Effect of lead and cadmium concentrations on the population density of bacteria in the soil contaminated in Tikrit city

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Abstract

Soil contamination with heavy metals such as lead (Pb) and cadmium (Cd) has become a growing environmental concern due to their persistence, toxicity, and adverse effects on soil microbial communities. This study aimed to determine some physical and chemical properties of the soils of the studied areas, and to evaluate the effect of varying concentrations of lead and cadmium on the density of soil bacteria in different polluted sites within Tikrit city. Four samples were collected from different areas of Tikrit Governorate. Sample collection began on winter (December 2023) and summer (May 2024). The modelling process began by taking samples of four environmental sites: a home garden (S1), an agricultural field (Al-Bu Ajil) (S2), a rea near the generator(S3), and a river bank area (S4). Soil textures ranged from loam (S1), loam and clay (S2, S3), to sandy loam (S4). Field capacity values showed slight variation, with the highest value in S3 (42%) and the lowest in S4 (29%). pH ranged between 6.1 and 6.9, indicating a near-neutral environment. Electrosalinity (EC) was significantly higher in S3 (221.4 dS/m), indicating potential salinization compared to the other samples. In terms of organic matter, the highest percentage was recorded in S1 (0.82%) and the lowest in S4 (0.66%). Nitrogen concentration was highest in S1 (11.8 ppm), while phosphorus and magnesium were highest in S3 (1.7 and 3.6 ppm, respectively). Potassium and calcium also reached their highest levels in S3. As for heavy metals, the highest concentration of lead was recorded in S3 (30 ppm), while cadmium ranged from 1.5–2.0 ppm. Cobalt and molybdeium varied between samples, with S3 predominating in most elements. Iron, zinc, and copper concentrations were relatively similar, with S3 and S2 slightly outperforming each other in some values. Lead (Pb) and cadmium (Cd) showed varying effects on bacterial growth at concentrations (0.5, 1, 2) mg/L, especially at the highest concentration (2 mg/L). Pb showed varying effects; bacterial growth continued in S3 (11 CFU/ml), S2 (5 CFU/ml), and S1 (2 CFU/ml), with dense growth observed in S4. Cadmium (Cd) completely stopped growth at all sites, indicating high toxicity at this concentration. The results indicate that physical and chemical properties influence bacterial growth. The effect of heavy metals on bacterial growth varies depending on the type of metal and the environmental location.

Keywords: Soil, Heavy metals, Physicochemical parameters, Bacterials

تأثير تراكيز الرصاص والكادميوم على الكثافة العددية للبكتيريا في التربة الملوّثة في مدينة تكريت

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الملخص

أصبحت تلوثات التربة بالمعادن الثقيلة مثل الرصاص (Pb) والكادميوم (Cd) مصدر قلق بيئي متزايد نتيجة لثباتها العالي وسمّيتها وتأثيراتها الضارة في المجتمعات الميكروبية في التربة. هدفت هذه الدراسة إلى تحديد بعض الخصائص الفيزيائية والكيميائية لترب مناطق الدراسة، وتقييم تأثير التراكيز المختلفة من الرصاص والكادميوم على الكثافة العددية للبكتيريا في مواقع مختلفة ملوّثة ضمن مدينة تكريت. جُمعت أربع عينات من مناطق مختلفة في محافظة تكريت خلال موسمي الشتاء (كانون الأول 2023) والصيف (أيار 2024). شملت مواقع أخذ العينات أربعة مواقع بيئية: حديقة منزلية(S1) ، حقل زراعي في منطقة البوعجيل (S2)، منطقة قرب مولّد كهربائي(S3) ، وضفة نهرية.(S4)

تراوحت قوامات التربة بين طميية(S1) ، طميية طينية (S2 و(S3، وطميية رملية .(S4) أظهرت قيم السعة الحقلية تباينًا طفيفًا حيث سجلت أعلى قيمة في الموقع (42%) S3 وأدنى قيمة في .(29%) S4 تراوح الأس الهيدروجيني (pH) بين 6.1–6.9 مما يشير إلى بيئة شبه متعادلة. لوحظ ارتفاع كبير في التوصيلية الكهربائية (EC) فيS3 (221.4 dS/m) ، مما يدل على احتمالية حدوث تملّح مقارنة ببقية العينات. من حيث المادة العضوية، سُجّلت أعلى نسبة في (0.82%) S1 وأقلها في .(0.66%) S4 أما

تركيز النيتروجين فسُجل الأعلى في(S1 (11.8 ppm ، بينما سُجل أعلى تركيز للفوسفور والمغنيسيوم في S3 (1.7 و3.6 ppm على التوالي). كما بلغت تراكيز البوتاسيوم والكالسيوم أعلى مستوياتها في S3. بالنسبة للمعادن الثقيلة، سُجّل أعلى تركيز للرصاص في(S3 (30 ppm ، بينما تراوح تركيز الكادميوم بين 1.5–2.0 ppm. أما الكوبالت والموليبدنيوم فتفاوتت بين العينات مع غلبة S3 في معظم العناصر. تراكيز الحديد والزنك والنحاس كانت متقاربة نسبيًا، مع تفوق بسيط لـ S3 و S2في بعض القيم.

