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RESEARCH ARTICLE

Ecological Risk and Bioaccumulation of Heavy Metals in Soil–Vegetable Systems under Wastewater Irrigation

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Abstract
This study investigates the implications of wastewater irrigation on soil and vegetable safety in Tamburawa, Kano State, Nigeria, amid challenges of limited freshwater resources. It highlights the ecological risks and bioaccumulation of heavy metals; copper (Cu), chromium (Cr), iron (Fe), lead (Pb), and zinc (Zn) in the rhizosphere soil and edible parts of vegetables (cabbage, carrot, lettuce, onion, and spinach) multiple samples of which were analyzed using Atomic Absorption Spectrophotometry (AAS). Key physicochemical soil parameters were assessed to determine their effects on metal mobility. Pollution indices, including the contamination factor (CF), pollution load index (PLI), and geo-accumulation index (Igeo), were employed to gauge pollution severity. The findings indicated that lead (Pb) and iron (Fe) levels surpassed FAO/WHO permissible limits, with Pb concentrations reaching 23.0 mg/kg in carrot shoots and Fe at 1046.5 mg/kg in onion leaves, whereas Cu and Zn remained within safe limits. The soils were slightly alkaline with pH 7.76 and a sandy-loam texture which, combined with low organic carbon and cation exchange capacity, facilitated metal mobility. The high CF values for Pb and Fe suggest severe contamination, particularly in carrot and spinach rhizosphere soils. PLI values exceeding 1 corroborated the presence of cumulative pollution at several sites. Overall, the results underscore the significant ecological risks and heavy metal bioaccumulation associated with wastewater irrigation, necessitating immediate action in wastewater treatment, soil remediation, and ongoing monitoring to safeguard urban food systems.

Keywords: Soil contamination; urban agriculture; rhizosphere soil; wastewater irrigation

Introduction

Irrigation using wastewater has become an increasingly important strategy for managing water scarcity and sustaining agricultural production in many developing countries (Singh 2021; Nowwar et al., 2023). In arid and semi-arid regions, particularly in urban and peri-urban areas where freshwater is scarce or costly, the use of untreated or partially treated wastewater is now a common practice because of its continuous availability and nutrient-rich composition (Qadir et al., 2022; Chen et al., 2023). Wastewater is known to contain essential plant nutrients such as nitrogen, phosphorus, and potassium, which can enhance soil fertility and crop productivity, thereby supporting food security and income generation for smallholder farmers in peri-urban regions (Hasheem et al., 2021; Woldetsadik et al., 2023). Despite these agronomic benefits, wastewater often contains substances that are highly toxic to both the environment and human health, including heavy metals that can accumulate in soils and pose long-term ecological and health risks (Abbas et al., 2023). Metals such as lead (Pb), cadmium (Cd), copper (Cu), zinc (Zn), and chromium (Cr) are commonly detected in industrial and municipal wastewater sources (Abdullahi et al., 2025; Ugya et al., 2019). These metals are non-biodegradable and can persist in the soil for extended periods, with concentrations increasing over time through repeated irrigation and cultivation (Bellanthudawa et al., 2023; Zhou et al., 2020).

The mobility and bioavailability of heavy metals in soil depend on several physicochemical properties, including pH, soil texture, organic matter content, redox potential, and irrigation practices (Wu et al., 2022). In many urban farming areas, soils often exhibit low cation exchange capacity (CEC), which enhances metal mobility and facilitates their uptake by plants (Golia, 2023; Lucija et al., 2025). Consequently, high concentrations of metals can accumulate in the edible parts of vegetables, exposing consumers to chronic health risks such as kidney damage, neurological disorders, and cancer (Boahen et al., 2024; Mawari et al., 2022). In Africa, wastewater irrigation is widespread in major cities such as Lagos, Kano, Ibadan, and Port Harcourt, where domestic, commercial, and industrial wastewaters are used for year-round vegetable production (Tayo, 2021). In Kano State, for instance, industrial zones such as Challawa and Sharada discharge untreated effluents directly into natural water channels, creating serious environmental hazards for downstream farms that rely on these waters for irrigation (Abdulsalam et., 2023). In such regions, monitoring programs are often absent or poorly managed, and farmers are generally unaware of the contamination risks associated with their irrigation water (Bellanthudawa et al., 2023; Oladipo et al., 2022). Heavy metal pollution not only threatens human health but also disrupts soil–plant interactions. Elevated concentrations of Cr, Pb, and Cd can suppress soil microbial biomass, enzyme activity, and the functioning of symbiotic bacteria such as *Rhizobium*, thereby reducing nitrogen fixation and nutrient cycling (Rashid et al., 2023). These ecological disruptions impair soil fertility, threaten sustainable agriculture, and increase the risk of bioaccumulation in crops.

