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# Using statistical analysis and pollution indices to characterize metal pollution in volcanic and calcareous soils in semi-arid regions

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## ABSTRACT

The main objective of this study was to evaluate heavy metal contamination in volcanic and calcareous soils within Morocco's semi-arid regions, focusing on the relationship between unique soil types and contamination dynamics. Using geographic information systems (GIS), statistical analyses, and several pollution indices, including the geoaccumulation index (Igeo), enrichment factor (EF), contamination factor (CF), and pollution load index (PLI), the research integrates physical and chemical properties to uncover the interactions driving contamination. A total of 64 soil samples from volcanic and calcareous origins, collected at a depth of 20 cm, were analyzed for properties such as organic matter, calcium carbonates $CaCO_3$, pH, electrical conductivity, and texture, and four heavy metals (Cu, Pb, Zn, and Fe). Findings reveal distinct contamination patterns: calcareous soils had elevated pH, high $CaCO_3$ levels, and moderate salinity, whereas volcanic soils were more acidic, with higher organic matter content and lower salinity. The contamination indices revealed that all soil samples exhibited some level of contamination, with Zn and Fe concentrations in volcanic soils showing moderate to high pollution levels, while calcareous soils generally displayed lower contamination. The Igeo and CF indices confirmed moderate to high contamination in volcanic soils, particularly for Zn and Fe, whereas calcareous soils showed minimal pollution. The EF analysis indicated slightly higher enrichment for Cu and Zn in calcareous soils than in volcanic soils. The PLI values for both soil types were below 1, suggesting low pollution levels overall. Statistical analyses demonstrated that contamination was shaped by soil characteristics like texture, organic matter, and pH, with anthropogenic sources contributing to heavy metal presence. This study provides new insights into the interaction between soil properties and contamination dynamics in contrasting soil types, revealing that volcanic soils are more prone to heavy metal accumulation due to their physicochemical characteristics. By integrating pollution indices and robust statistical approaches, this work highlights the influence of soil geochemistry on contamination patterns and offers valuable information for informing sustainable land management strategies in vulnerable semi-arid regions.

**Keywords:** heavy metals, GIS, metallic pollution, pollution indices, Morocco.

## INTRODUCTION

Soil, a dynamic and delicate environment, is shaped by complex biological and physico-chemical interactions essential for sustaining ecosystem functions (Gros, 2002; Robert, 1996). As the outermost layer of the Earth's crust, soil is composed of a complex mixture of minerals, organic matter, water, air, and a diverse array of organisms. It supports its own internal ecosystem with diverse flora and fauna. Moreover, soil is widely acknowledged as a component of the environment vulnerable to pollution, particularly through the accumulation of heavy metals over time (Mazurek et al., 2017). In arid regions, calcareous-magnesium soils are characterized by high alkalinity, low organic matter content, and limited capacity to retain heavy metals, increasing their vulnerability to pollution (Adhikari et al., 2018; Chai et al., 2015; Chen et al., 2021; Khosravani et al., 2023; Suleymanov et al., 2024). In contrast, volcanic soils originating from materials ejected during volcanic eruptions, are characterized by mineral richness and exceptional water and nutrient retention, owing to their unique structure and high cation exchange properties (Delvaux et al., 1989; Shoji et al., 1993; Takahashi et al., 1993). Soil contamination primarily occurs through the application of agrochemicals, organic amendments, herbicides, pesticides, irrigation with wastewater, and phosphate fertilizers (Barakat et al., 2017; Hilali et al., 2020; Huang et al., 2007), which can impair soil productivity. Furthermore, the accumulation of contaminants in crops such as maize poses significant risks to human and animal health as well as to the wider ecosystem.

In Morocco, studies conducted in the Tadla Plain provide valuable insights into soil metal contamination. For instance, Oumenskou et al. (2018) evaluated heavy metal levels (Zn, Cr, Pb, Cu, and Cd) in the Beni-Amir region. The findings demonstrated that the industrial zones exhibited the highest concentrations of metals. Similarly, El Hamzaoui et al. (2020) found that the agricultural soils of Beni Moussa are contaminated with heavy metals, predominantly stemming from anthropogenic and agricultural sources. Additionally, Hilali et al. (2020) measured metallic elements including Cr, Ni, Cd, As, Pb, Fe, Zn, and Cu in the Day River of Beni Mellal. Their results indicated contamination levels ranging from moderate to high, likely caused by anthropogenic activities such as irrigation with wastewater. Consequently, this excessive accumulation of heavy metals in soils can lead not only to soil contamination but also to the absorption of heavy metals by plants grown in contaminated soils, potentially affecting food security (Muchuweti et al., 2006). Although previous studies have assessed heavy metal concentrations in specific areas, a comprehensive spatial analysis of pollutant distribution, considering soil types and their physico-chemical properties, remains limited. This constrains our understanding of the mechanisms influencing the distribution of heavy metals in different geological contexts.

Among the various soil types, calcareous and volcanic soils are particularly relevant in semi-arid regions due to their distinct properties and vulnerability to pollution. These properties directly influence the ability of soils to immobilize or release heavy metals, as demonstrated by several studies on the physico-chemical interactions between soils and contaminants (Chai et al., 2015; Brady et al., 2008). For instance, the high pH of calcareous soils promotes the precipitation of certain metals, while volcanic soils, rich in minerals, retain metals through their microporous structure. Comparative studies here refer to the analysis of the properties and mechanisms of heavy metal retention in different soil types, such as calcareous and volcanic soils, under similar conditions. Few studies focus on these interactions, particularly in semi-arid regions where these soil types coexist (Shoji et al., 1993; Delvaux et al., 1989).

In this regard, the physicochemical and metallic characterization of soils is essential to understanding their agricultural potential, environmental behavior, and capacity to support various forms of life. Moreover, several indices have been proposed to assess metallic pollution, which may have natural, lithogenic, pedogenic, or anthropogenic origins (El Baghdadi et al., 2015; El Baghdadi et al., 2012; Kowalska et al., 2018; Mazurek et al., 2019). These indices include the EF, CF, Igeo, and PLI (Barakat et al., 2012; Barakat, et al., 2020; El Hamzaoui et al., 2020; Ennaji et al., 2020; Hilali et al., 2020; Mohammadi et al., 2018; Oumenskou et al., 2018; Rastegari Mehr et al., 2017; Zhu et al., 2020).

However, the existing literature often overlooks how soil type mediates the accumulation and mobility of heavy metals, particularly in regions with contrasting geological conditions. While significant research has been conducted, the interplay between soil physicochemical properties and contamination levels in semi-arid regions calcareous and volcanic soils is poorly understood. Additionally, the lack of specific data on the mobility of heavy metals in these soils hinders the implementation of targeted strategies, such as organic amendments tailored for calcareous soils to reduce metal bioavailability or the use of hyper accumulator plants in volcanic soils to extract contaminants (Chen et al., 2021; Mazurek et al., 2017).

To address these gaps, this study aims to characterize calcareous and volcanic soils by conducting a detailed analysis of their physicochemical properties and heavy metal assessment. A better understanding of these parameters is crucial, as it helps grasp the complex interactions among soil components, thereby influencing soil fertility and sustainable management (Brady et al., 2008; Cornell & Schwertmann, 2003). This study is guided by two main hypotheses. First, the distinct physicochemical properties of calcareous and volcanic soils lead to significant differences in their capacity to retain and mobilize heavy metals. Second, contamination patterns are hypothesized to vary spatially, influenced by anthropogenic activities and intrinsic soil characteristics. Thus, this study focuses on the characterization of calcareous and volcanic soils in a semi-arid region of Morocco. By analyzing their physicochemical properties and heavy metal concentrations, pollution indices such as CF, PLI, EF, and Igeo are used to evaluate contamination levels. Furthermore, GIS-based distribution maps and statistical analyses further enhance the understanding of spatial and relational patterns. Focusing on the underexplored interaction between soil types and contamination dynamics in semi-arid regions fills a critical gap in understanding the implications for sustainable soil management and remediation strategies.

