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Assessment of soil characteristics and heavy metal pollution in a semi-arid region of northeast Algeria

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ABSTRACT

Dynamics of heavy metal pollution in soil is crucial for devising effective measures to address its negative impacts. The purpose of this study is to assess the concentration of heavy metals in soil in a semi-arid area and to evaluate the effects of these metals on the environment. Sampling of soil occurs at 15 sites spanning over the study area. Each site covers an area of 100 m^2. Composite soil samples are then composed, each comprising five individual samples collected from each site. The study evaluates various physicochemical soil parameters, including potential hydrogen (pH), electrical conductivity (EC), organic matter (OM), soil texture, calcium carbonate ($CaCO_3$), soil nutrients, and the level of heavy metal (lead (Pb), copper (Cu), zinc (Zn), iron (Fe), and Cadmium (Cd)) toxicity in soils. After analyzing our data, we found that the soil samples are characterized by moderate pH levels. It ranges from 7.08 ± 0.07 to 7.71 ± 0.25. It also is character iced by a salinity of soil from 1740.00 to 1270.33 µS cm^{-1}, low organic matter content from 0.26 % ± 0.06 to 0.44 % ± 0.14, and a moderate presence of calcium carbonate between 32.16% ± 2.36 and 45.16% ± 3.51. The Cd concentrations in agricultural soils have exceeded background values; it varied from 1.83 mg kg^{-1} ± 0.28 to 6.50 mg kg^{-1} ± 0.50 indicating ecological danger. The findings underscore the importance of continuous monitoring and remediation efforts to mitigate the negative effects of heavy metal pollution on soil quality and, consequently, on the environment and human health.

Keywords: Heavy metal pollution, Soil characteristics, Semi-arid, Northeast Algeria.

Avaliação das características do solo e da poluição por metais pesados em uma região semiárida do nordeste da Argélia

RESUMO

A dinâmica da poluição por metais pesados no solo é crucial para elaborar medidas eficazes para lidar com seus impactos adversos. O objetivo deste estudo é avaliar a concentração de metais pesados no solo em uma área semiárida e avaliar os efeitos desses metais no meio ambiente. A amostragem do solo ocorre em 15 locais que abrangem a área de estudo. Cada local cobre uma área de 100 m^2. Amostras compostas de solo são então compostas, cada uma compreendendo cinco amostras individuais coletadas de cada local. O estudo avalia vários parâmetros físico-químicos do solo, incluindo hidrogênio potencial (pH), condutividade elétrica (CE), matéria orgânica (MO), textura do solo, carbonato de cálcio ($CaCO_3$), nutrientes do solo e o nível de toxicidade de metais pesados (chumbo (Pb), cobre (Cu), zinco (Zn), ferro (Fe) e cádmio (Cd)) nos solos. Após analisar nossos resultados, descobrimos que as amostras de solo são caracterizadas por níveis moderados de pH, variando de 7,08 ± 0,07 a 7,71 ± 0,25, também uma salinidade do solo de 1740,00 a 1270,33 µS cm^{-1}, baixo teor de matéria orgânica de 0,26% ± 0,06 a 0,44% ± 0,14 e uma presença moderada de carbonato de cálcio entre 32,16% ± 2,36 e 45,16% ± 3,51. As concentrações de Cd em solos agrícolas excederam os valores de fundo; variaram de 1,83 mg kg^{-1} ± 0,28 a 6,50 mg kg^{-1} ± 0,50, indicando perigo ecológico. As descobertas ressaltam a importância do monitoramento contínuo e dos esforços de remediação para mitigar os efeitos adversos da poluição por metais pesados na qualidade do solo e, consequentemente, na saúde ambiental e humana.

Palavras-chave: Poluição por metais pesados, Características do solo, Semiárido, Nordeste da Argélia.