أظهرت نتائج تأثير الرصاص (Pb) والكادميوم (Cd) على نمو البكتيريا بتراكيز (0.5، 1، 2) ملغم/لتر تباينًا ملحوظًا، خاصة عند التركيز الأعلى (2 ملغم/لتر). حيث أبدى الرصاص تأثيرات متفاوتة، إذ استمر نمو البكتيريا في(S3 (11 CFU/ml ، S2 (5 CFU/ml)، و(S1 (2 CFU/ml، مع ملاحظة نمو كثيف في S4. بينما أدى الكادميوم (Cd) إلى تثبيط النمو كليًا في جميع المواقع، مما يدل على سُميته العالية عند هذا التركيز. تشير النتائج إلى أن الخصائص الفيزيائية والكيميائية للتربة تؤثر بشكل مباشر على نمو البكتيريا، وأن تأثير المعادن الثقيلة يختلف تبعًا لنوع المعدن والموقع البيئي.

الكلمات المفتاحية :التربة، المعادن الثقيلة، الخصائص الفيزيائية والكيميائية، البكتيريا

INTRODUCTION

Soil is the fragile surface layer of the ecosystem and represents an essential natural resource that supports all life forms on planet Earth[1]. Soil microorganisms constitute a major component of its biological structure, contributing 80–90% of its biological processes and acting as a fundamental regulator of its fertility and quality. Soil productivity depends largely on the density and activity of these microbes, which play a pivotal role in decomposing organic matter and regulating the availability of nutrients for plants [2]. There are many biotic and abiotic factors that have a direct or indirect impact on the growth and activity of soil **microorganisms**. Among the biotic factors that clearly influence microorganisms are the metabolic activity of each organism and the synergies, competition, and symbiosis between them and plants within the environment in which these microorganisms live[3]. Abiotic factors include pH, moisture, temperature, and the major nutrients represented by nitrogen and phosphorus, as well as minor or trace nutrients, which must be at levels that do not harm living organisms [4].

Heavy elements are those elements like (lead, cadmium, zinc, and cobalt) that have an atomic number greater than (20) and a density greater than five times the density of water[5]. They are considered among the most dangerous soil pollutants, and their danger increases as a result of their remaining in the soil for a long period of time without decomposing or undergoing a chemical change[6]. Thus, they pose a threat to agricultural and animal production, in addition to their impact on human health. Some of them also have an important biological role in metabolic processes and the work of enzymes, but when large quantities of them are consumed and present in very high concentrations, they are harmful and toxic to living organisms and result in what is called heavy metal poisoning [7].

Heavy metal pollution is one of the most dangerous forms of environmental pollution and has the greatest impact on living organisms. It represents a major environmental issue facing all countries without exception, given the lack of clear boundaries to prevent its spread[8]. Therefore, there is an urgent need to address this problem using methods that keep pace with technological progress and the industrial revolution, ensuring that people can carry out their daily activities within a safe and healthy environment[9]. This requires concerted efforts to reduce sources of pollution, spread environmental awareness, and motivate communities to adopt more effective practices and strategies to achieve sustainable environmental protection [10]

Therefore, the current study aims to evaluate the impact of some heavy metals (lead and cadmium) on microbial diversity in different soil sections, and to assess the relationship between heavy metal concentrations and microbial community characteristics.

MATERIAL AND METHODS

Four samples were collected from different areas of Tikrit Governorate. Sample collection began on winter (December 2023) and summer (May 2024). The modelling process began by taking samples of four environmental sites: a home garden, an agricultural field (Al-Bu Ajil), a rea near the generator, and a river bank area, as shown in Table 1.

Table 1; Description of sampling location and pollution sources in Salah al-Din Governorate

Sampling Site	**Description**
S1	Home garden
S2	Agricultural field (Al-Bu Ajil)
S3	Area near the generator
S4	River bank area

Description of the Study Area

The study area is located within the administrative borders of Salah al-Din Governorate, specifically in the city of Tikrit, which is located on the western bank of the Tigris River. The city is approximately 140 km northwest of the capital, Baghdad, and approximately 220 km southeast of Mosul, at longitude 43°40′43″ east (≈43.6786°E) and latitude 34°36′57″ north (≈34.6158°N). Figure (1).

