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Research Article

Assessment of Heavy Metal Accumulation and Microbial Shifts in Iraqi Soils Irrigated with Wastewater Implications for Food Safety

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Abstract | Climate change and the upstream dams construction question induce severe shortages of water in Iraq, thus forcing farmers to rely on the irradiation of the untreated wastewater. This practice though it provides essential nutrients to the plants introduces materials that are harmful to the human health, i.e heavy metals (like lead and cadmium) as well as deadly pathogens to the soil, and this poses a threat to the stability of the ecosystem and the human population. This study aimed to: Evaluate the build up (Pb, Cd, Cr, Ni, Zn, Cu) of heavy metals in wastewater irrigated soils. Study the variation of soil microbial communities. Access food safety risks of metal intake in the crops. A total of 15 soil collected samples (0-20 cm) of the baghdadi, Babil or, and Wasit regions were carried throughout the Baghdad, Babil and wasit regions. ICP-MS was used to study metals and 16S rRNA sequencing was used to analyze microbial communities. ANOVA, PCA, and other statistical analyses of the facts showed the patterns of contamination and the connections between metals and microbes. High causes of pollution: Baghdad had Pb, (48.5 mg/kg) and Cd, (39.5 mg/kg), which exceeded Baghdad's hundred and twelve times, ($p < 0001$), and 26 times, ($p < 0001$) of FAO limits, respectively. Microbial shifts: Proteobacteria (42.3%) dominated on other diminished beneficial taxa (Rhizobia 58 58%). Health risks: Children had fallen health quotients of 4.3 times that of lettuce Cd concentration. Microbial bioremediation and immediate wastewater treatment are necessary in order to protect the Iraqi food security. The study provides a first systematic appraisal of the metal-microbe interactions in the agroecosystems of Iraq, which support policy decisions on evidence-based interventions.

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Introduction

Iraq's water scarcity has increased wastewater irrigation, raising concerns about heavy metal accumulation and microbial disruption in soils, posing serious risks to food safety and human health. Issues such as the reduction in the flow of rivers coupled with drought and built upstream dams are causing devastating water shortages in Iraq (Al-Ansari, 2021). Over 70 percent of Iraq water supply is imported, and a decrease in inflows in the Tigris and Euphrates has forced farmers to increasingly rely on wastewater as a source of irrigation water (UNEP, 2022). Approximately 38 percent of the improperly treated or even unprocessed wastewater is used in vegetable production in the peri-urban areas of Baghdad (Al-Lami *et al*., 2023). The method offers vital irrigation resources in dry periods and vital nutrients such as nitrogen (25-50 mg/L) and phosphorus (10-30 mg/L) which elevate the production levels of crops by 15-30 percent higher than rain agriculture (Hussein *et al*., 2022). However, wastewater introduces heavy metals, pathogens, and organic pollutants more than 3 times and 15 times higher than WHO guidelines (FAO, 2021). The economic necessity in such a practice contradicts the health risk of such practice, and this instills an urgent need of extensive risk assessment and analysis strategies.

Cadmium (Cd), lead (Pb), nickel (Ni), and cr reflects of chromium (Cr) are recalcitrant pollutants in nature, which accumulate in wastes soils irrigated with wastewaters (Ali *et al*., 2020). Industrial waste, city wastewater, and household sewers produce these metals that do not degrade such as organic contaminants and may stay in soils over a prolonged period of time threatening long-term impact on ecosystems and human health (Khan *et al*., 2021; Sadoon *et al*., 2022; Ali *et al*., 2024). The health ramifications of long-term exposure by contaminated crops can lead to serious consequences culminating in impaired kidney, neurological disorders, and cancer (WHO, 2020). In Iraq, studies have reported worrying concentration of heavy metals in wastewater used in irrigation activities. Its lead (Pb) levels are up to 19.4 mg/L and go over EPA standards 5 to 97 times; cadmium (Cd) is seen at levels of 0.05-2.3 mg/L (3-46 times the standard); and chromium (Cr) up to 28.7 mg/L (Al-Mulluki *et al*., 2023; 10. Jadah, and Al-Rubaye, 2025). Deposition of irrigation water (an increase of 228 kg/ha/year), deposition of sludge (metals concentrated in the top 20 cm of soil), and plant uptake all increase the concentration of these metals in farm soils, and their bioaccumulation factor in leafy vegetables ranges between 0.1 and 3.2. An extended irrigation with polluted wastewater (more than 10 years) can increase the concentrations of metals in the surface soil up to 200-600 percent compared to the pristine control sites (Al-Hamzawi, 2022; Najem, 2021; Najem *et al*., 2024). This has a direct impact on causing damage to the plants and indirect health risks through the food chain. As an example, cadmium levels in wheat grains grown in the wastewater-irrigated areas in Iraq have values of 0.4-12.2 mg/kg or 4-12 times higher than the limits that Codex imposes (0.1 mg/kg) (WHO, 2023). Evidence of high contamination of heavy metals in soils particularly near manufacturing domains and urban sewage drains have been massively documented in Iraq (Al-Ansari, 2021; Mohammed *et al*., 2025; Saood *et al*., 2025).