## MATERIALS AND METHODS

### Study area

The study area is situated in the semi-arid regions of Morocco and comprises two distinct sections: the first located in the Tadla Plain near Beni Mellal, and the second in the Ifrane region. Both zones are important for agricultural activities, but they differ significantly in terms of geological formations and soil characteristics.

The Tadla Plain, which is part of the Beni Mellal province, represents one of Morocco's key agricultural areas, characterized by its fertile soils, favorable climate, and access to both surface and groundwater resources. Figure 1 shows a map of the study area. Agriculture in this area mainly revolves around cereals, forage crops, olive orchards, and vegetables. However, in recent decades, drought and the intensification of farming activities have led to increased use of irrigation and agricultural inputs, which have impacted the soil and water quality (Barakat et al., 2017; Barakat et al., 2020). The plain is characterized by calcareous soils, which are predominantly composed of limestone and marl from the Quaternary period, contributing to its high agricultural potential (Bouchaou et al., 2009; Ennaji et al., 2020).

The Ifrane region, located within the Middle Atlas Mountains, is known for its volcanic soils,

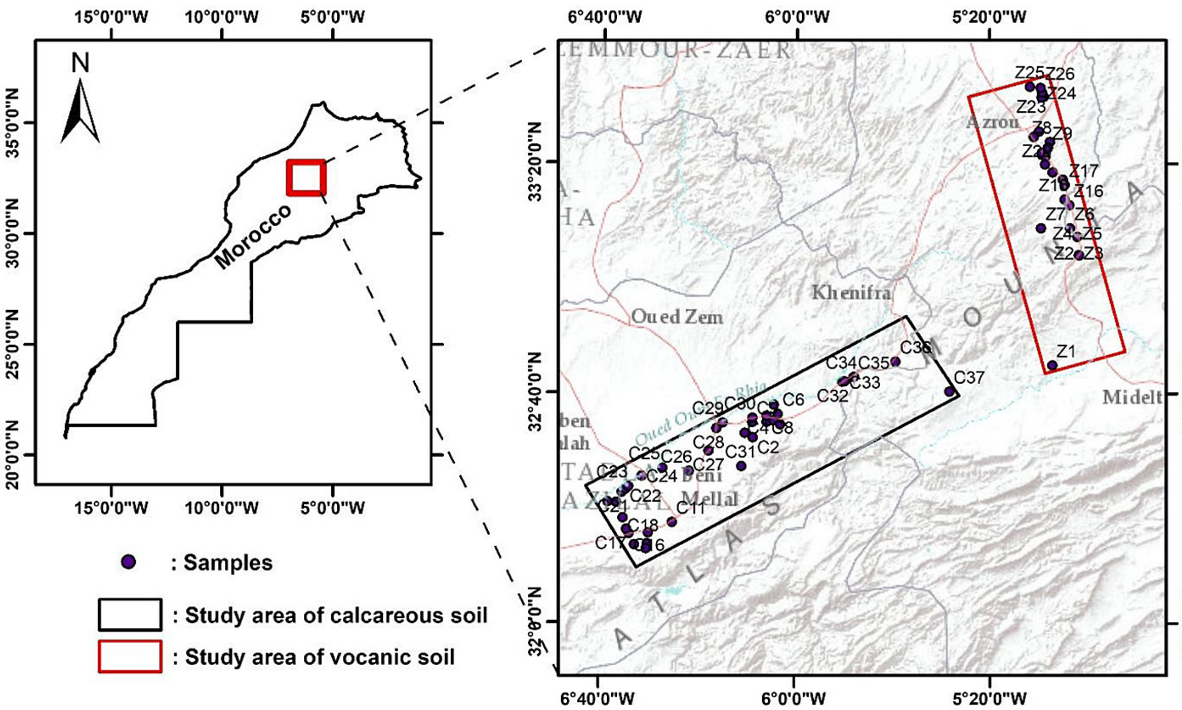


**Figure 1.** Geographical location of the study areas

which result from volcanic activity during the Miocene to Pleistocene epochs (Baadi, 2023; De Waele and Melis, 2009; Michard, 1976). The volcanic soils are rich in minerals and are primarily used for the cultivation of cereals and fruit orchards (Martin, 1981). This region is also known for its distinctive topography, with altitudes ranging from 1300 to 2400 m, creating a complex environment for soil conservation and water management (Michard et al., 2008). The geology in the Ifrane region is dominated by basaltic formations, which, combined with the area's mountainous terrain, present challenges for erosion control and agricultural productivity (Gray, 2013; Sharples, 1995).

Both regions are influenced by a Mediterranean climate with semi-arid characteristics. In Beni Mellal, the climate features a prolonged dry season lasting from April to October, followed by a rainy season extending from November to March. Temperatures range between 40 °C in summer and 3 °C in winter, while the average annual precipitation is approximately 259 mm (Barakat et al., 2017). In contrast, the Ifrane region experiences cooler temperatures due to its higher elevation, with annual rainfall varying between 500 and 700 mm, often in the form of snow in the winter months (De Waele and Melis, 2009).

These climatic conditions, combined with the geological diversity, make the study area particularly vulnerable to soil degradation processes such as erosion, especially in the absence of sustainable land management practices (Benamrane et al., 2022; De Waele and Melis, 2009).

## Sample collection

A total of 64 soil samples were collected, including 37 samples from calcareous soils in the Tadla plain (labeled C1 to C37) and 27 samples from volcanic soils in Ifrane (labeled Z1 to Z27), to assess soil contamination and compare the two soil types. The samples were collected from the surface layer (0–20 cm) using a random method, documented with geographic coordinates, and carefully packed to avoid contamination. In the laboratory, particles larger than 2 mm were removed, and the samples were then homogenized, air-dried, ground, and sieved to less than 63 µm for further analysis. During sampling, special care was taken to avoid contamination by removing surface vegetation while preserving the underlying organic layer. The analysis aimed to evaluate the presence and concentration of heavy metals in both types of soil and to understand the differences in contamination levels between calcareous and volcanic soils.

## Soil analysis

To determine the physicochemical properties and heavy metal concentrations of the soil samples, several analyses were conducted under controlled conditions to prevent contamination. After air-drying, the samples were homogenized and sieved to retain particles smaller than 2 mm. Key properties such as organic matter (OM), calcium carbonate content ($CaCO_3$), pH, electrical conductivity (EC), and particle size distribution (sand, silt, and clay) were measured. EC and pH were determined using soil suspensions in distilled water at specific ratios, while OM and $CaCO_3$ were quantified using the loss on ignition method at elevated temperatures. Texture of soil was assessed following the Robinson pipette method. The concentrations of heavy metals, including Cu, Pb, Zn, and Fe, were measured using X-ray fluorescence (XRF).

## Spatial distribution based on GIS

GIS techniques were used to produce thematic maps for all analyzed parameters, using the inverse distance weighting (IDW) interpolation method. IDW, a deterministic spatial interpolation approach, calculates a point's value by averaging the values of surrounding points, with weights inversely proportional to their distance from the point being estimated.