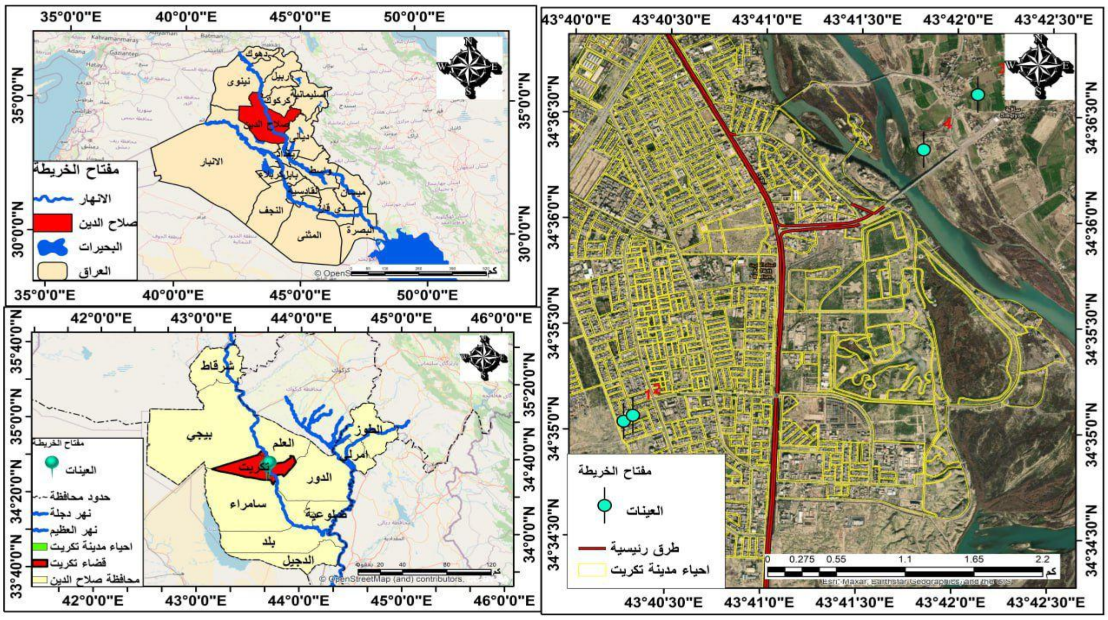

Figure (1) Map and locations of soil sample collection in different areas of Salah al-Din Governorate (Google Earth).

Sample Collection and Preparation

The study was conducted in the laboratories of the Department of Life Sciences/College of Education for Girls, Tikrit University, and lasted from November 2023 to December 2024. The current study samples included four different environmental sites in the city of Tikrit, including a home garden, an environment near generators, an Al-Bu Ajil field, and a Tigris River bank, at different depths **(0, 10, 20, and 30)** cm. Soil samples weighing 100 grams were collected from the aforementioned environmental sites using an iron coring tool (karak). The samples were then placed in plastic bags labeled with the necessary data (sample number, date, depth, and quantity). They were then transported to the laboratory for the required analysis and studies.

Heavy metal solutions

Standard solutions with a concentration of (10) g/L were prepared for the metals by dissolving the pure salts of $Pb(C_2H_3O_2)_2.3H_2O$), ($CdSO_4$), in distilled water. The concentrations were prepared by performing the necessary dilution. The concentrations of lead and cadmium elements were prepared (0.5, 1, 2) mg/L.

Physicochemical parameters

This study involved the analysis of water samples, and the physicochemical parameters were studied. **Soil texture** (volumetric analysis of soil fractions) was estimated by hydrometer method according to the method of Day (1965) described in Black *et al*, [11]. Field capacity was estimated by moistening the soil to saturation and leaving it to drain dry for 48 hours, then weighing the moist sample and drying it in an oven at 105°C for 24 hours to determine the moisture content[11]. The pH was evaluated using a pH meter from Eutech. Electrical conduction (EC) using a conductivity device. The total content of organic matter was estimated by the wet oxidation method using chromic acid according to the Walkley-Black method described in Black *et al*., [11]. Sodium (Na^{+1})and potassium (K^{+}) were determined by flame absorption spectrophotometer. In addition, Calcium (Ca^{+2})and Magnesium (Mg^{+2}) were determined using the titration method, Phosphorus (P) was determined using a modified sodium bicarbonate method as described by Murphy and Riley [12] and Olsen *et al*., [13]. Nitrogen (N) was determined colorimetrically using Nessler's reagent as described in Peech *et al*., [14].

Effect of heavy elements on the growth, diversity, and density of bacterial and fungal isolates

Previously identified bacterial and fungal isolates were cultured on newly prepared culture media. Mueller-Hinton Agar was used for bacterial isolates, and Potato Dextrose Broth was used for fungal isolates. Heavy metal solutions were added to the culture media at different concentrations (0.5, 1, 2) mg/L. The isolates were cultured on these media after an incubation period. Colony counts were counted, morphological changes in the isolates were evaluated, and the results were compared with those of isolates grown in untreated media (control) to determine the effect of heavy metal concentrations on the growth, diversity, and density of bacterial and fungal isolates.