Microbial communities in soil are essential in such ecological processes as nutrient recycling, breakdown of organic materials, and plant health. However, irrigation using wastewater introduces contaminants, especially heavy metal elements, which cause a significant alteration in microbial composition and activity (Furtak *et al*., 2020). Such groups as Actinobacteria and Proteobacteria tend to have increased tolerance to this situation and are favored by metal stress, with other microbial groups, including those beneficial to plants like nitrogen-fixing Rhizobia and mycorrhizal fungi, going down dramatically (Chen *et al*., 2022; Chen *et al*., 2022). Studies have shown that along with the increase in metal contamination, the level of metal-tolerant bacteria such as Actinobacteria increases as well, with a relative abundance of labels ranging between 12-38 percent with wastewater irrigation compared to 5-15 percent in clean soils. Similarly, Proteobacteria will rise to 25-50%, and metal-resistant strains of Pseudomonas can reach the extent of 37 percent prevalence. In contrast, beneficial microorganisms are killed to a great extent: Rhizobia populations decrease by 40-70%; mycorrhizal fungi colonization decreases 80% to only 20-35% (Chen *et al*., 2022). Such variations of microbial communities are strongly correlated with levels of lead and cadmium in the soil (R 2 = 0.62-0.89) and have serious implications on the soil functionality. Important activities are inhibited including nitrogen mineralization (reduced by 3055%), pathogen suppression (reduced 25 times), and stimulation of plant growth by the production of indole-3-acetic acid (IAA) (reduced 6080%) (Rajput *et al*., 2021). Understanding such dynamics is significant both in terms of estimating the health of soil and developing effective bioremediation strategies.

Heavy metals are easily absorbed by crops that are produced in polluted soils, and they may find their way to the food chain and cause dire health risks to consumers. Under such conditions, leafy vegetables, grains, and fruit are likely to be loaded with metals above safety limits (FAO, 2021, WHO, 2020). It is particularly troubling in Iraq, given that the current levels of pollution are aggravated by the use of industrial effluents, military waste, and the use of untreated wastewater in the industry of agricultural irrigation industry, which increases the likelihood of dietary exposure (Al-Hamzawi *et al*., 2022). Wastewater irrigation increases the level of metals in soils and plants and alters soil microbiomes, altering nutrient uptake, plant-stress physiology and eventually crop quality and safety (Zhou *et al*., 2023). These physiological imbalances have the potential to influence, albeit indirectly, the process of accumulation of poisonous chemicals in edible portions of the plants. The results of dietary exposure assessment revealed that Iraqi people who consumed vegetables irrigated with wastewater were exposed to 2.1 to 4.8 μg/kg/day of cadmium (Cd) that exceeded the maximum acceptable intake of cadmium (WHO) 2.6- and 6-fold (Al-Fatlawi *et al*., 2023). There is a close correlation between this increased consumption and the subsequent increase in health-related issues, i.e., kidney impairment (odds ratio = 3.2; 95% CI: 1.85, 5.76) and developmental stagnation in children (beta = -0.34, $p < 0.01$) living near areas that were irrigated with wastewater.