1. Introduction

Heavy metals, including lead, cadmium, and zinc, are elements the occur naturally (Nyiramigisha, 2021). These metals are found in the environment due to various source s like geogenic, agricultural, industrial (Tchounwou et al., 2012). When present in excessive concentrations in soil, they can pose a major threat to both biotic and abiotic parts of the ecosystem (Souahi, 2021; Gonzalez Henao and Ghneim-Herrera, 2021). The rapid processes of industrialization and urbanization have led to a substantial increase in toxic heavy metal levels in the environment (Gao, 2022). Studies have indicated that the primary cause of heavy metal pollution in soils stems from anthropogenic activities (Li et al., 2022). Consequently, the concentration of heavy metals in soil has increased due to these processes (Adewumi and Ogundele, 2024). This increase has resulted in a widespread contamination of soil, which has severe implications on for ecosystem health (Wang et al., 2022; Souahi et al., 2021a). In recent years, heavy metal contamination has emerged as a significant concern due to its potential toxicity, even at low concentrations (Rashid et al., 2023). The majority of heavy metals exhibit a propensity for bioaccumulation and biomagnification, and they are resistant to biodegradation (Jamil Emon et al., 2023; Pande et al., 2022). Heavy metal contamination not only deteriorates soil fertility at high concentrations but also affects crop productivity and quality (Souahi et al., 2021b, Liu et al., 2013).

Soil characteristics are essential for forming the ecosystem and affecting different ecological processes in semi-arid areas (Bazgir et al., 2021). Semi-arid soils have unique characteristics that are indicative of the aridity and scarcity of available water (He et al., 2023; Denissen et al., 2022). These features include low organic matter content, high mineral concentration, and pronounced variability in soil texture and structure (Hag Husein et al., 2021). The scarcity of rainfall and high evaporation rates contribute to soil desiccation and the accumulation of salts near the surface, leading to the formation of saline and sodic soils (Zhang et al., 2023; Li *et al*., 2021). Additionally, the intermittent nature of precipitation level results in irregular moisture distribution within the soil profile, creating spatial heterogeneity in soil moisture levels (Chang et al., 2023; Cheng et al., 2018). As a result, semi-arid soils often exhibit low fertility and productivity, posing challenges for agricultural development and land rehabilitation efforts (Kugedera et al., 2023).

Monitoring and evaluating soil heavy metal pollution in semi-arid areas are crucial to prevent further contamination and mitigate associated health risks (Asaiduli et al., 2023; Gacem et al., 2023). Various indices and assessments are used to analyze soil pollution levels and associated health risks in these environments (Rezapour et al., 2023; Chebout et al., 2025). Continuous monitoring of metal accumulation in soil is crucial even if heavy metal concentrations fall below standards (Zhao et al., 2022). Studies have shown that heavy metal elements can enter the soil environment through various pathways, harming human health (Panqing et al., 2023). They are introduced into the soil environment through both natural processes and anthropogenic activities, such as industrial emissions from factories, smelters, and mining operations (Wan et al., 2024; Ayaz et al., 2023; Witkowska et al., 2021). The application of inorganic fertilizers, including phosphate-based fertilizers and fungicides, significantly contributes to the accumulation of heavy metals in agricultural soils, particularly with prolonged use (Xu et al., 2024; Srivastava et al., 2017). Additionally, long-term irrigation with wastewater can lead to the building up of heavy metals in soils, often exceeding permissible (Tarus et al., 2023; Mohanty and Das, 2023). Atmospheric deposition serves as a critical pathway for heavy metal input into soils, with air pollution, particularly from vehicle emissions, being a major source of such pollutants released into the atmosphere (Yang et al., 2024; Deng et al., 2024; Naderizadeh et al., 2016). Therefore, it is essential to conduct a comprehensive assessment that includes evaluating water quality, soil characteristics, and the potential accumulation of heavy metals (Ahmad et al., 2021). This study aims to investigate the presence and distribution of heavy metals in soil in a semi-arid region. Heavy metal concentrations are expected to be influenced by both natural geological processes and anthropogenic activities, with higher levels anticipated in areas affected by industrial, agricultural, or urban sources. The study also assesses their environmental impact and proposes recommendations for sustainable soil management practices. By comprehensively examining the interactions between heavy metals and soil, this research contributes to a broader understanding of soil pollution and its implications for environmental health.