Statistical Analysis

The results were statistically analyzed using one-way ANOVA. This was used to test differences between different environmental sites in physical and chemical characteristics. The F test was used as the main indicator of statistical differences. Spearman's rho correlation coefficient was applied to measure the relationship between heavy metal concentrations and bacterial growth density in different environments.

RESULTS AND DISCUSSION

Physicochemical analysis

Table (2) compares the physical and chemical properties in four different environmental locations (S1: home garden, S2: agricultural field, S3: near a generator, S4: river bank). The results indicated that, in terms of soil texture, it was loam in S1, clay loam in both S2 and S3, and sandy clay loam in S4. Field capacity showed the highest value in S3 (42%) and the lowest in S4 (29%), indicating a variation in water holding capacity among the studied soils. The highest pH value was recorded in S1 (6.9), and the lowest in S3 (6.1), reflecting a difference in the acid-base reaction of the soil. Electrical conductivity (EC) was high in S3 (221.4 dS/m), indicating increased soil salinity in this area, while it was the lowest value in S2 (137.4 dS/m). Also, the organic matter percentage was highest in the S1, reaching (0.82%), compared to the S4, which recorded the lowest percentage, reaching (0.66%), while there was no difference between the percentages of S2 and S3. The table also indicates the percentages of mineral elements, as nitrogen (N) was higher, reaching (11.8 ppm), compared to the S3, which recorded the lowest value, reaching (8.5 ppm). As for the elements (P, Mg, K, Ca, Pb, Co, Mo, Fe), they recorded the highest values in the S3, reaching (1.7, 3.6, 753.66, 5.2, 30, 21, 16, 16.23) ppm, respectively, compared to the S4, which recorded the lowest values. As for (Zn), the highest values were recorded in the S2, reaching (0.658) ppm, while (Cu) recorded the highest values in the S1, reaching (0.6) ppm, compared to the S4, respectively. These results reflect significant variation in soil properties across environmental locations, which may in turn affect soil use and the activity of soil organisms.

Table 2. Effect of physical and chemical properties of soils in different environmental locations

Properties	**S1**	**S2**	**S3**	**S4**
Soil texture	Loam	Clay loam	Clay loam	Sandy clay loam
Field capacity (%)	38	41	42	29
pH	6.9	6.5	6.1	6.6
EC (dS/m)	152.5	137.4	221.4	144.6

O.M (%)	0.82	0.78	0.78	0.66
N (ppm)	11.8	11.2	8.5	10.6
P (ppm)	1.4	1.2	1.7	0.8
Mg (ppm)	2.2	1.8	3.6	1.7
K (ppm)	535.34	521.45	753.66	421.80
Ca (ppm)	4.9	4.2	5.2	4.0
Pb (ppm)	27	29	30	26
Cd (ppm)	1.5	1.8	1.9	2.0
Co (ppm)	14	11	21	8
Mo (ppm)	8	11	16	13
Fe (ppm)	15.57	15.34	16.23	13.48
Zn (ppm)	0.623	0.658	0.587	0.521
Cu (ppm)	0.6	0.4	0.5	0.3

Soil texture is one of the basic physical properties that influences many biological and chemical processes within the soil, such as water and air movement, moisture and nutrient retention, and the growth of microorganisms and plants[15]. The results in the table showed that soil texture varied across different environmental sites. S1 was loam, a balanced texture of sand, silt, and clay. It is considered one of the most suitable types for agriculture due to its good water retention and adequate drainage. At sites S2 and S3, the soil texture was clay loam, indicating a higher proportion of clay compared to sand and silt. This type of soil has a high capacity to retain water and nutrients, but can suffer from poor drainage and aeration, which can negatively impact root growth and the proliferation of aerobic organisms[16, 17].