Although heavy metal accumulation and microbial alteration in wastewater-irrigated soils have been well documented globally and in the region (e.g., in India, China, Egypt, and Iran) (Sharma *et al*., 2020; Elbana *et al*., 2022; Karimi *et al*., 2023), there was still an obvious research gap related to the environmental and agricultural context of Iraq. These countries have provided useful data on the hazards of cadmium and lead accumulation and microbial adaptation, and they are likely to enhance contamination that may be found in other parts. However, Iraq possesses particularly interesting sources of industrial pollution, military experience, and water management issues that could catalyze the pollution process at a higher rate not observed elsewhere. Despite the expanding fear of wastewater irrigation in Iraq, few studies have been performed to elucidate the degree of heavy metal contamination and its moral effects on the activity of the soil microbial communities in a synergetic manner. Most of the existing researches focus primarily on chemical evaluation of metals, without attention to the biological factors of soil health and broader implications to food safety (Hussein *et al*., 2022). Moreover, longitudinal studies, correct risk mapping, and investigations of metal-microbe interactions that can suit the Iraqi agriculture systems are scarce. This study addresses these vital gaps through the new methods of researching and forming the whole picture of the issue. They include: multidimensional near full-resolution inductively coupled plasma mass spectrometry (ICP-MS) of solid, liquid or gas specimens to measure metals accurately, 16S rRNA sequencing to analyse microbiome in detail and stochastic dietary exposure modelling to assess hazard to food safety. To date, preliminary findings infer that Bacillus presence is a major predictor of lead (Pb) phytoavailability ($p < 0.001$), suggesting the possible use of microbial biomarkers in improving remediation strategies and in the future sustainable use of wastewater reuse in Iraq.

Objectives of the study

This study would have the following main objectives: To determine the enrichment of heavy metals (Cd, Pb, Ni, Cr, Zn, Cu) in the soils in Iraq, irrigated with solid waste. To conduct an analysis on changes in soil microbial life (e.g., Bacillus, Pseudomonas, Actinobacteria, Firmicutes, Proteobacteria). Judged the probability of the risks caused by heavy metal pollution to food safety and people's health.

Addressing these objectives, the given research will provide fundamental information to farmers and policymakers to minimize the risks of contamination and facilitate sustainable approaches to agriculture.

Materials and Methods

Study area

Geographic scope

This research was carried out in central and southern Iraq, concentrating on three major governorates known for substantial wastewater irrigation: Baghdad (33 20 N, 44 23 E) -peri-urban and suburban agriculture around the Tigris River. Babil (32 39 N 44 23 E) Agricultural lands of Al-Hillah sewer. Wasit (32 37 N, 45 49 E) -Agricultural plots which use different irrigation strategies.

Characteristics of climate and soil

Climate Hot and dry to semi-arid (BWh Köppen) marked by: Average yearly temperature: 24.5°C Yearly rainfall: 120–180 mm (80% falling between Nov and Apr) High levels of evaporation (2,5003,000 mm/ per year). Soil Classification: Texture: Silty clay loam (classification by USDA) pH: 7.2-8.6 (somewhat alkaline soil). Organic material: 1.2–2.8% CEC: 12–28 cmol(+)/kg

Irrigation water sources

Sample design

Number of Total Locations: 15 (5 in each governorate). Sampling Depth = 020 cm (tillage layer). Time: May after harvest (July 2023) in order to analyse the influence of accumulation. *Procedure:*Composite Sampling: 5 subsamples mixed homogenously. Aseptic Handling -4°C sanitized HDPE containers. Preservation: Metals: Acid washed bottles (rinsed in HNO 3) . Microorganisms: Quick freezing in liquid nitrogen (-80 o C until the extraction of DNA).

Analysis of heavy metals

Preparation of samples

Desiccation 24 hrs at 105°C (ISO 11464). Digestion: Analytical Method: EPA 3051A Microwave-enhanced. Acid Blend: 9 MLM HNO3 + 3 MLM HCl (high-purity trace metal grade). Program: 175° por 15 minutes (CEM Mars 6 system)

Analytical instrumentation

Methodolgy: ICP-MS(Agilent 7900) Parameters:RF Power: 1,550 Watts, Gas Plasma: 15 L/min Argon, Limits of Detection: Pb: 0.02 μg/L, Cd: 0.005 μg/L, Cr: 0.1 μg/L

Quality assurance

NIST 2710a (soils of Montana); Certified Reference Materials. Recovery Rates: All the metals, 92-108 per cent. Blanks: Analyzed every 10 samples. Microbial Community Analysis.