2. Material and Methods

The study area is located at the entrance to the desert, approximately 230 kilometers south of the Mediterranean coast, in the far east of Algeria. The total site area covers ~12 000 km^2 at altitudes between 700 and 1000 meters above sea level. The region is limited to the West of Souk Ahras, Khenchela, Oum El Bouaghi, to the South by the city of El Oued, and to the East of Tunisia (Figure 1).

According to the Köppen climatic classification, Tebessa, Algeria has a semi-arid or mid-latitude steppe climate with a BSk dominating climate. This kind of climate experiences minimal annual precipitation and sharp temperature changes. The most important aspect of Tebessa's climate is that, since it occasionally experiences rainfall, it usually stays dry for the majority of the year. Soil samples were collected from fifteen sites. Each five samples are taken from each site at a depth of (0 - 30 cm) in order to assess the soil's properties. The soil samples were air-dried, and each sample was divided into two parts. The first for soil texture and the second crushed and sieved to 2 mm to obtain fine soil, which will be used to measure other parameters.

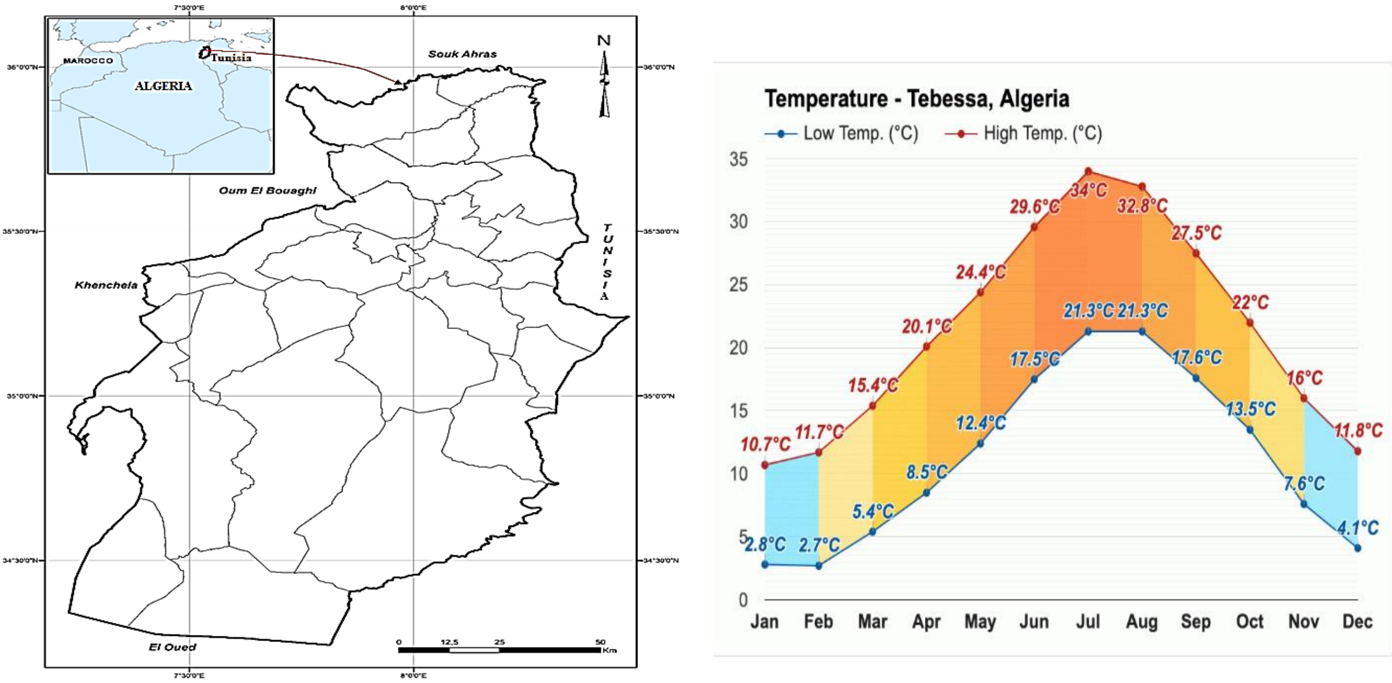

Figure 1. Location map and comprehensive analysis of the climate conditions in the study area.