In contrast, the soil texture at site S4 was sandy clay, a soil containing a significant proportion of sand and clay, giving it a higher capacity to drain compared to loam, but with a lower capacity to retain water and nutrients. This difference is likely due to different environmental conditions, such as water movement and sediment accumulation, especially in areas close to water sources such as rivers. The soil texture explains the lower field capacity in S4 (29%) compared to S3, which recorded the highest value (42%), due to its high clay content. pH values ranged from 6.1 in S3 to 6.9 in S1, indicating a near-neutral to slightly acidic soil, conditions relatively suitable for the availability of most nutrients. Electrical conductivity (EC) recorded the highest value in S3 (221.4 dS/m), indicating high salinity, possibly caused by salt accumulation or human activity, which could negatively affect seed germination and plant growth[18]. In terms of organic matter (O.M), all sites showed relatively low percentages (0.66–0.82%), an indicator of soils lacking the organic matter necessary to improve soil structure and water retention. For nitrogen (N) and phosphorus (P), two essential elements for plant growth, the highest nitrogen concentration was recorded in S1 (11.8 ppm) and the lowest in S3 (8.5 ppm). Meanwhile, the highest phosphorus concentration was in S3 (1.7 ppm) and the lowest in S4 (0.8 ppm), reflecting the influence of environmental conditions and pollution on the availability of these nutrients. The results for potassium (K), calcium (Ca), and magnesium (Mg) show a clear contrast, with K and Mg concentrations being relatively high in S3, supporting the hypothesis of external sources of these elements, while the values were lower in S4. The results for heavy elements (Pb, Cd, Co, Mo, Fe, Zn, Cu) also indicate a significant increase in the concentrations of some toxic metals in the S3 soil, particularly lead, cadmium, and cobalt. This suggests that the soil may be affected by pollutants emitted from industrial activities or fossil fuel sources, such as its proximity to power generators or industrial areas. This overall variation in properties indicates that soil type, geographic location, and exposure to environmental pollution all directly influence soil quality and suitability for agriculture or environmental use[19].

Ali et al. (2023) pointed out that soil is the primary environment for the accumulation of many materials, wastes, chemical and organic elements. When these materials and elements enter the soil, they become part of it, directly or indirectly affecting the biological system. Therefore, heavy elements accumulated in agricultural soil have become a growing concern due to their relationship to food safety, or their access to groundwater, as well as surface water represented by rivers and water bodies. Exposure of the natural environment to certain stress factors, such as sharp changes in temperature, high acidity levels, or chemical pollution, may negatively affect the microorganisms present in the soil, which in turn is reflected in the environmental processes regulated by these organisms [20]. Another study showed that heavy metals (lead, cadmium, cobalt, chromium, copper, mercury, manganese, nickel, tin, and thallium) are among the most polluting elements of water and soil. These elements are found naturally in the components of the Earth's crust and in various soils, where they contribute with other elements to the ecological balance [21]. This study agreed with the results of a study indicating that toxic elements are harmful even at low concentrations when ingested over a long period of time, due to their ability to accumulate in the human and animal bodies (Balaid et al., 2019). They also represent dangerous environmental pollutants because they are non-degradable and enter the body through food, air, or contaminated water [2]. Another study confirms that lead has a high affinity for thiol and oxygen groups compared to other essential metals such as calcium and zinc, which makes it capable of interfering with the survival and reproduction of bacteria by destroying nucleic acids, proteins, and lipids, and replacing vital mineral ions such as zinc, calcium, and iron in sites. Its association with enzymes indicates that cadmium is a highly toxic element for all living organisms [22].

Effect of different heavy metal concentrations on bacterial growth in the studied environmental sites

Table 3, shown the effect of lead (Pb) and cadmium (Cd), on bacterial growth in four different environments: (S1: home garden, S2: agricultural field, S3: near a generator, S4: river bank). Three concentrations of each element (**0.5, 1, and 2 mg/L**) were tested to evaluate the bacterial growth response.

For lead (Pb), the results showed that the lowest concentration (0.5 mg/L) had the highest bacterial growth rates in the S3(126 CFU/ml), indicating the presence of resistant strains in that environment, followed by the S1 (30 CFU/ml), then the S2 (18 CFU/ml), and finally the S4 (14 CFU/ml). As the lead concentration increased to 1 mg/L, bacterial growth decreased significantly in S1(8 CFU/ml) and S2 (9 CFU/ml), while "dense growth" continued in the S4, which may indicate that some local species have adapted to higher lead concentrations. At the highest concentration (2 mg/L), growth declined significantly in the garden (2 CFU/ml), S2 (5 CFU/ml), and S3(11 CFU/ml), but the S4 continued to show dense growth, reinforcing the hypothesis that resistant microbes exist in this particular environment.

As **for cadmium (Cd),** the inhibitory effect on bacterial growth was more pronounced than lead. At a concentration of 0.5 mg/L, growth was relatively weak in S1(12 CFU/ml), S2 (8 CFU/ml), and S4 (8 CFU/ml), while it was lower in the S3(4 CFU/ml), which may indicate the high toxicity of cadmium even at low concentrations. When the concentration was raised to 1 mg/L, a complete absence of growth was recorded in theS1, S3, and S4, while very weak growth remained in the S2 (2 CFU/ml). At the highest concentration (2 mg/L), bacterial growth completely disappeared at all sites, indicating that cadmium is more toxic and bactericidal than lead at the same concentrations.