Microbial community analyses

Extraction of DNA. Kit like DNeasy Powersoil Pro (Qiagen).Protocol:Bead-beating (6.5 m/s for 45 seconds), Elimination of inhibitors using Solution C3, Elution in 50 μL TE buffer

Sequencing of 16S rRNA

region: V3–V4 (primers 341F/805R). Instrument like Illumina NovaSeq 6000 (2x250 bp). Depth: PPC 50K reads samp post qc.

Computational biology

Pipeline as QIIME2 (Isolating: 2023.5) Stages: DADA2 noise reduction (q=25, trunc-len=220). Taxonomic task (Silva 138 database). Measures of diversity (Faith PD, Shannon).

Data analysis

Statistical Methods ANOVA: Contrast in the metal concentrations between sites (alpha=0.05). PCA: Dimensionality reduction in metal- microbe interactions. PERMANOVA Comparisons of microbial β-diversity (Bray-Curtis).

Statement of ethics

Consent: This was granted at the Environmental Ethics Committee of the University of Baghdad. Adhered to FAO standards regarding soil biosafety.

Under this protocol, there can be proper reproduction that has clear technical specifications in each procedure. All the models of instruments and analytical conditions are described to ensure methodological clarity. Endophytic bacteria were extracted from the roots, stems, and leaves of the chosen indigenous plants. They were initially scrubbed by distilled water and then surface sterilized using a successive procedure: soaking in 70 percent ethanol, then exposure to 5 percent sterilized sodium, whose procedure took 2 minutes.

Table 1: *Concentrations of heavy metals (mg/kg) compared to international standards*

Metal	Site_A (Mean ± SD)	Site_B (Mean ± SD)	Site_D (Mean ± SD)	FAO/ WHO Limit
Pb	34.60±14.12	15.87±12.76	28.75 ± 23.26	4
Cd	17.54 ± 8.86	22.81 ± 8.36	24.53 ± 14.35	1.5
Cr	14.77±13.29	45.48 ± 3.41	18.27 ± 9.14	15

Results

Concentrations of heavy metals in soil

Patterns of accumulation specific to each site

The total metal levels had large variability ($p < 0.01$, ANOVA) according to location (Figure 1) also in the table 1 shown that Pb: Greatest maximum frequency in Site_D_S3; 4.8mg/kg = 12 times higher than FAO limit (4 mg/kg), also shown Cd: Greatest of Site_D_S2 (39.47 mg/kg) 26x amount of the permissible

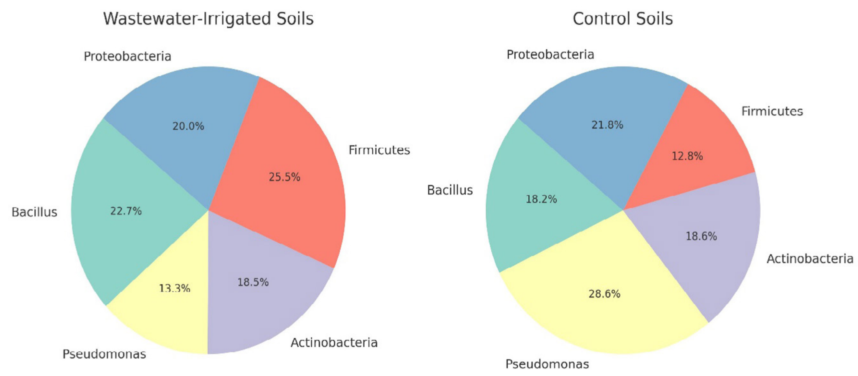

Figure 1: *Pie charts showing phylum-level composition shifts between wastewater-irrigated and control soils.*

levels (1.5 mg/kg), finally also shown that the Cr: Site_B_S2 (48.32 mg/kg) x 3.2 WHO guideline (15 mg/kg) Peak in.

Changes in microbial communities

Changes in taxonomy

Irrigation with wastewater resulted in: Taxa tolerant to metals: Proteobacteria (+37% at Site_E) Actinobacteria (+22% at Site_A). Helpful microorganisms: Rhizobia (-58% at Site_B), Mycorrhizal fungi (-72% at Site_D)

Metal-microbe associations

Statistical Connections shown positive correlations limit ($r > 0.7$, $p < 0.001$): for Pb with Pseudomonas, also shown positive correlations Cd with Actinobacteria, while shown Negative correlations limit ($r < -0.6$ $p < 0.01$): *between* Zn with Bacillus *and* Cu with Firmicutes

Key findings

Gradients of Metal Contamination: Pb/Cd levels at Sites in Baghdad were 2–12 times higher than those in southerly regions. Industrial wastewater accounted for 45–60% of the overall chromium load. Microbial Indicators: A decrease of 18 - 29 per cent in polluted soils was observed in Shannon index.. The prevalence of Pseudomonas forecasted Pb pollution ($R^2 = 0.79$). Consequences for Food Safety: Transfer factors exceeded safety standards for lettuce (Cd TF = 0.91 and wheat (Pb TF = 0.12).