These parameters comprised acidity pH, electrical conductivity (EC), organic matter (OM), calcium carbonate ($CaCO_3$), soil nutrients, and finally heavy metals concentrations (HMs).

The pH measurements were conducted using a glass electrode pH meter on a fine soil suspension with a (1/5) soil/water ratio, and the electrometric reading of the filtrate was obtained using a universal pH meter V503-10. The EC was measured in the same way as the pH. The EC reading was recorded using a WTW/LF-330 conductivity meter (Mathieu and Pieltain, 2003).

The $CaCO_3$ content was determined using the Bernard calcimeter. The procedure involved adding 2 g of fine soil into a beaker containing 10 ml of HCl diluted to 1/3 of a known weight (W1). After stirring, the solution was weighed again to obtain the weight (W2). The percentage of $CaCO_3$ was calculated from the volume of CO_2 emitted (W1 – W2), following the formula: $CaCO_3$ (%) = $CO_2 \times 2.274 \times 100$ / soil weight (Baize, 2018). The determination of organic matter (OM) was based on the measurement of soil organic carbon (SOC) using the Walkley-Black (1974) method (Baize, 2018).

The soil texture and particle size were analyzed using an electric sieving machine in accordance with the NF P94-056 standard. One kilogram of soil was weighed, a column of sieves with different mesh sizes was arranged in descending order, and the soil was placed on the first sieve. After vibrating the electric sifter, the soil retained in each sieve was weighed.

The percentages of various particle fractions were then calculated. Stones were classified as materials > 2 cm in diameter, gravel as materials between 2 cm and 2 mm, sand (< 2 mm and > 0.05 mm), silt (< 0.05 mm and > 0.02 mm), and clay (< 0.002 mm in diameter) were all considered components of fine soil (Huq and Shoaib, 2013). Concentrations of soil nutrients (N, P, K, Mg, Ca, Na) were analyzed at Fertilisantes of Algeria FERTIAL SPA/Groupe Villar Mir-Annaba.

The determination of heavy metal concentrations in soil was conducted following seedling growth using the method described by Hébrard-Labit and Meffray (2004). Soil samples were digested by treating 1 g of soil with a mixture of hydrochloric acid (HCl) and nitric acid (HNO_3) in a 1:3 ratio to dissolve mineral compounds and release heavy metals. The resulting digestate was then analyzed using atomic absorption spectroscopy (AAS) to quantify the concentrations of heavy metals.

Before each test, the homoscedasticity of the data is assessed by Bartlett tests, and the normality is verified with Shapiro-Wilk tests. Non-parametric Kruskal-Wallis tests and parametric one-way ANOVAs are performed to examine differences between soil characteristics. All statistical analyses are conducted by the software R 3.6.3 (R Development Core Team).

3. Results and Discussion

Soil characterization results play a crucial role in understanding the composition and characteristics of soils in different regions, in assessing their state of health, and in evaluating their impact on surrounding ecosystems.

The soil samples analyzed in this study were collected over a period spanning from February to June 2021, providing a comprehensive representation of soil conditions during this timeframe. Properties analyzed include acidity (pH), electrical conductivity (EC), soil texture, organic matter (OM) content, calcium carbonate ($CaCO_3$) levels, and soil nutrients.

Months within each region were compared. Figure 3 shows that pH of the soils ranges from 7.08 ± 0.07 to 7.71 ± 0.25 between sampling months. $CaCO_3$ content ranges between 32.16% ± 2.36 and 45.16% ± 3.51. The increase in $CaCO_3$ is higher in both February 35.16% ± 2.84 and April 36.83% ± 5.25.

Soils are considered moderately alkaline in the five months (Figure 3A). The EC measures the number of soluble salts in the soil. The EC values obtained confirm the presence of saline soil. The EC values range from 1740.00 to 1270.33 µS cm^{-1} (Figure 3B). The analyzed soil has very low OM values, ranging from 0.26% ± 0.06 to 0.44% ± 0.14.

The months with the lowest OM content are February and June, consistent with 0.26%, while the maximum is 0.44 ± 0.14% in the month of April (Figure 3C).