Table 3. Effect of lead (Pb) and cadmium (Cd) on bacterial growth in the studied environmental sites

Heavy metals	**Concentration (mg/ml)**	**S1**	**S2**	**S3**	**S4**
Pb	0.5	30	18	126	14
	1	8	9	67	Dense growth
	2	2	5	11	Dense growth
Cd	0.5	12	8	4	8
	1	No growth	2	No growth	No growth
	2	No growth	No growth	No growth	No growth

The impact of heavy metals on bacterial and fungal communities is attributed to the fact that heavy metal concentrations significantly inhibited bacterial growth at the site with the highest lead and cadmium concentrations. A significant decrease in bacterial density was also observed compared to other sites. Conversely, zinc and copper levels had a lesser impact on growth, suggesting that bacteria may be able to adapt to low concentration conditions. Bacteria are microorganisms sensitive to changes in their environment, and their ability to resist heavy metals varies depending on the bacterial species and the concentration of the toxic element. In sites with high pollution, some bacteria capable of tolerating harsh conditions are stimulated, contributing to changes in the bacterial community composition. Meanwhile, high concentrations of heavy metals can lead to the extinction of sensitive species, reducing biodiversity within different sites *ref.

Frei *et al*. indicated in a study that bacteria have adapted to the presence of heavy metal ions in their various environments, as they have developed the ability to tolerate high concentrations of these elements in locations such as ore deposits, hydrothermal vents, and areas near active volcanoes[23]. This adaptation has resulted in the development of specialized mechanisms to protect sensitive cellular components from the toxic effects of heavy metal ions. The ability of bacteria to tolerate heavy elements depends on several factors, including the mechanism of ion transport into the cell, the location of the genes responsible for resistance (whether located on the chromosome or carried on a plasmid), and the role the ion plays in metabolic processes within the cell.

A study by Angon *et al*., indicated that heavy metals are essential components of soil and play a key role in the soil's ability to exchange cations and achieve optimal plant growth[24]. They also represent an essential medium for bacterial growth, as these components, including potassium (K), have the ability to bind to mineral crystals in the soil. The results of this study are consistent with the findings of Rashid *et al*.,[25]. Several studies have also shown that potassium-dissolving bacteria can facilitate potassium solubilization, leading to optimal potassium availability. However, the use of bacteria as biofertilizers remains limited due to challenges related to survival and growth patterns. To address these challenges, it is important to monitor microbial growth and optimize their selection process for effective use[26].

Correlation coefficients (Spearman's rho) between heavy metal concentrations and bacterial growth

The results in **Table 4**, based on Spearman's rho correlation test, showed a significant inverse relationship between heavy metal concentrations and bacterial growth in both the first site—the home garden ($r = -0.769$, $p = 0.003$) and the second site—the agricultural S2 ($r = -0.919$, $p = 0.000$). This indicates that increasing concentrations leads to a clear decrease in bacterial density in these environments. This reflects the sensitivity of microorganisms in clean environments to the accumulation of toxic elements. In polluted environments, however, a non-significant negative correlation emerged ($r = -0.503$, $p = 0.096$), indicating the presence of relative resistance or adaptation of bacteria to polluted conditions. In the S4, the relationship was weak and insignificant ($r = -0.314$, $p = 0.321$), which may be due to the influence of various environmental factors such as water movement or high biodiversity. The results in the same table also showed a significant positive correlation between the different environments, as in the relationship between the third site - the agricultural S2 and the fourth site - the polluted environment near the generator ($r = 0.733$, $p = 0.007$), and between the fourth site - the river bank ($r = 0.616$, $p = 0.033$), indicating a similarity in the characteristics of these environments or the presence of adapted bacterial species that share the ability to resist heavy metals. These results reflect the clear inhibitory effect of metals on bacterial growth in unpolluted environments, with the possibility of the survival or development of resistant microbial species in polluted and natural environments.

Table (4) Correlation coefficients (Spearman's rho) between heavy metal concentrations and bacterial growth in different environmental sites

Variables	R/P	Conc.	S1	S2	S3	S4
Conc.	R	1.000	-0.769	-0.919	-0.503	-0.314
	P	–	0.003	0.000	0.096	0.321
S1	R	-0.769	1.000	0.705	0.614	0.211
	P	0.003	–	0.010	0.034	0.510
S2	R	-0.919	0.705	1.000	0.733	0.602
	P	0.000	0.010	–	0.007	0.038
S3	R	-0.503	0.614	0.733	1.000	0.616
	P	0.096	0.034	0.007	–	0.033
S4	R	-0.314	0.211	0.602	0.616	1.000
	P	0.321	0.510	0.038	0.033	–

Spearman's rho correlation coefficients measure the concentrations of heavy metals and bacterial growth and are an important statistical tool for understanding relationships between variables. This coefficient is characterized by its ability to measure the strength and direction of the relationship between two variables without assuming a normal distribution of the data, making it suitable for analyzing environmental pollution data and bacterial growth. Data related to heavy metal concentrations (lead, and cadmium) were collected from four different environmental sites.