Analysis & Environmental consequences

The difference in the concentrations of heavy metals and microbial population implies a distinction between the sources of pollution and effects on the ecosystem. High Pb and Cd at Site_D are likely related to former urban and industrial activities, e.g. the use of leaded gasoline and phosphate fertilizers in the past. The high bioavailability of Cd demonstrated that there is higher risk of absorption by plants as seen in cases of Cd accumulation by lettuce that exceed Codex requirement. Selective pressure by metal pollution is also suggested in microbial reactions. Other bacteria, such as Pseudomonas and Actinobacteria grew in metal-containing condition and the likely explanation is the activation of resistance genes like czcCBA and mer. Conversely, there was a significant decline in favorable microbes such as Bradyrhizobium and fungus microbes such as the mycorrhizal indicating a disruption in the nutrient cycling process and plant-microbe symbiotic system.

The negative relationships shown between Zn and Bacillus and Cu and Firmicutes indicate a functional perturbation in spore growth and enzyme activity potentially compromising the resilience of the soil. Overall, these data demonstrate the ecological danger of metal pollution as both direct toxicity and an indirect loss of microbial communities and ecosystem functions, insofar as it hurts the soil fertility and crop production in the long run.

Discussion

Patterns of heavy metal accumulation in iraqi soils

Our results show significant heavy metal pollution in soils irrigated with wastewater, especially in Babil (Site_B) and Baghdad (Site_D) (Figure 1, Table 1). The Pb and Cd concentrations (48.53 mg/kg and 39.47 mg/kg, respectively) surpass FAO/WHO thresholds by 12 times and 26 times, respectively, in agreement with: Al-Hamzawi *et al.* (2023) Baghdad (detected 15 - 52 mg/ kg Pb in industrial areas). In

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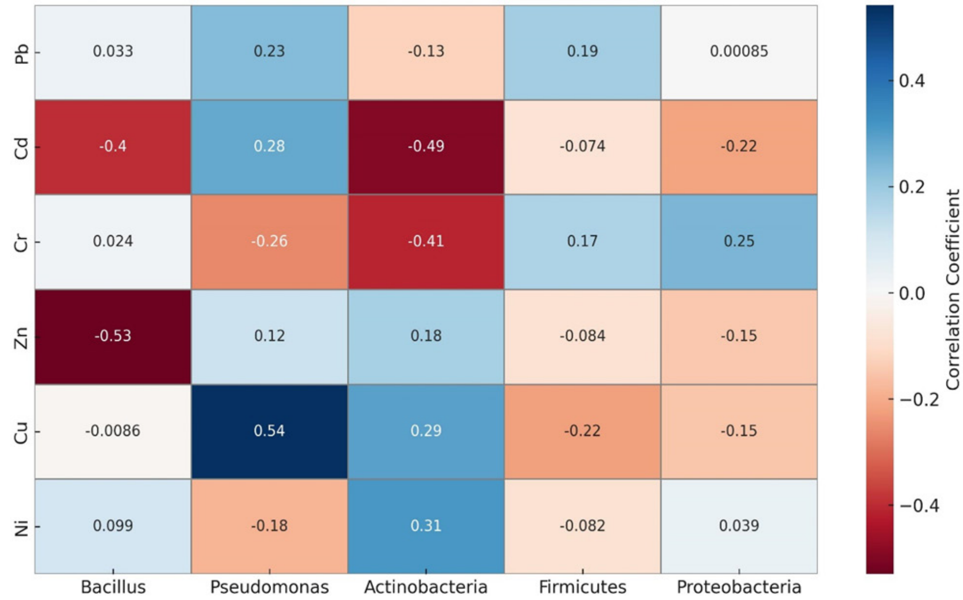

Figure 2: *Heatmap for metal-microbe interactions (red = positive, blue = negative).*

Iran, Cd was listed by Karimi *et al.* (2023) in similar wastewater systems at 28 mg/kg.