## Pollution indices

To evaluate the levels of heavy metal contamination in soil samples, several pollution indices were employed, including EF, Igeo, PLI, and CF. These indices are commonly utilized to gauge heavy metal pollution in soils (Gąsiorek et al., 2017; Mazurek et al., 2017). The details of these pollution indices are summarized in Table 1.

## Geoaccumulation index (Igeo)

This index allows for the assessment of heavy metal contamination by comparing its concentration to defined background levels (Muller, 1969). The Igeo was calculated using Equation 1:

$$Igeo = log2 \frac{ci}{1.5Bn} \tag{1}$$

**Table 1.** Pollution index categories: Igeo by Muller (1969), EF by Sutherland (2000), CF by Hakanson (1980), and PLI by Tomlinson et al. (1980)

| Igeo | | EF | | CF | | PLI | |
|---|---|---|---|---|---|---|---|
| Degree of pollution | Value | Degree of enrichment | Value | Degree of contamination | Value | Degree of pollution | Value |
| Uncontaminated | ≤ 0 | Low | < 2 | Low | < 1 | No pollution | < 1 |
| Low | 0–1 | Moderate | 2–5 | Moderate | 1–3 | Polluted | > 1 |
| Moderate | 1–2 | Important | 5–20 | Considerable | 3–6 | | |
| Moderate to high | 2–3 | Very large | 20–40 | Very hight | > 6 | | |
| High pollution | 3–4 | Extremely large | >= 40 | | | | |
| Severe | 4–5 | | | | | | |
| Very severe | > 5 | | | | | | |

where: *ci* represents the metal content in the analyzed soil, and Bn denotes the background metal content. A constant value of 1.5 is used to evaluate minor anthropogenic impacts (Li Fei et al., 2011).

### Contamination factor (CF)

The CF is determined as the ratio between the concentration of each metal (Ci) in the soil and its corresponding background value (C0), calculated using Equation 2:

$$CF = \frac{Ci}{C0} \tag{2}$$

### Enrichment factor (EF)

EF distinguishes elements originating from human activities from those of natural source and evaluates the extent of anthropogenic impact (Lu et al., 2014; Yongming et al., 2006). Its calculation is based on Equation 3:

$$FE = \frac{(Cm/Cfe)sample}{(Cm/Cfe)background} \tag{3}$$

In the context of this study, Cm denotes the concentration of a metallic element in the soil, while Cfe represents the concentration of iron. Elements such as Mn, Al, Sc, Ti, Ca or Fe have commonly been used as reference elements for the Enrichment Factor (EF) (Salmanighabeshi et al., 2015). For this analysis, Fe was selected as the reference element due to its predominant presence in the studied soils. EF values exceeding 1 indicate a likely anthropogenic origin, whereas values below 1 may suggest either mobilization or reduction of the metals (Szefer et al., 1996).

### *Pollution load index (PLI)*

PLI is the number of times the soil metal content exceeds the average background natural concentration (Ololade, 2014), providing an assessment of the overall toxicity level of a sample. The PLI, as proposed by Tomlinson et al. (1980) was used in this study using Equation 4:

$$PLI = \sqrt[n]{CF1 \times CF2 \times CF3 \times \ldots \times CFn} \tag{4}$$

### Statistical analysis

This study used multivariate statistical analysis, including principal component analysis (PCA), hierarchical cluster analysis (HCA), and correlation matrix, to assess soil contamination by heavy metals (Anju and Banerjee, 2012; Idris, 2008; Wang et al., 2012; Yongming et al., 2006). PCA was used to identify pollution sources (natural or anthropogenic) by reducing the number of variables. HCA grouped components with similar properties, while the correlation matrix assessed linear relationships between soil physical and chemical properties (pH, EC, OM, $CaCO_3$, and texture) and metal concentrations (Cu, Pb, Zn, and Fe). All analyses were performed using the R programming language within the RStudio environment.

## RESULTS

### Physico-chemical and heavy metals analysis

Table 2 presents the results of the physico-chemical properties and heavy metals analysis. The results reveal significant differences between calcareous soils and volcanic soils (Figs. 2 and 3). Calcareous soils have a neutral to slightly

**Table 2.** Physical and chemical properties and heavy metal concentrations (mg/kg) in studied soils

| Parameters | | pH | EC (µS/cm) | OM (%) | $CaCO_3$ (%) | Silt (%) | Sand (%) | Clay (%) | Pb | Zn | Cu | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calcareous soils | Min | 6.52 | 60.00 | 0.30 | 1.20 | 66.86 | 3.61 | 0.80 | 0.00 | 41.61 | 0.00 | 11732.33 |
| | Max | 8.46 | 390.00 | 8.01 | 9.74 | 90.79 | 17.13 | 22.60 | 728.77 | 1810.68 | 160.75 | 61019.50 |
| | Mean | 7.74 | 161.11 | 3.85 | 4.01 | 77.94 | 8.88 | 13.18 | 48.03 | 161.75 | 21.44 | 29475.24 |
| Volcanic soils | Min | 6.33 | 59.00 | 1.04 | 0.51 | 11.51 | 6.82 | 0.40 | 0.00 | 90.28 | 0.00 | 13365.32 |
| | Max | 8.13 | 305.00 | 7.70 | 4.11 | 85.89 | 48.66 | 75.00 | 90.03 | 628.78 | 74.12 | 109739.02 |
| | Mean | 7.30 | 140.78 | 3.31 | 1.62 | 62.16 | 24.03 | 13.81 | 29.36 | 218.07 | 40.74 | 71270.50 |

alkaline pH range from 6.52 to 8.46, with an average of 7.74. This is explained by the presence of calcium carbonate ($CaCO_3$), which increases soil alkalinity. In contrast, volcanic soils have a pH ranging from 6.33 to 8.13, with an average of 7.30, indicating a more neutral to slightly acidic trend. The basaltic composition of volcanic soils contributes to this trend by incorporating minerals that can lower pH levels.

Electrical conductivity (EC), an indicator of soil salinity, varies from 60 to 390 µS/cm (average of 161.11 µS/cm) in calcareous soils, indicating moderate salinity. This is likely due to the dissolution of carbonates and irrigation practices that introduce salts. Volcanic soils, however, show an EC ranging from 59 to 305 µS/cm (average of 140.78 µS/cm), indicating lower salinity. This lower salinity in volcanic soils can be attributed to their generally higher drainage capacity, which helps prevent the accumulation of soluble salts.