In addition to bacterial growth data for each site, the effect of each element can be inferred. Lead (Pb) showed a strong negative correlation with bacterial growth, indicating that increased lead concentrations are associated with a severe decrease in bacterial growth. Cadmium (Cd) also showed a negative correlation, indicating that increased cadmium levels may negatively affect bacterial activity.

This suggests a negative relationship between heavy metal concentrations and bacterial growth in the studied sites. These results may also be explained by the toxic effect of heavy metals on bacterial cells, reducing their ability to reproduce and grow. It is also important to note that some elements, such as zinc and copper, may exhibit different effects at certain concentrations, necessitating further research into the thresholds at which these elements begin to negatively impact bacterial growth.

Studies indicate that some bacterial genera, such as *Pseudomonas aeruginosa* and *Bacillus subtilis*, have a high tolerance to high concentrations of heavy metals through various mechanisms, including biosorption, enzymatic reduction, and complex formation [27]. Nitrogen-fixing bacteria, such as *Rhizobium leguminosarum* and *Azospirillum brasilense*, are more sensitive to heavy metal concentrations, which negatively impacts soil fertility. It has also been observed that some saprophytic fungi, such as *Aspergillus niger* and *Penicillium chrysogenum*, have demonstrated remarkable flexibility in accumulating heavy metals within their cells or binding them to their cell surfaces, making them important organisms that contribute to bioremediation technologies [28].

A study by Hembrom *et al*.,[29] confirmed that soil contamination with heavy metals (HM) poses a significant threat to various environments. When heavy metal levels in agricultural soil reach dangerous levels, they harm plants and humans [30]. A study by Renu *et al*., showed that chromium (Cr), arsenic (As), nickel (Ni), cadmium (Cd), lead (Pb), mercury (Hg), zinc (Zn), and copper (Cu) are the major heavy metals present in the environment to varying degrees, such as soil, food, water, and even air [31]. These substances cause harm to soil and plants and alter the physical and chemical properties of soil.

CONCLUSION

The study results showed a clear variation in the physical and chemical properties of the soils depending on the different environmental sites. A clayey texture prevailed in most of the soils, with the exception of Site S4, which was characterized by a sandy clayey nature with less water-retention capacity. Higher electrical conductivity and concentrations of some heavy elements, such as lead and cadmium, were also observed at Site S3, which is close to the generator, indicating the impact of human activity and environmental pollution. The results highlight the importance of monitoring soil quality to determine its suitability for agriculture or the need for environmental treatments.

REFERENCES

1. Singh V. Land and Soil Resources. Textbook of Environment and Ecology: Springer; 2024. p. 123-41.
2. Al-Kinani HA. Investigation of Possible Pollution by Some Trace Elements and Some Environmental Factors in Water of the Euphrates River in Suq Al Shioukh Southern Iraq. Central Asian Journal of Medical and Natural Science. 2024;5(4):12-23.
3. Rouhani A, Gutiérrez M, Newton RA, Al Souki KS. An overview of potentially toxic element pollution in soil around lead–zinc mining areas. Environmental Reviews. 2024;33:1-16.
4. Ayari J, Barbieri M, Agnan Y, Sellami A, Braham A, Dhaha F, et al. Trace element contamination in the mine-affected stream sediments of Oued Rarai in north-western Tunisia: A river basin scale assessment. Environmental Geochemistry and Health. 2021;43(10):4027-42.

5. Mohammadi S, Keshavarzi B, Moore F, Afzali SF, Sorooshian A. Macronutrients, trace metals and health risk assessment in agricultural soil and edible plants of Mahshahr City, Iran. Environmental Monitoring and Assessment. 2022;194(2):131.

6. Škrbić BD, Živančev J, Antić I, Buljovčić M. Pollution status and health risk caused by heavy elements in the flooded soil and vegetables from typical agricultural region in Vojvodina Province, Serbia. Environmental Science and Pollution Research. 2021;28(13):16065-80.

7. Levan AJ, Gompertz BP, Salafia OS, Bulla M, Burns E, Hotokezaka K, et al. Heavy-element production in a compact object merger observed by JWST. Nature. 2024;626(8000):737-41.

8. Ali MM, Hossain D, Khan MS, Begum M, Osman MH. Environmental pollution with heavy metals: A public health concern. Heavy metals-their environmental impacts and mitigation: IntechOpen; 2021.

9. Kumari S, Mishra A. Heavy metal contamination. Soil contamination-threats and sustainable solutions: IntechOpen; 2021.

10. Aziz KHH, Mustafa FS, Omer KM, Hama S, Hamarawf RF, Rahman KO. Heavy metal pollution in the aquatic environment: efficient and low-cost removal approaches to eliminate their toxicity: a review. RSC advances. 2023;13(26):17595-610.