Tamburawa, located on the outskirts of Kano metropolis, is one of the most productive vegetable-growing regions in northern Nigeria. The area relies heavily on irrigation water from the River Kano, which is frequently contaminated with industrial effluents (Abdullahi et al., 2025; Shawai et al., 2019). Crops such as lettuce, spinach, carrot, onion, and cabbage are cultivated on a commercial scale; however, there is limited empirical evidence on the extent of heavy metal contamination in the soils and vegetables grown in this area (Abdullahi et al., 2025; Shawai et al., 2019). Previous studies have reported elevated levels of lead and cadmium in vegetable tissues from Tamburawa, but comprehensive assessments of contamination depth and associated ecological risks remain scarce (Zhang et al., 2023). The long-term accumulation of heavy metals in soil can degrade soil quality by affecting microbial activity and nutrient cycling, while also posing significant food safety risks—undermining efforts to promote sustainable urban agriculture (Bellanthudawa et al., 2023; Zhou et al., 2020).

While direct measurements of metal concentrations provide essential baseline information, interpreting ecological and food-safety risks requires standardized pollution indices. The Contamination Factor (CF), Geo-accumulation Index (Igeo), and Pollution Load Index (PLI) are widely used to assess both the magnitude and severity of contamination relative to background levels (Hakanson, 1980; Müller, 1969; Tomlinson et al., 1980). These indices enable classification of soil pollution levels, inter-regional comparison, and identification of the most ecologically hazardous metals.

Therefore, this study aimed to determine the concentrations of selected heavy metals (Cu, Cr, Fe, Pb, and Zn) in the edible parts of five commonly cultivated vegetables and their rhizosphere soils from wastewater-irrigated farms in Tamburawa, Kano State. Furthermore, the study evaluated ecological contamination using CF, Igeo, and PLI indices and provided evidence-based recommendations for monitoring and remediation to promote safe and sustainable urban agriculture.

Materials and methods

Study area

The research was conducted in Tamburawa, located approximately 25 km southeast of Kano metropolis, Nigeria (Figure 1). The area lies within the Sudan savanna ecological zone, characterized by distinct wet and dry seasons. Tamburawa has developed into a major commercial hub for vegetable cultivation, supported primarily by wastewater irrigation sourced from the Kano River, which receives effluents from the Challawa industrial estate. The soils of the study area are predominantly sandy loam, well-drained, and moderately fertile. Local farmers engage in year-round cultivation of various vegetables, including lettuce, spinach, cabbage, onion, and carrot, among others. The intensive use of wastewater for irrigation has made Tamburawa an ideal site for assessing soil contamination and ecological risks associated with heavy metal accumulation in wastewater-irrigated farmlands.

Sampling procedure

Sampling of vegetables

Five commonly consumed vegetable species were selected for this study: cabbage (*Brassica oleracea*), carrot (*Daucus carota*), lettuce (*Lactuca sativa*), onion (*Allium cepa*), and spinach (*Spinacia oleracea*). The selection was based on their nutritional importance, regional cultivation prevalence, and potential for heavy metal accumulation. Mature and healthy plants were randomly harvested using clean stainless-steel tools, following standard protocols for trace metal studies in crops (Anirban et al., 2023; Ene et al., 2024). At each sampling plot, three composite replicate samples were collected per vegetable species. Each composite comprised five randomly selected healthy plants, pooled to form one replicate (n = 3 per species). This sampling design ensured statistical robustness and followed established procedures in heavy metal assessment studies in vegetables (Sultana et al., 2022).