The textural properties of the soils are presented in Table 1. The percentage of gravel varied from 91.96% to 31.9%, which is the most abundant soil fraction. The clay content showed an opposite trend compared to that of gravel content. The clay fraction was relatively low, varying from 5.01% to 0.38%. The percentage of clay in the samples was low.

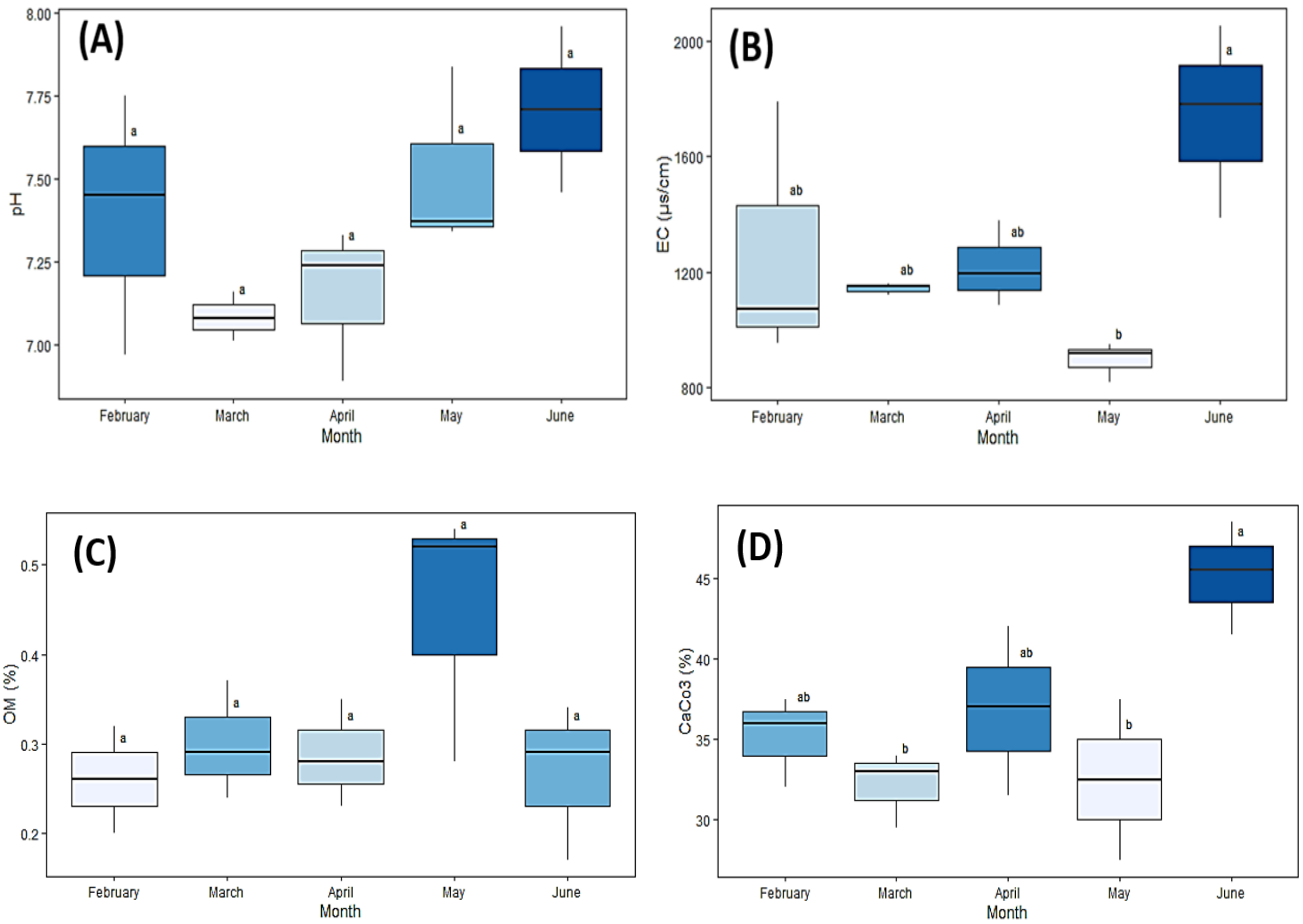

Figure 3. Boxplots displaying the Soil pH variation (A), electrical conductivity (EC) of soil (B), organic matter (OM) content variation (C) and calcium carbonate ($CaCO_3$) content variation (C) across sampling months. Following the Kruscall-Wallis test, the identical letters associated with average values are not substantially different.