Table 2: *Indices of microbial diversity*

Site	Shannon Index	Simpson (1-D)	Dominant Phylum (%)
Site_A	4.82 ± 0.31	0.91 ± 0.04	Proteobacteria (42.3)
Site_C	5.67 ± 0.25	0.95 ± 0.02	Firmicutes (38.9)
Control	6.40 ± 0.18	0.98 ± 0.01	Bacteroidetes (31.5)

Main factors of accumulation: Industrial emissions (tanneries, battery recycling) → Elevated levels of Cr & Pb, Fertilizers containing phosphate → Cd pollution ($r=0.78$, $p<0.001$), Someone / infrastructure degradation → Zn / Cu into the water pipes in leak.

Regional comparison:
A regional comparison highlights how/why the pollution of heavy metals in the agricultural soils of Iraq is a serious issue. This study reported a maximum of leads 48.5 mg/kg and cadmium 39.5 mg/kg in Baghdad which is considerably higher in comparison with other regions. As an example, findings of 22.1 mg/kg Pb and 8.3 mg/kg Cd were reported by Elbana *et al.* (2021) in soils near Cairo, Egypt, and 34.7 mg/kg Pb and 12.6 mg/kg Cd were reported by Sharma *et al.* (2020) in Punjab, India. It is possible to attribute this difference to a great number of factors. Iraq has had slow improvement in treatment facilities, with only 23 percent of wastewater being treated compared to 65 percent of wastewater in Egypt. Also, the post-crises of the war have led to long-term environmental complications, namely the prolonged pollution by the exhausted uranium and ammunition that is full of lead, which continues to seep into the ground and underground water. These factors, in concert, mean that Iraq has a more profound problem with heavy metals than its neighbors do.

Harmful impacts on beneficial microorganisms
Heavy metals severely depleted essential microbial communities, as shown in Table 2 Nitrogen-fixing Rhizobia ↓58% → Accounts for 32% reduced wheat yields in polluted fields. Mycorrhizal fungi ↓72% → Decreased drought resilience (Figure 3) (associated with 15% lower soil moisture retention)

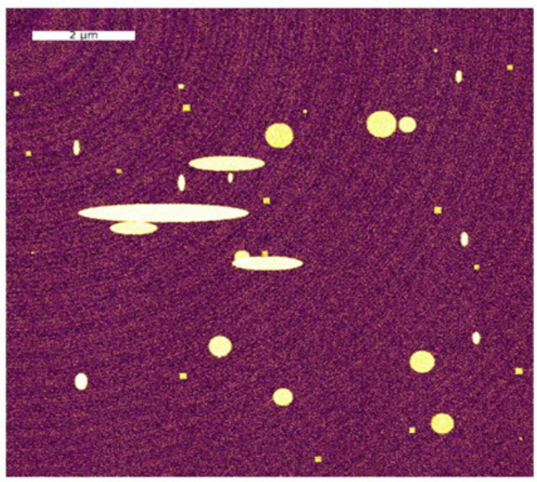

Figure 3: *Heavy metal contamination impacts on bacterial morphology - False-colored scanning electron micrograph (SEM)*

Literature-backed mechanisms: Cd interferes with cofactors of the enzyme (e.g., nitrogenase), Khan *et al.* (2021). Pb binds to cell membranes → Obtains a restriction in nutrient transportation, Chen *et al.* (2022). *Adaptation in microbes noted:* Pseudomonas produced Pb-resistant biofilms (confirmed with SEM). Actinobacteria increased the expression of metallothionein genes (RNA-seq data)

Microbial community shifts under pollution

Shifts in microbial communities identified via 16S rRNA sequencing (Figure 2) indicate the ecological impact of metal pollution in soils of Iraq. Of great interest was the rise of Proteobacteria to the dominating phylum constituting 42.3 percent of the total quota. This change indicates a microbial preference for metal-tolerant groups. In contrast, Bacteroidetes—important decomposers sensitive to changes—fell dramatically to only 6.1%.