Organic matter (OM) also differs between the two soil types. Calcareous soils have OM ranging from 0.3% to 8.01%, with an average of 3.85%. The moderate level of OM in calcareous soils

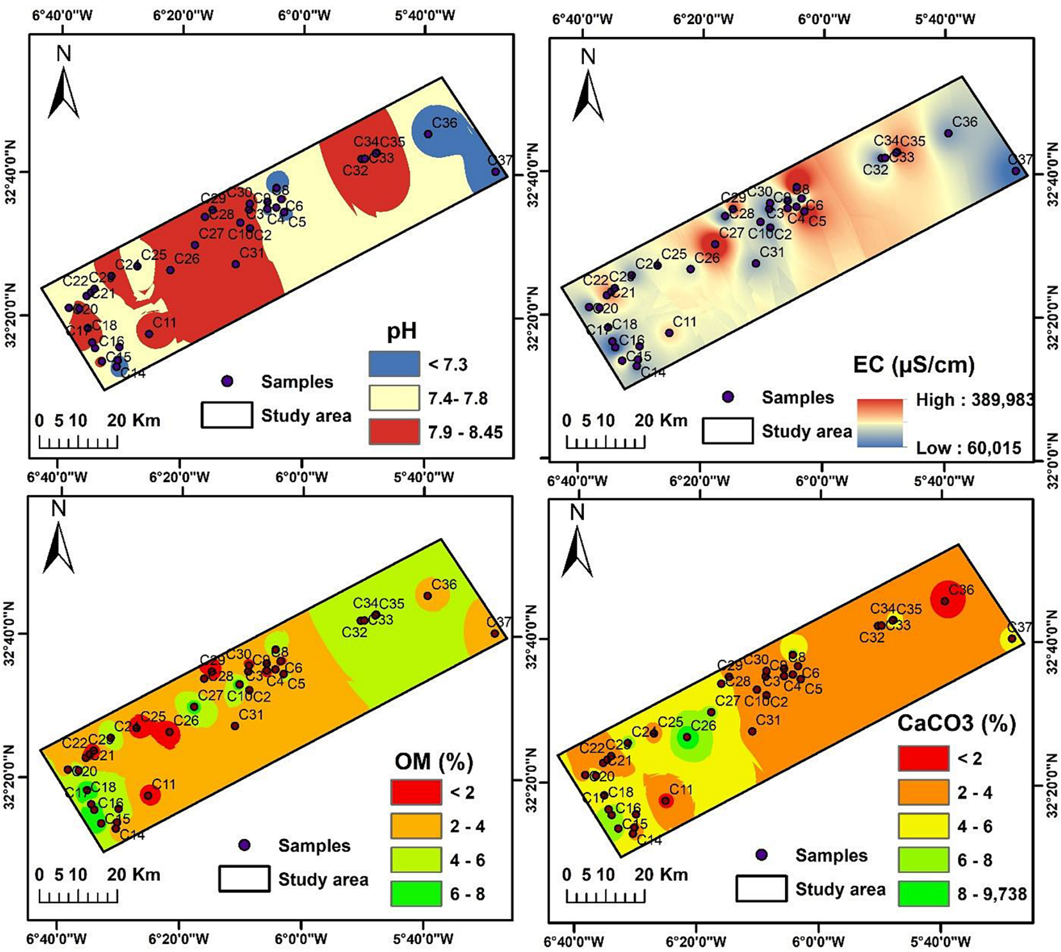


**Figure 2.** Chemical properties of calcareous soil

suggests a slow decomposition rate due to the slightly alkaline conditions. In contrast, volcanic soils show OM values between 1.04% and 7.7%, with an average of 3.31%. The higher organic matter content in volcanic soils can be attributed to their more favorable conditions for organic matter accumulation and decomposition, aided by better nutrient retention and higher biological activity.

For calcium carbonate ($CaCO_3$), calcareous soils exhibit very high levels, ranging from 1.2% to 9.74% (average of 4.01%), reflecting their geological origin rich in carbonates. This high $CaCO_3$ content contributes to the stability and alkalinity of the soil, influencing its physical and chemical properties. In contrast, volcanic soils show much lower levels of $CaCO_3$, ranging from 0.51% to 4.11% (average of 1.62%), which aligns with the absence of carbonate-rich materials in these soils and explains their slightly more acidic nature. Heavy metal concentrations vary considerably between calcareous and volcanic soils. For lead (Pb), calcareous soils have concentrations ranging from 0 to 728.77 mg/kg, with an average of 48.03 mg/kg, while volcanic soils range from 0 to 90.03 mg/kg, with an average of 29.36 mg/kg. The higher variability in Pb levels in calcareous soils may be due to their greater capacity to retain and release Pb, influenced by the high $CaCO_3$ content. For zinc (Zn), calcareous soils range from 41.61 to 1810.68 mg/kg, with an average of 161.75 mg/kg, while volcanic soils range from 90.28 to 628.78 mg/kg, with an average of 218.07 mg/kg. The higher average Zn concentration in volcanic soils suggests a greater enrichment of this metal, possibly due to the volcanic minerals that can contribute to higher Zn levels. Copper (Cu) concentrations in calcareous soils range from 0 to 160.75 mg/kg, with an average of 21.44 mg/kg, whereas volcanic soils range from 0 to 74.12 mg/kg, with an average of 40.74 mg/kg. The higher Cu levels in volcanic soils could be attributed to the presence of Cu-bearing minerals in the volcanic rock. Finally, iron (Fe) concentrations in calcareous soils range from 11732.33 to 61019.50 mg/kg, with an average of 29475.24 mg/kg, while volcanic soils range from 13365.32

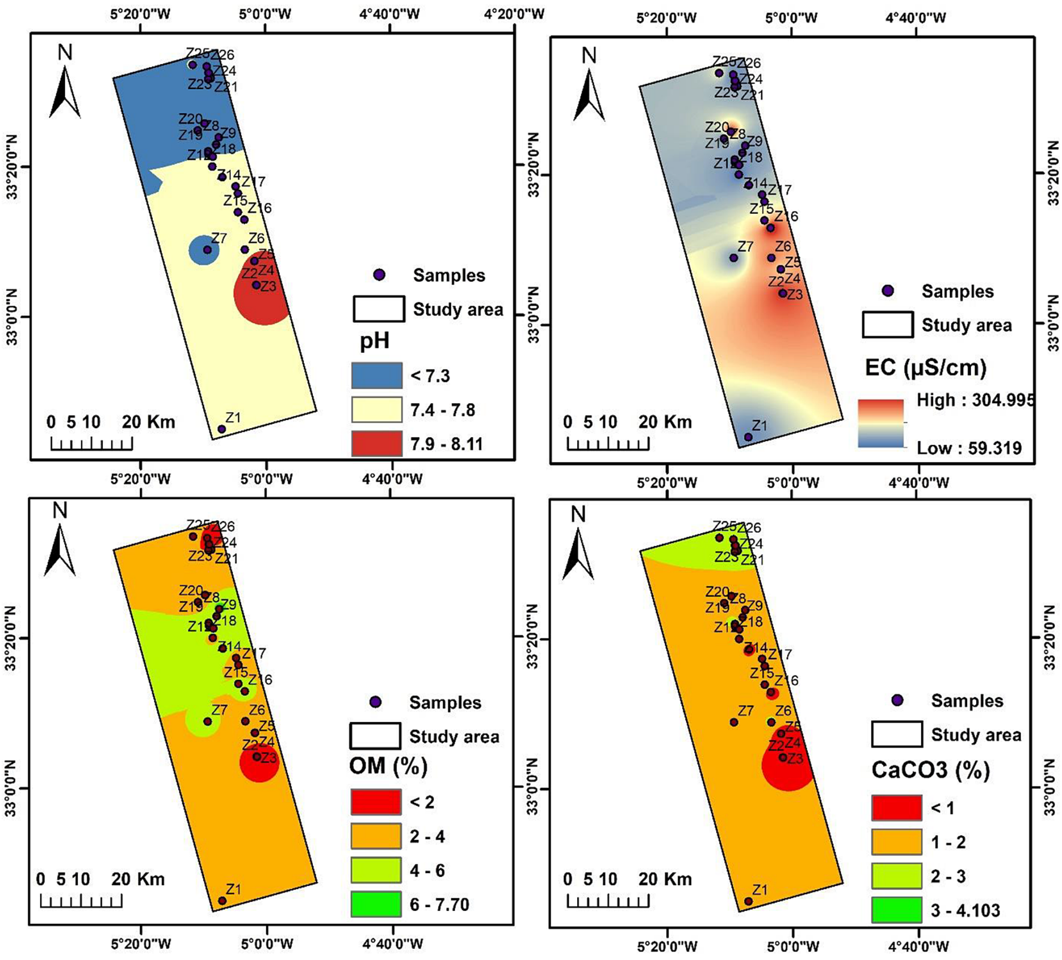


**Figure 3.** Chemical properties of volcanic soil

to 109739.02 mg/kg, with a higher average of 71270.50 mg/kg. The higher Fe content in volcanic soils may be related to the abundance of Fe-rich minerals in volcanic rocks.