Table 1. Particle Size Distribution (Gravel %, Coarse Sand %, Medium Sand %, Fine Sand %, Silt %, Clay %) recorded in different regions of the watershed (Each region is represented by the letter R followed by the region number).

	Gravel%	Coarse sand %	Medium sand %	Fine sand %	Silt%	Clay %
R1	72.84	18.84	5.28	2.18	0.14	0.72
R2	74.56	17.94	3.88	1.6	0.14	1.88
R3	85.86	10.6	1.98	1	1.18	0.38
R4	35.04	9.73	2.97	7.38	31.24	13.64
R5	82.04	5.8	2.88	3.83	2.4	3.05
R6	72	8.81	6.6	2.59	3.7	6.3
R7	62.76	12.07	5.01	15.64	1.91	2.61
R8	63.6	16	6.33	9.02	3.9	1.1
R9	61.2	16	7.46	4.16	6.16	5.01
R10	91.96	1.96	2.36	1.2	1.56	0.91
R11	75.1	3.77	7.28	5.35	5.04	3.49
R12	62.45	6.2	11.6	11.36	4.78	3.58
R13	63.53	19.93	4.19	9.58	1.95	0.79
R14	49.58	20.56	3.34	16.72	8.21	1.57
R15	31.9	24.7	5.08	27.4	7.94	2.9

The contents of sand subtractions: coarse, medium and fine sand were varied between (24.7 to 1.96%), (11.6 to 1.98%) and (27.4 to 1.00%) respectively. The comparative analysis of soil nutrient content spanning February to June reveals dynamic fluctuations in sodium, potassium, and magnesium levels (Table 2).

Sodium concentrations range from 843.3 mg kg^{-1} ± 54.42 in February to 423.6 mg kg^{-1} ± 17.54 in June, indicating a substantial decrease over the study period. Potassium levels fluctuate from 496.1 mg kg^{-1} ± 38. 25 in February to 339.9 mg kg^{-1} ± 30.69 in June. Magnesium exhibits similar trends, with concentrations ranging from 188.3 mg kg^{-1} ± 4.981 in February to 168.5 mg kg^{-1} ± 20.7 in June. Calcium remains relatively stable throughout the study period, with concentrations ranging from 8885 mg kg^{-1} ± 362.1 to 9045 mg kg^{-1} ± 91.91.

Nitrogen content shows modest fluctuations, ranging from 0.08333 % ± 0.01155 to 0.1133% ± 0.01528. Phosphorus levels also remain relatively consistent, ranging from 25.03 mg kg^{-1} ± 2.248 mg kg^{-1} to 27.2 mg kg^{-1} ± 1.3. The average HMs concentrations found in the soil samples are shown in Table 3.

Table 2. Comparative Analysis of Soil Nutrient Content from February to June.

Month	Na (mg kg^{-1})	Ca (mg kg^{-1})	K (mg kg^{-1})	N (%)	P (mg kg^{-1})	Mg (mg kg^{-1})
February	843.3 ± 54.42	8885 ± 362.1	496.1 ± 38.25	0.113 ± 0.015	27.2 ± 1.3	188.3 ± 4.981
March	907.6 ± 48.36	9045 ± 91.91	384.8 ± 27.63	0.083 ± 0.011	25.55 ± 1.812	190.7 ± 2.465
April	871.9 ± 46.08	7872 ± 349.6	338.9 ± 47.05	0.083 ± 0.015	25.03 ± 2.248	168.1 ± 5.028
May	481.9 ± 4.63	8343 ± 862.7	385.2 ± 30.36	0.113 ± 0.011	26.65 ± 1.765	169.3 ± 8.087
June	423.6 ± 17.54	7480 ± 321.2	339.9 ± 30.69	0.083 ± 0.011	25.39 ± 0.618	168.5 ± 20.7

Pb values ranged from 28.33 mg kg^{-1} ± 1.15 to 75.00 mg kg^{-1} ± 5.00 on average. Cd varied from 1.83 mg kg^{-1} ± 0.28 to 6.50 mg kg^{-1} ± 0.50. Cu varied from 13.50 mg kg^{-1} ± 0.86 to 320.00 mg kg^{-1} ± 5.00. Zn concentrations ranged from 2.66 mg kg^{-1} ± 0.28 to 52.33 mg kg^{-1} ± 11.89, whereas Fe concentrations ranged from 0.65% ± 0.08 to 1.63% ± 0.03.