The harvested vegetables were separated into distinct anatomical parts for analysis: cabbage (leaves and shoots), carrot (taproot and shoot), lettuce (leaves and shoots), onion (bulb and leaves), and spinach (leaves and shoots). This partitioning enabled evaluation of metal distribution within different plant tissues.

Immediately after collection, samples were thoroughly washed with tap water to remove visible soil and dust particles, followed by rinsing with deionized water to eliminate surface contaminants. This cleaning procedure ensured that subsequent analyses reflected internal metal accumulation rather than external deposition (Li et al., 2023). The cleaned plant materials were then cut into small pieces, air-dried under shade for 5–7 days, and stored in labeled paper envelopes pending laboratory digestion and heavy metal analysis.

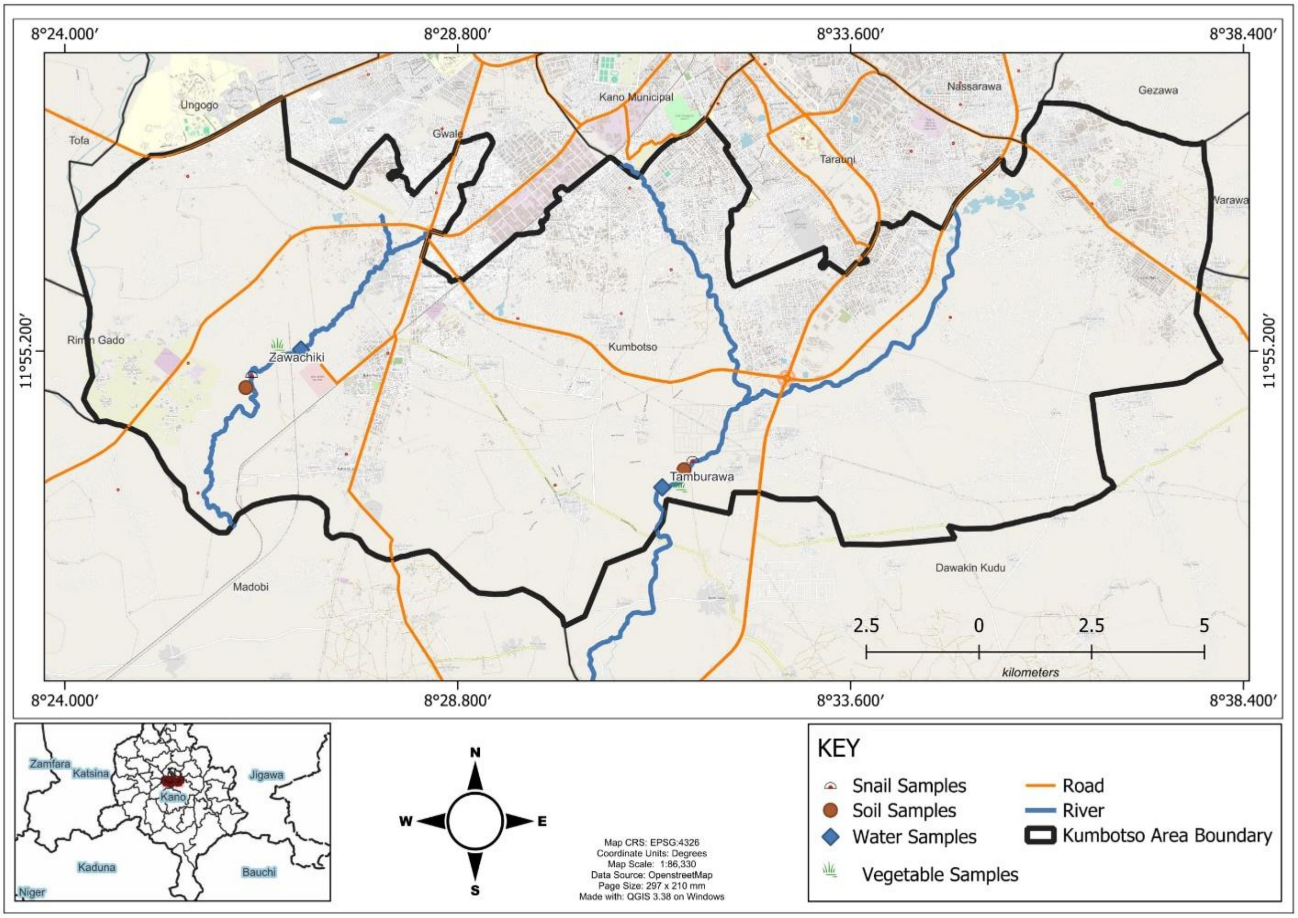

Figure 1. Study Area; Tamburawa, Kumbotso Local Government Area, Kano State, Nigeria