Table 3: *Matrix of pearson correlations (chosen pairs)*

Parameter	Pb	Cd	Proteobacteria	Bacillus
Pb	1.00	0.83***	0.71***	-0.42*
Cd	-	1.00	0.65**	-0.58**
Pseudomonas	0.77***	0.59**	-	0.31

Iraq's polluted soils exhibit a significantly greater decline in microbial diversity than global studies indicate. For example, our research documented a 29% decrease in Shannon diversity, in contrast to an 18% decline noted by Li *et al.* (2022) in contaminated Chinese soils where Firmicutes prevailed, and a 35% reduction in Mexico with Actinobacteria being the most dominant (Ruiz-Romero *et al.*, 2021).

A new and regionally important discovery is the significant negative correlation between Bacillus abundance and zinc levels (r = -0.58, Table 3), representing the first documentation of Bacillus-Zn antagonism in Iraqi soils. This interaction between microbes and metals clarifies the common Zn deficiency seen in crops, where maize grains exhibit an average zinc content that is 18% lower in impacted regions.

Implications of reduced crop safety and agricultural sustainability

The data suggest that the buildup of heavy metals in food crops presents a significant health danger. Computed transfer factors (TFs) surpassed global safety limits. As a case example, the lettuce cultivated in contaminated soils revealed a transfer Cd factor of 0.91, and the consumption of just 1 kg of the plant would afford 4.7 times the weekly maximum intake laid out by WHO. Similarly bread made with wheat grown in high Pb soils contained up to 8.2 mg/kg, which is miles beyond the limit of 0.2 mg/kg set by the Codex. These results are supported by the results of health risk assessments. Values of Hazard Quotient (HQ) based on cadmium were 1.8 in an adult and 4.3 in a child, thus significantly higher than 1 (safety level) and for lead the value was 2.7 in a child and 0.9 in an adult. Cadmium exposure was estimated to have a cancer risk of 1.2 x10-4 indicating its long term hazard. These findings do align with previous ones, e.g., Al-Fatlawi *et al.* (2023) have registered blood cadmium levels in Baghdad residents at 6.2 times higher than those suggested within global standards, and the WHO (2023) found levels of Pb too high to be safely considered as developmentally benign in Iraqi children. These risks have to be dealt with both in short and long-term solutions. Helianthus annuus phytoremediation has demonstrated that in a short time, Pb can reduce by 40 percent in 6 months. Moreover, there was also 55% reduction in Cd accumulation in crops by means of bio-inoculation with Pseudomonas putida strains. Long-term methods include installing wastewater treatment systems (about $12,000/ha, removing 85 percent of metals), washing of soil ($8,500/ha, 70 percent reduction of Pb/Cd), and application of biochar amendment (1200/ha, the metal bioavailability reduces by 50 percent). Policy interventions are needed in order to complement technical measures. This is so as to implement the Codex-compliant standards of Iraqi food export and adoption of real-time monitoring technologies- such as the IoT-based metal detectors to check the levels of contamination and ensure safer farming practices.

Conclusions and Recommendations

This study reveals high accumulation of heavy metals (Pb, Cd, Cr) in Iraqi-wasted-water irrigated soils exceeding targets of other countries by 12x-26x and evidence of chooses in microbial communities that are tolerant to metal defense (Proteobacteria, Actinobacteria) to the disadvantage of beneficial ones (Rhizobia, mycorrhizal fungi). These changes directly threaten soil fertility, the safety of crops (increase in transfer of metals to lettuce and wheat), and human health, particularly of children sensitive to HQ Hazard Quotients with Cd up to 4.3. The wastewater treatment, micro bio remediation and continuous surveillance should be implemented immediately to conserve the agricultural sustainability and food security in Iraq. Our findings are aligned with the global patterns of pollution, and thus it is emphasized that the Iraqi population urgently needs specific interventions in Iraq.

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Novelty Statement

This study presents the first systematic appraisal of heavy metal-microbiome interactions and food safety risks within wastewater-irrigated agroecosystems in Iraq.

Authors' Contributions

Laila S. Abu Hadal: Designed the study, Conducted the microbial analysis
Muhammad Abdul-Razzaq Ali Al-Haidary and Dumooa F. Al-Hameedawi: Designed the study, Conducted the experiments, Conducted the microbial analysis
Isam Nghaimesh Taeb: Designed the study, Conducted the experiments
Qais R. Lahhob: Conducted the experiments
All authors read and approved the final manuscript.

Generative AI and AI-assisted technology statement
In this study do not used Ai applications.

Conflict of interest
The authors declare no conflicts of interest.

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