Semi-arid areas are characterized by low rainfall and high temperatures, which result in a high evaporation rate and a soil moisture regime that is dry throughout most of the year (Gacem and Souahi, 2024; O'Donnell and Manier, 2022; Hag Husein *et al*., 2021). The soils in these areas typically have low organic matter content and low nutrient levels (Quoreshi et al., 2022). The formation and development of arid and semi-arid soils are influenced by several factors, including lack of water and significant daily temperature variations (Abdelmalek et al., 2023). Soil pH and EC are important indicators of physicochemical properties, which can reflect the acidity and alkalinity of the soil, and has an impact on trace element solubility, mobility, and bioavailability.

Metal mobility often diminishes as soil pH rises due to metal precipitation. In addition, soil pH affects the solubility of soil OM. (Neina, 2019; Lei et al., 2016). Furthermore, the study area in the Region of Tebessa, located in northeast Algeria, boasts soil with confirmed alkaline pH levels. This alkaline nature is a significant characteristic influencing various soil properties and interactions within the ecosystem (Macheroum and Chenchouni, 2022).

Our results are consistent with several studies, which reported the soils in the semi-arid region of Tebessa are saline (Souahi et al., 2022). The pH was slightly alkaline (Chenchouni, 2017).

Table 3. Monthly variations of soil properties in semi-arid sites

Month	Pb	Cd	Cu	Zn	Fe
February	64.33 ± 7.14 a	1.50 ±0.50 d	16.0 ±1.00 a	2.66 ± 0.28 b	0.78 ±0.07 b
March	28.33 ± 1.15 b	6.50 ± 0.50 a	20.00 ± 5.00 a	52.33 ± 11.89 a	1.63 ±0.03 a
April	65.00 ±5.00 a	2.66 ±0.28 cd	19.00 ± 11.25 a	8.50 ±0.45 b	0.69 ±0.03 b
May	65.00 ± 5.00 a	1.83 ±0.28 bc	19.33 ±0.28 a	7.83 ±0.28 b	0.69 ±0.01 b
June	75.00 ± 5.00 a	3.16 ± 0.28 b	13.50 ±0.86 a	9.08 ±0.52 b	0.65 ±0.08 b

The average physicochemical properties and heavy metals concentrations (mg kg^{-1}) in soil samples in the studied regions. Results are presented as mean values ± standard deviations.

The decreased level of calcium carbonate content was recorded (Boudjabi and Chenchouni, 2022; Lin et al., 2017). Semi-arid soils are generally poor in organic matter; soil fertility in arid and semi-arid areas is limited not only by water availability, but also by low organic matter content (Mureva et al., 2018; Vecchio et al., 2018). Soil chemical properties did not differ significantly through months (Naeth et al., 2020). Soils are generally poor in organic matter, fragile and shallow. Pedogenesis processes occur under semi-arid climatic conditions. Soil formation is influenced not only by rainfall but also by high evaporation (Charef, 2010). In general, the brown soil is light and coarse-textured, with a top layer of loamy sand or sandy loam and an assortment of gravels of various sizes, and subsoil richer in clays than the humus layer (Li et al., 2020).

In semi-arid regions, soil is characterized by low fertility, low nitrogen and phosphorus content and low water retention capacity. Semi-arid soils are also known for declining soil quality and water scarcity, which can further impact nutrient availability (Ayangbenro and Babalola, 2021). Research shows that arid and semi-arid regions are generally characterized by nutrient deficiency and declining soil quality due to water scarcity and unfavorable climatic regimes (Malik et al., 2013). Semi-arid soils are characterized by low nutrient content and availability, which can limit plant growth (Liu et al., 2021).