11. Black C, Evans D, White J, Ensminger L, Clarke F. Methods of soil analysis. American Society of Agronomy. Madison, Wisconsin, part I. 1965:1-770.

12. Murphy J, Riley JP. A modified single solution method for the determination of phosphate in natural waters. Analytica chimica acta. 1962;27:31-6.

13. Olsen SR. Estimation of available phosphorus in soils by extraction with sodium bicarbonate: US Department of Agriculture; 1954.

14. Peech M. Methods of soil analysis for soil-fertility investigations: US Department of Agriculture; 1947.

15. Guo Z, Li P, Yang X, Wang Z, Lu B, Chen W, et al. Soil texture is an important factor determining how microplastics affect soil hydraulic characteristics. Environment International. 2022;165:107293.

16. Angst G, Pokorný J, Mueller CW, Prater I, Preusser S, Kandeler E, et al. Soil texture affects the coupling of litter decomposition and soil organic matter formation. Soil Biology and Biochemistry. 2021;159:108302.

17. Wang X, Wang L, Zhang Q, Liang T, Li J, Hansen HCB, et al. Integrated assessment of the impact of land use types on soil pollution by potentially toxic elements and the associated ecological and human health risk. Environmental Pollution. 2022;299:118911.

18. Mishra S, Alomar R, Barala J, Patel S, Panda D, Pattnaik M, et al. Potassium, Zinc, Gypsum and Organic Manure Influence Electrical Conductivity, Biomass Yield and Nutrient Accumulation in Maize Irrigated with Brackish Water in Coastal Saline Soil. Malaysian Journal of Soil Science. 2024;28.

19. Feng Z, Wang L, Peng Q, Li J, Liang T. Effect of environmental factors on soil properties under different land use types in a typical basin of the North China Plain. Journal of Cleaner Production. 2022;344:131084.

20. Kundu MC. Contribution of Soil Microorganisms in Upkeeping Soil Health. Agricultural Sciences: Techniques and Innovations Vol 1. 2025:30-41.

21. Mahdi IN, Suood AM, Mahadi MN. Spatial Assessment of Heavy Metals and Thermal Pollution in the Tigris River near Salah Al-Din Thermal Power Plant using Heavy Metal Pollution Index and Metal Index. EnvironmentAsia. 2025;18(1).

22. Singh V, Ahmed G, Vedika S, Kumar P, Chaturvedi SK, Rai SN, et al. Toxic heavy metal ions contamination in water and their sustainable reduction by eco-friendly methods: isotherms, thermodynamics and kinetics study. Scientific Reports. 2024;14(1):7595.

23. Frei A, Verderosa AD, Elliott AG, Zuegg J, Blaskovich MA. Metals to combat antimicrobial resistance. Nature Reviews Chemistry. 2023;7(3):202-24.

24. Angon PB, Islam MS, Das A, Anjum N, Poudel A, Suchi SA. Sources, effects and present perspectives of heavy metals contamination: Soil, plants and human food chain. Heliyon. 2024;10(7).

25. Rashid A, Schutte BJ, Ulery A, Deyholos MK, Sanogo S, Lehnhoff EA, et al. Heavy metal contamination in agricultural soil: environmental pollutants affecting crop health. Agronomy. 2023;13(6):1521.

26. Orozco-Mosqueda MdC, Flores A, Rojas-Sánchez B, Urtis-Flores CA, Morales-Cedeño LR, Valencia-Marin MF, et al. Plant growth-promoting bacteria as bioinoculants: attributes and challenges for sustainable crop improvement. Agronomy. 2021;11(6):1167.

27. Philippot L, Chenu C, Kappler A, Rillig MC, Fierer N. The interplay between microbial communities and soil properties. Nature Reviews Microbiology. 2024;22(4):226-39.

28. Khan I, Ali M, Aftab M, Shakir S, Qayyum S, Haleem KS, et al. Mycoremediation: a treatment for heavy metal-polluted soil using indigenous metallotolerant fungi. Environmental Monitoring and Assessment. 2019;191(10):622.

29. Hembrom S, Singh B, Gupta SK, Nema AK. A comprehensive evaluation of heavy metal contamination in foodstuff and associated human health risk: a global perspective. Contemporary environmental issues and challenges in era of climate change: Springer; 2019. p. 33-63.

30. Hu B, Jia X, Hu J, Xu D, Xia F, Li Y. Assessment of heavy metal pollution and health risks in the soil-plant-human system in the Yangtze River Delta, China. International journal of environmental research and public health. 2017;14(9):1042.
31. Renu K, Chakraborty R, Myakala H, Koti R, Famurewa AC, Madhyastha H, et al. Molecular mechanism of heavy metals (Lead, Chromium, Arsenic, Mercury, Nickel and Cadmium)-induced hepatotoxicity–A review. Chemosphere. 2021;271:129735.