Finally, calcareous soils, characterized by higher pH, high $CaCO_3$ content, and moderate salinity, contrast markedly with volcanic soils, which are more acidic, richer in organic matter, and exhibit lower salinity. These differences reflect the distinct geological and mineralogical characteristics of each soil type, influencing their chemical and physical properties, and consequently, their suitability for various land uses and agricultural practices.

## Principal component analysis

The statistical analysis of the relationships between the physical and chemical parameters and heavy metals in the studied soils provides critical insights into the data's structure, as demonstrated by the results displayed in the following figures.

The scree plot reveals that the first principal component explains 25.7% of the total variance, while the second explains 18.8% (Fig. 4a). Together, these two components capture 44.5% of the data's variability, indicating that they contain a substantial portion of the information from the dataset, which includes both physicochemical parameters and heavy metal concentrations. As we move beyond the second component, the explained variance decreases, suggesting that the additional components contribute less to the overall understanding of the data. Therefore, focusing on the first three or four principal components could be sufficient for reducing dimensionality while retaining most of the critical information. Figure 4b present the quality of variables to dimensions 1 and 2, we observe the quality of representation (Cos2) of the different variables on the first two principal components. Variables such as Zn, Pb, Fe, and soil texture are well represented on these dimensions, with high Cos2 values greater than 0.8. This means that these variables are strongly correlated with the first two components and play a significant role in the overall structure of the data. On the other hand, variables like EC and OM have lower Cos2 values, indicating that they contribute less to the first two dimensions. This suggests that these parameters have a lesser influence on the variation of soil samples in relation to the heavy metals being studied.

PCA of studied variables presents the projection of the variables in the space defined by the first two dimensions (Fig. 5a). The vectors for variables such as Zn, Pb, Fe, and silt are relatively long, indicating their strong contribution to these principal components. These variables emerge as the main drivers of the variability captured by the first two dimensions, suggesting a significant interaction between these heavy metals and the physicochemical properties of the soils. In contrast, the vectors for OM and EC are shorter and closer to the center, confirming their low contribution to these main components. The directions of the vectors also reveal relationships between variables; for instance, the close alignment of the Zn and Pb vectors indicates a positive correlation between these two elements in the principal component space.

Finally, the biplot visualizes the distribution of samples across the first two principal components, Dim1 (25.7%) and Dim2 (18.8%). The samples are categorized into three distinct groups, represented by different colors and shapes (Fig.

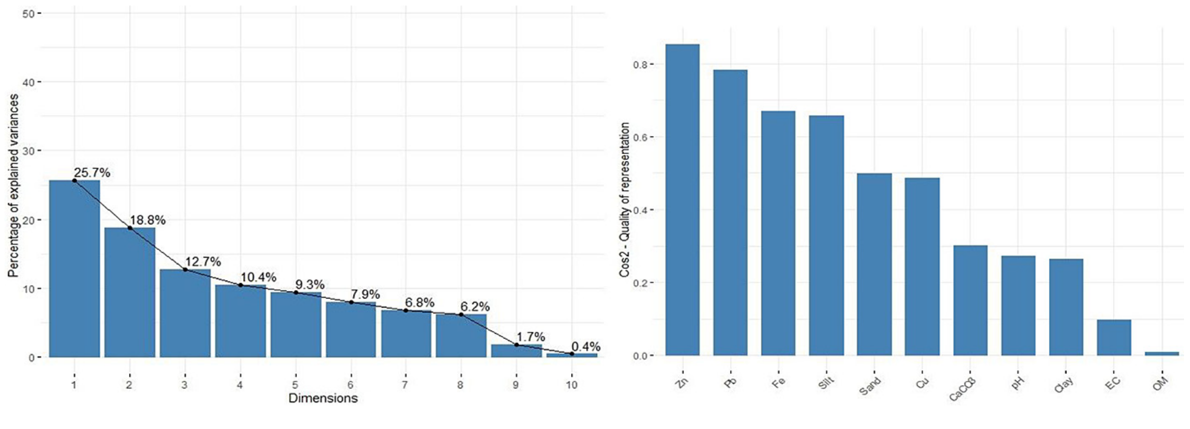


**Figure 4.** (a) Contribution of all dimensions; (b) quality of variables to Dimensions 1 and 2

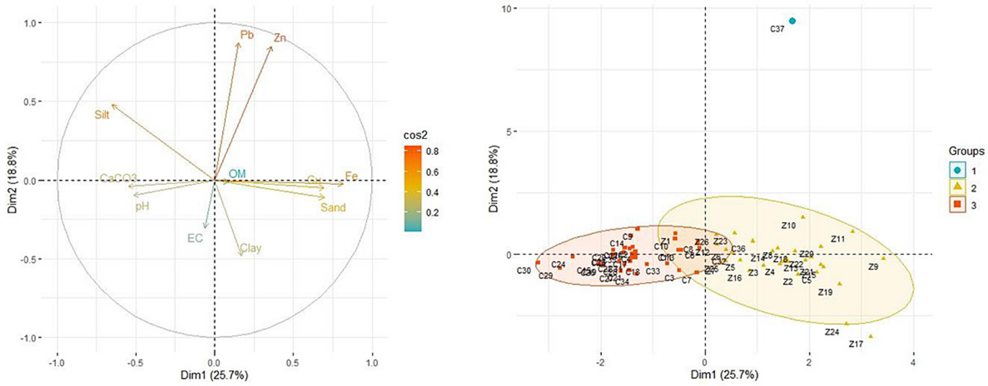


**Figure 5.** (a) PCA of studied variables; (b) PCA of all individuals

5b). Group 1, containing the outlier sample C37, is notably separated from the other groups, indicating unique characteristics, perhaps due to specific concentrations of heavy metals or distinct physicochemical parameters. Groups 2 and 3, while positioned along different sides of Dim1, show some overlap, suggesting shared features. The ellipses represent confidence intervals, highlighting the variability and clustering within each group. The clear separation between Groups 2 and 3 along Dim1 suggests that this component captures the primary differences between these groups, potentially related to variations in heavy metals or the physicochemical properties of the studied soils.

## Hierarchical cluster analysis

The hierarchical clustering dendrogram presented in Figure 6 illustrates the grouping of samples based on their similarities. The vertical axis (height) represents the dissimilarity between clusters, with larger distances indicating greater differences between merged clusters. At the highest level of the dendrogram, two major clusters emerge, suggesting that the samples can be broadly divided into two groups, corresponding to the differences between calcareous and volcanic soils. Within these major clusters, smaller subclusters form at lower heights, revealing more detailed groupings that reflect finer similarities between studied soil samples.