Heavy metal pollution can significantly impact soil properties in semi-arid regions, as shown by a study in a semi-arid environment (Rezapour et al., 2023). The accumulation of heavy metals in soil can significantly alter its chemical composition, affecting plant growth and biodiversity (Friedlova, 2010, Souahi et al., 2017). Heavy metals present in the soil and water are entering the food chain, which in turn causes severe health hazards (Souahi et al., 2023a). Identifying the sources of heavy metal pollution is crucial for effective pollution management and remediation efforts (Selvi et al., 2019). In our study, the concentrations of heavy metals in soil were investigated, revealing significant contamination levels, particularly for cadmium (Cd) and lead (Pb). The analysis of soil samples collected from various locations demonstrated elevated concentrations of these metals, with higher levels observed in areas adjacent to industrial and mining activities (Gacem et al., 2023). The pollution of Tebessa with heavy metals, particularly cadmium, is primarily driven by several anthropogenic factors, including rapid industrialization and historical mining activities. Mining wastes from phosphate treatment processes are a significant source of potentially toxic metals, as highlighted by Boumaza et al. (2023). The region's proximity to ancient mining areas further exacerbates heavy metal pollution, with abandoned mines leaching contaminants into surrounding soils and water systems, as noted by Djabri et al. (2009). Additionally, industrial activities in Tébessa contribute to the problem through the discharge of waste containing heavy metals, leading to soil and water contamination, as reported by Sellami et al. (2022). Previous results have confirmed that the city of Tebessa is contaminated by toxic metals through the introduction of polluted mining-related waste (Boumaza et al., 2023). Heavy metals have been detected in groundwater, surface water and spring water in the Tebessa phosphorite mining area (Boumaza et al., 2021; Fehdi et al., 2016). In the soil, the results obtained showed the presence of a significant proportion of heavy metals such as zinc and copper (Rezkallah et al., 2023), with heavy contamination of soil and water by high levels of Pb, Cd, Cu and Zn mineralization (Brahmi et al., 2021).

The values of Fe, Zn, and Cu were within the norms limits according to the results of Vermeire et al., 2020. To determine the concentrations of HMs in the soils they were also compared with the norm AFNOR (N F U 44-041). Except for Cd, which was outside the allowed range for agricultural soils, average HMs concentrations in all zones were within the allowable range for agricultural soils. Among the heavy metals studied, Cd poses the greatest environmental threat (Chebout et al., 2023; Turhun and Eziz, 2022). Cd is a heavy metal ion and environmental pollutant that can cause major harmful effects in organisms even at low doses (Souahi et al., 2023b; Mohammadi et al., 2022). The large discrepancies in metal concentrations and physicochemical qualities could be related to temperature variations in different seasons, which affect heavy metal absorption in soils (Salem et al., 2020). Among the various toxic heavy metals, Cd stands out as one of the most prevalent soil pollutants due to its extreme toxicity and hazardous nature (Jiang et al., 2022). The presence of cadmium in agricultural soils leads to a decline in soil quality (Kameyama et al., 2021; Fu et al., 2019). Additionally, crops cultivated in contaminated soils tend to accumulate cadmium, resulting in impaired root and shoot growth, as well as disruptions in nutrient uptake and homeostasis (Souahi et al., 2021a; Shah et al., 2017).

4. Conclusions

In conclusion, the assessment conducted in the semi-arid region of Northeast Algeria, highlights critical issues related to soil characteristics and heavy metal pollution. The findings reveal that the city's environmental pollution is driven by multiple anthropogenic activities, including industrial emissions from cement factories and manufacturing plants, improper waste management leading to uncontrolled landfills, and mining activities that contribute to soil and water contamination through heavy metal deposition. These factors collectively degrade air quality, water resources, and soil health, posing significant risks to both the environment and public health. The study underscores the urgent need for continuous monitoring, effective waste management strategies, stricter emission regulations, and targeted remediation efforts to mitigate the negative effects of pollution and safeguard the region ecological and human well-being. Coordinated action is essential to address these challenges and ensure sustainable environmental management in Northeast Algeria.

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