted, with the exception of minor Pb contamination, suggesting that the natural geochemical background predominantly governs the observed HM concentrations.

These findings have important implications for environmental management. Highly weathered zones within granitic catchments are more sensitive to potential contamination. Although current heavy metal levels are mainly geogenic, these zones remain vulnerable to anthropogenic inputs from agriculture, traffic, and localized industrial activities. Differentiating natural geochemical background levels from anthropogenic contributions is therefore crucial for accurate risk assessment, sustainable land-use planning, and the long-term protection of soil and water resources in granitoid terrains.

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8 Author contribution declaration

Özlem Güllü and Bahattin Güllü declare that they contributed equally to the study within their disciplines at the manuscript conception, field, laboratory, and writing stages.

9 Ethics committee approval and conflict of interest declaration

"Ethics committee permission is not required for the prepared article". "There is no conflict of interest with any person/institution in the prepared article".

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