Sampling of rhizosphere soil

Rhizosphere soil samples were collected simultaneously with the vegetable samples. The rhizosphere was defined as the soil loosely adhering to the roots after gently shaking off bulk soil. For each composite replicate, approximately 200 g of root-adhered soil was collected from a 0–20 cm depth at three points per plant, pooled, air-dried, and sieved through a 2 mm mesh (Asamoah et al., 2025; Carrera et al, 2025). Thus, each vegetable species had three rhizosphere composite replicates (n = 3).

Sampling was conducted on the same vegetable plots used for plant collection. For each species, three sub-samples were taken across the root zone and combined to form one representative sample. The rhizosphere soils were coded as follows:

RSPC – rhizosphere soil from cabbage
RSPCR – rhizosphere soil from carrot
RSPL – rhizosphere soil from lettuce
RSPO – rhizosphere soil from onion
RSPS – rhizosphere soil from spinach

Following standard soil preparation procedures, samples were air-dried at ambient temperature, crushed to disaggregate clods, and sieved through a 2 mm mesh to remove stones and coarse debris (Asamoah et al.,2025; Carrera et al, 2025). The processed samples were stored in clean polyethylene zip-lock bags and kept in a desiccator until further analysis. This procedure ensured uniformity and comparability between plant tissues and corresponding rhizosphere soils for assessing heavy metal distribution.

Sample digestion and heavy metal analysis

Heavy metals in soil and plant samples were extracted using the wet digestion method following APHA (2012) and USEPA (1996) protocols. Approximately 1.0 g of the sieved sample was weighed into a digestion flask, followed by the addition of 10 mL nitric acid (HNO_3) and 2 mL perchloric acid ($HClO_4$). The mixture was heated on a hot plate at 120°C until the volume was reduced to approximately 2 mL, and a clear solution indicated complete digestion. After cooling, each digest was filtered through Whatman No. 42 filter paper into a 50 mL volumetric flask, and the volume was made up to the mark with deionized water. The resulting solution served as the stock digest for heavy metal determination. Samples with concentrations exceeding the calibration range of the Atomic Absorption Spectrophotometer (AAS) were appropriately diluted (1:2, 1:5, or 1:10) with deionized water, and the corresponding dilution factors were applied to obtain accurate concentrations.
The concentrations of copper (Cu), chromium (Cr), iron (Fe), lead (Pb), and zinc (Zn) were determined using AAS following the APHA (2012) standard procedure. To ensure quality assurance and quality control (QA/QC), reagent blanks, duplicate samples, and certified reference materials were included throughout the analytical process.

Physicochemical properties of rhizosphere soil

The physicochemical properties of rhizosphere soil were analyzed because these parameters significantly influence heavy metal solubility, mobility, and bioavailability. Soil pH and electrical conductivity (EC) were determined in a 1:2.5 soil-to-water suspension using a calibrated glass-electrode pH meter and a conductivity meter, respectively (Song et al., 2025). Organic matter (OM) content was estimated by the Walkley–Black dichromate oxidation method (Dong et al., 2021). The cation exchange capacity (CEC) was measured using the ammonium acetate extraction method at pH 7.0 (Purnamasari et al., 2021). These soil parameters are well-recognized regulators of heavy metal retention and release (Kumar et al., 2023), and their determination helps to interpret the potential bioavailability of metals in wastewater-irrigated soils.

Pollution indices for soil assessment

To evaluate the degree of heavy metal contamination in rhizosphere soils, the Contamination Factor (CF), Geo-accumulation Index (Igeo), and Pollution Load Index (PLI) were calculated following standard approaches (Müller, 1969; Hakanson, 1980; Tomlinson et al., 1980).