## Correlation between physico-chemical properties and heavy metals

The correlation matrix reveals significant relationships between soil properties and heavy metal concentrations (Fig. 7). Clay content shows weak negative correlations with Zn (r = -0.173)

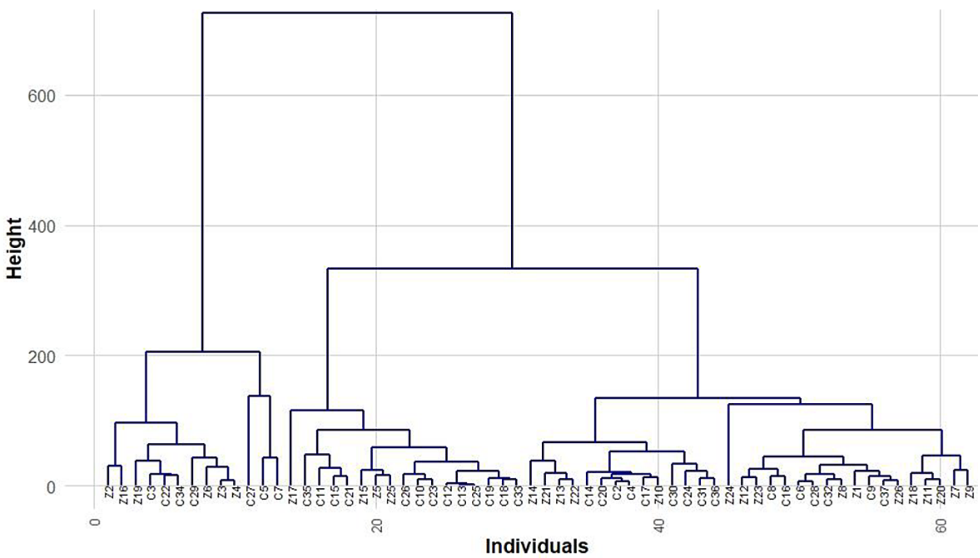


**Figure 6.** Hierarchical clustering dendrogram

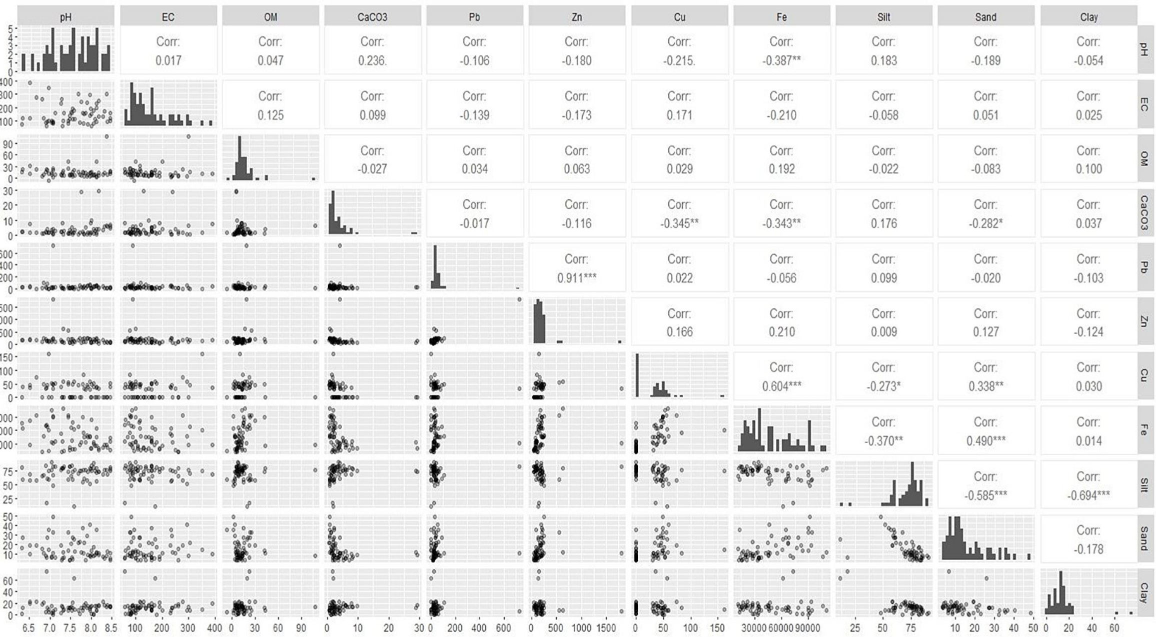


**Figure 7.** Scaterplot between physical and chemical properties and heavy metal concentrations (mg/kg) in the studied soils

and Fe (r = -0.178), suggesting that higher clay content may limit their accumulation. Organic matter exhibits positive correlations with Cu (r = 0.425) and Zn (r = 0.373), indicating its role in retaining these metals. Electrical conductivity (EC) is positively correlated with Zn (r = 0.180) and Cu (r = 0.210), while having weaker correlations with Pb (r = 0.034) and Fe (r = 0.056). $CaCO_3$ displays a significant negative correlation with Fe (r = -0.343**), suggesting that iron is less correlated with carbonate minerals (Barakat et al., 2012). Silt has a moderately positive correlation with Fe (r = 0.330**), highlighting the role of soil texture in the retention of heavy metals. These results suggest that soil texture influences the retention and mobility of heavy metals, with finer particles such as silt potentially retaining more heavy metals like Fe.

## POLLUTION INDICES

### Geoaccumulation index (Igeo)

The comparison of Igeo indice for calcareous and volcanic soils reveals notable differences in contamination levels across the two soil types (Fig. 8). For calcareous soils, the Igeo values for Cu range from -0.64 to 1.77, with a mean of 0.00, indicating a generally low to moderate level of contamination. Pb has an Igeo range of -1.95 to 1.11, with a mean of -0.92, suggesting that these soils are predominantly uncontaminated with occasional low levels of pollution. Zn values vary from -0.66 to 1.93, with a mean of 0.65, reflecting a low to moderate contamination level. Fe shows an Igeo range from -0.63 to 1.74, with a mean of 0.56, indicating similar low to moderate contamination.

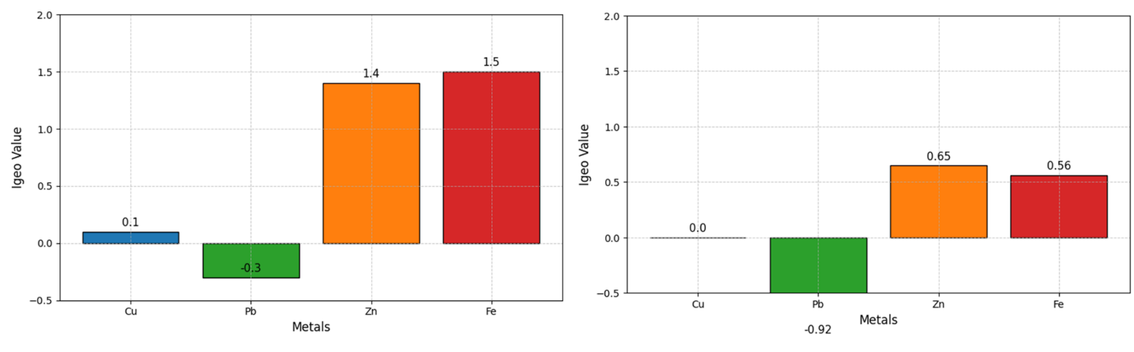


**Figure 8.** Geo-accumulation index for different metals; (a) calcareous soils; (b) volcanic soils

In contrast, volcanic soils exhibit different pollution patterns. The Igeo values for Cu range from -0.46 to 0.34, with a mean of -0.02, suggesting low to moderate contamination levels. Pb ranges from -1.29 to 0.88, with a mean of -0.24, indicating a generally uncontaminated status with sporadic low pollution. Zn has Igeo values between 0.46 and 1.92, with a mean of 1.42, which denotes moderate contamination. Fe shows a broader range from -0.45 to 2.30, with a mean of 1.51, reflecting moderate to high contamination levels.

Overall, the calcareous soils tend to have lower average Igeo values compared to volcanic soils, suggesting that volcanic soils are more prone to moderate to high levels of pollution, particularly for zinc and iron. These differences are likely due to the distinct geological compositions of the soil types, influencing their capacity to accumulate and retain heavy metals. The higher contamination indices in volcanic soils may be attributed to the presence of mineralogical components that favor the accumulation of these metals.

## Enrichment factor (EF)

The analysis of EF indices for calcareous and volcanic soils reveals notable differences in heavy metal contamination levels (Fig. 9). For calcareous soils, EF values for Cu range from 0 to 1.02, with an average of 0.21, indicating a low level of enrichment in Cu. Pb shows values from 0 to 0.83, with an average of 0.37, also suggesting a low level of enrichment. Zn presents an EF ranging from 0.52 to 2.70, with an average of 1.17, indicating a low to moderate level of enrichment in Zn.

In comparison, volcanic soils exhibit distinct enrichment indices. EF values for Cu range from 0 to 0.50, with an average of 0.28, indicating a low level of enrichment in Cu, which is lower than that observed in calcareous soils. Pb has values ranging from 0 to 0.50, with an average of 0.23, suggesting a low level of enrichment, similar to calcareous soils. For Zn, EF values range from 0.53 to 1.87, with an average of 1.02, indicating a low to moderate level of enrichment in Zn, but slightly lower than that in calcareous soils.

However, calcareous soils show slightly higher enrichment levels for Cu and Zn compared to volcanic soils, but these levels are generally classified as low according to the EF classification. Volcanic soils tend to have even lower enrichment levels, especially for Cu and Pb, while the enrichment level for Zn is slightly lower than that observed in calcareous soils. These differences can be attributed to the geological and mineralogical variations between the two soil types, influencing their capacity to accumulate these heavy metals. The results highlight the impact of mineralogical and geochemical characteristics on soil enrichment and contamination.

## Contamination factor (CF)

The CF analysis provides an understanding of the levels of heavy metal contamination in both calcareous and volcanic soils (Fig. 10). According to the classification, Cu in calcareous soils shows a CF ranging from 0 to 5.12, with an average of 0.67, indicating a generally low level of contamination. Pb presents CF values from 0 to 3.24, with an average of 0.88, also reflecting a low level of contamination. Zn shows CF values between 0.95 and 5.73, with an average of 2.62, which indicates a moderate level of contamination. Fe has CF values ranging from 0.97 to 5.03, with an average of 2.42, suggesting a moderate level of contamination as well.

In contrast, volcanic soils demonstrate higher CF values. Cu has CF values ranging from 0 to 1.90, with an average of 1.35, indicating a low to

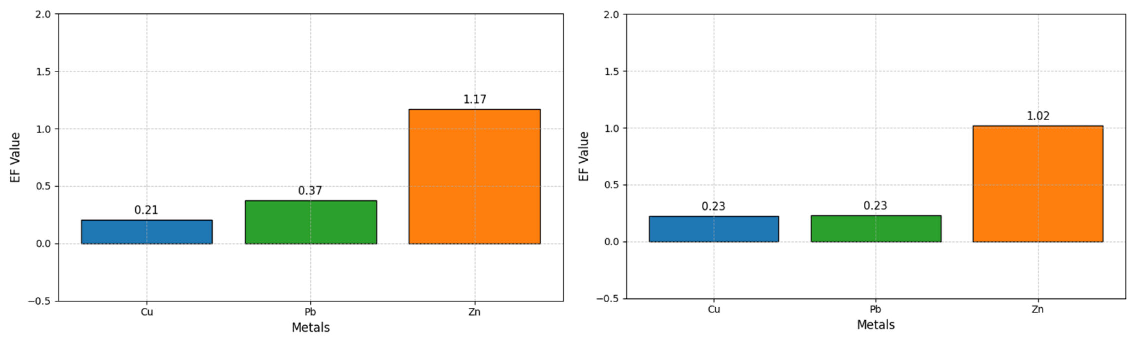


**Figure 9.** Enrichment factor for different metals; (a) calcareous soils; (b) volcanic soils

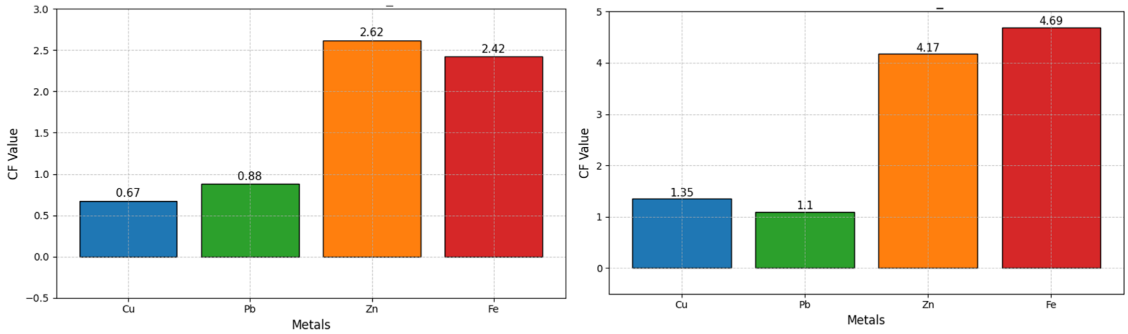


**Figure 10.** Contamination factor for different metals; (a) calcareous soils; (b) volcanic soils

moderate level of contamination. Pb exhibits CF values from 0 to 2.77, with an average of 1.10, reflecting a moderate level of contamination. Zn shows CF values ranging from 2.06 to 5.66, with an average of 4.17, indicating a moderate to considerable level of contamination. Fe presents CF values from 1.10 to 7.38, with an average of 4.69, suggesting a considerable to very high level of contamination. Overall, the results reveal that volcanic soils have higher CF values for Zn and Fe compared to calcareous soils, reflecting a higher degree of contamination. The higher contamination levels in volcanic soils are attributed to their mineralogical composition, which may facilitate the accumulation of these metals. In comparison, calcareous soils generally exhibit lower contamination levels, indicating less environmental impact from heavy metals. These findings underscore the influence of soil type on heavy metal contamination and highlight the need for targeted monitoring and management practices based on soil composition.

### Pollution load index (PLI)

The analysis of the PLI reveals that both calcareous and volcanic soils exhibit low levels of pollution. For calcareous soils, the PLI ranges from 0 to 3.24, with an average of 0.72, indicating that these soils are classified as non-polluted, as all values are below 1. Similarly, volcanic soils show a PLI range of 0 to 2.86, with an average of 0.78, which also falls under the non-polluted category. According to Tomlinson et al. (1980), since both soil types have PLI values less than 1, the pollution levels in these soils are considered within acceptable limits. This suggests that neither calcareous nor volcanic soils exhibit significant pollution, reflecting a generally healthy environmental status in terms of metal contamination.

## DISCUSSION

The findings of this study highlight significant contamination by heavy metals in the studied areas, attributable to both natural and anthropogenic sources. In addition, several previous studies have indicated that metal contaminants originate from various sources, such as the decomposition of parent materials, agricultural and industrial activities, vehicular emissions, and mining operations (Barakat, et al., 2020; Bouzekri et al., 2019; El Azhari et al., 2017; Hilali et al., 2020; Khafouri et al., 2021). Thus, the spatial variation in heavy metal concentrations observed in this study indicates a substantial anthropogenic contribution, particularly in agricultural areas and regions near human activities. These results align with the observations of (Barakat, et al., 2020; El Hamzaoui et al., 2020; Ennaji et al., 2020; Hilali et al., 2020), who also reported elevated concentrations of heavy metals in agricultural soils in the Tadla plain.

The differences observed between calcareous and volcanic soils highlight the influence of their geological characteristics on their physicochemical properties and heavy metal content. Calcareous soils, with their alkaline tendency, exhibit distinct properties due to their high calcium carbonate ($CaCO_3$) content. This carbonate not only increases the pH but also moderates salinity despite the potential dissolution of carbonates and the introduction of salts through irrigation (Weil & Brady, 2016). In contrast, volcanic soils are generally more acidic and less saline, which can be attributed to their basaltic mineral composition and better drainage capacity (Buol et al., 2011). This drainage capacity prevents excessive accumulation of soluble salts and promotes conditions more favorable for organic matter accumulation (White, 2005). Higher levels of organic matter in volcanic soils suggest that these soils, due to their drainage and nutrient retention properties, support greater organic matter accumulation and biological activity (Sparks, 2003). This observation aligns with the understanding that volcanic soils, with their mineral-rich composition, facilitate conditions that support the decomposition and retention of organic matter (Meharg, 2011).

In terms of heavy metal contamination, calcareous soils exhibit a more pronounced ability to retain certain metals, which is partly due to their high $CaCO_3$ content (Alloway, 2012). This retention capacity may explain the higher levels and greater variability of certain heavy metals in these soils. In contrast, volcanic soils show different enrichment patterns, with higher levels of certain metals like zinc, which may be related to the presence of specific volcanic minerals (Sumner, 1999). The presence of copper in these soils, in particular, suggests a direct mineralogical influence on the concentration of this metal. The higher iron concentrations in volcanic soils can be attributed to the abundance of iron-rich minerals in volcanic rocks (Weil and Brady, 2016). This fact underscores that geological characteristics influence not only pH and salinity but also the distribution and concentration of heavy metals in soils. Furthermore, the proximity of mining sites may also explain the high concentrations of heavy metals in this region. In fact, several studies conducted near mines in Morocco have shown that mining activities, such as mineral processing and the erosion of mining residues, significantly contribute to soil and water contamination (Bouzekri et al., 2019; El Amari et al., 2014; El Hamiani et al., 2015; Khafouri et al., 2021). Thus, water and wind erosion of mining waste facilitates the dispersion of particles rich in heavy metals, which is consistent with the coarse particle size observed in the soils of the study area. These findings are in line with those of Deng-feng et al. (2014), who also noted that erosion increased the proportion of coarse metallic particles in areas affected by mining activities.

Moreover, the PCA analysis conducted in this study confirms that heavy metals originate from both lithogenic and anthropogenic sources, supporting the work of Wang et al. (2018), which suggested that agricultural fertilization plays a role in the accumulation of certain metals in addition to magnetic particles. Additionally, the Igeo and the PLI reveal significant pollution, particularly by Zn and Pb, which are identified as the main contributors to soil toxicity. These findings are consistent with those of (Barakat, et al., 2020; Hilali et al., 2020; Hilali et al., 2023), who also reported abnormal accumulations of heavy metals and ecotoxicological risks in soils irrigated by wastewater from Day River.

Finally, the differences between calcareous and volcanic soils illustrate how geological characteristics impact physicochemical properties and heavy metal contamination levels. These differences should be considered in soil management practices and environmental assessments, especially in agricultural and industrial contexts where soil composition can affect fertility, salinity, and heavy metal contamination. Integrating these considerations into soil management strategies can help minimize environmental impacts and improve the sustainability of agricultural practices (Sparks, 2003). The high contamination by toxic metals such as Cu, Zn, and Pb necessitates appropriate environmental management. As highlighted by Hilali et al. (2020), the overuse use of chemical fertilizers, pesticides, and wastewater irrigation in agriculture leads to soil contamination by heavy metals. This underscores the urgency of implementing sustainable soil and management practices to mitigate the environmental and health hazards linked to heavy metal contamination. This study confirms that the combination of intensive agricultural activities significantly contributes to heavy metal contamination in soils, whether in calcareous or volcanic soils. It is, therefore, imperative to adopt sustainable management practices, particularly in vulnerable areas, to minimize the dispersion of heavy metals and prevent long-term toxic effects on the environment and human health.

Despite the comprehensive approach used in this study, several avenues for improvement in future research emerge. This study is geographically constrained to two regions in Morocco, using a small sample size of 64 soil samples from a single depth (0–20 cm), which may not represent complex spatial and vertical soil composition variations. The cross-sectional design prevents long-term trend assessment, providing only a current soil condition snapshot. Future research could enhance soil contamination mapping by integrating hyperspectral remote sensing data, offering continuous spectral mapping of heavy metal distributions and enabling high-resolution detection of soil composition variations across larger spatial scales and long-term monitoring (Wang et al., 2024).

## CONCLUSIONS

The study has successfully provided a comprehensive understanding of how soil characteristics influence contamination patterns in the studied soils. The findings demonstrate the influence of soil type on heavy metal behavior. Calcareous soils, characterized by their alkaline pH, high $CaCO_3$ content, moderate salinity, and lower organic matter, were found to have a higher variability in Pb concentrations. This is likely due to Pb interactions with carbonate minerals, which affect its mobility. On the other hand, volcanic soils, with their basaltic composition, more neutral to slightly acidic pH, and higher organic matter, exhibited elevated concentrations of Zn and Cu, linked to their mineralogical properties. The Fe content was also notably higher in volcanic soils, consistent with their iron-rich composition.

Statistical analyses revealed that soil texture and heavy metals such as Zn, Pb, and Fe were the most influential variables, with the first two principal components explaining 44.5% of the variability in the data. Hierarchical cluster analysis further confirmed the clear distinction between calcareous and volcanic soils. The correlation matrix provided insight into the complex interactions among variables, such as the negative correlation between heavy metals and $CaCO_3$ and the strong positive correlation of Fe with Zn and Cu, but not Pb. Pollution indices highlighted contrasting contamination levels. Volcanic soils showed higher contamination levels for Zn and Fe compared to calcareous soils, which exhibited moderate contamination levels primarily for Pb. Both soil types displayed low enrichment levels, though slight enrichment for Cu and Zn was observed in calcareous soils. The contamination factor indicated moderate to high contamination in volcanic soils for Zn and Cu, while calcareous soils exhibited generally lower contamination levels. Despite these localized variations, the pollution load index remained below 1 for both soil types, indicating that neither soil type showed significant overall pollution, and the environment was in a generally healthy state.

The originality of this study lies in its integrated methodological framework, which combined geochemical, statistical, and spatial analyses to assess soil contamination dynamics in two contrasting geological contexts. Such an approach is rare in studies from semi-arid Morocco and offers a novel perspective on how intrinsic soil properties and mineralogical compositions influence heavy metal retention, release, and mobility. The observed differences in heavy metal contamination and physicochemical properties between calcareous and volcanic soils have important implications for agriculture and environmental management. Volcanic soils, with higher metal concentrations and organic matter content, may require specific management to mitigate contamination risks, while calcareous soils, despite their generally lower contamination, demand attention due to their variability in Pb and lower organic matter content. Tailored soil management strategies that address these unique characteristics are crucial for enhancing soil health, ensuring sustainable agricultural productivity, and minimizing environmental risks in semi-arid regions.

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