Contamination factor (CF)

The contamination factor expresses the extent of metal accumulation in the soil relative to a background concentration and is calculated by following equation 1.

$$CF = \frac{C_{metal}}{C_{background}} \text{.......................................Equation (1)}$$

Where:
C_{metal} = measured concentration of heavy metal in the sample (mg/kg)
$C_{background}$ = reference value (mg/kg)

Classification of CF (Hakanson, 1980)

- $CF < 1$: Low contamination
- $1 \leq CF < 3$: Moderate contamination
- $3 \leq CF < 6$: Considerable contamination
- $CF \geq 6$: Very high contamination

Background values used (mg/kg)

In this study, the background values were adopted from Kabata-Pendias (2011), which provides global average concentrations trace elements in uncontaminated soils, which offers regional background data for Nigerian soils (Sulaiman et al., 2021). These sources are widely used in heavy metal contamination studies in Africa for comparable soil types. The background vales are as follows:

- Pb: 2.0 mg/kg
- Cd: 0.3 mg/kg
- Cu: 20.0 mg/kg
- Zn: 50.0 mg/kg
- Ni: 10.0 mg/kg

Geo-accumulation Index (Igeo)

The Geo-accumulation Index uses background levels of concentration of metals in soil, along with a correction factor, as a measure of the degree of concentration of a metal in the soil (Equation 2).

$$I_{geo} = \log_2 \left(\frac{C_n}{1.5 \times B_n}\right) \text{...Equation (2)}$$

Where:

- Cn = measured concentration of the metal
- Bn = geochemical background values
- 1.5 = constant for natural variability (Muller, 1969; Kabata-Pendias, 2011)

Classification of Igeo (Muller, 1969):

- Igeo ≤ 0: Unpolluted
- $0 <$ Igeo ≤ 1: Unpolluted to moderately polluted
- $1 <$ Igeo ≤ 2: Moderately polluted
- $2 <$ Igeo ≤ 3: Moderately to strongly polluted

• 3 < Igeo ≤ 4: Strongly polluted
• 4 < Igeo ≤ 5: Strongly to extremely polluted
• Igeo > 5: Extremely polluted

Pollution Load Index (PLI)

The Pollution Load Index is a measure developed through combining all the other measures given in a sample into one index which reflects overall heavy metal pollution in the sample. It is computed as the nth root of the product of CF of the metals that are being analyzed (Equation 3). The method was adopted by Tomlinson et al., (1980) for marine and estuarine sediments and has since widely applied to terrestrial and agricultural soils (Nasir et al., 2023; Soleimani et al., 2023).

PLI was calculated using equation3:

$$PLI = (CF_1 \times CF_2 \times \ldots CF_n)\ \frac{1}{n} \qquad \text{Equation (3)}$$

Where:

CF = contamination factor of each metal
n = number of metals considered
PLI Interpretation (Tomlinson et al., 1980):
PLI < 1: No pollution
PLI = 1: Baseline level
PLI > 1: Pollution present

Statistical analysis

All experimental data were expressed as mean ± standard error (SE) of triplicate determinations. Statistical analyses were performed using GENSTAT 17th Edition. One-way Analysis of Variance (ANOVA) was applied to test for significant differences among heavy metal concentrations across vegetable plots. Where significant differences were observed, means were separated using Duncan's Multiple Range Test (DMRT) at a 5% significance level ($p < 0.05$). Distinct letters (a–d) in the tables indicate statistically significant differences among means.

Results and discussion

Physicochemical properties of the rhizosphere soil

The physicochemical properties of the rhizosphere soil are presented in Table 1. These properties are fundamental in determining the solubility, retention, and bioavailability of heavy metals within the soil–plant system. The soil pH was 7.76, falling within the FAO/WHO (2007) safe agricultural range of 6.0–8.5. Soils with alkaline pH generally reduce the solubility of cationic metals such as Pb^{2+}, Zn^{2+}, and Cu^{2+}, owing to their precipitation as hydroxides, carbonates, or phosphates, and adsorption onto negatively charged soil colloids

(Muhammad et al., 2025). However, under low-buffering conditions, typical of sandy soils with minimal organic colloids, these metals can remain relatively mobile despite alkalinity (Burachevskaya et al., 2024). This suggests that the alkaline condition in the study area may not be sufficient to prevent metal mobility and bioavailability. The electrical conductivity (EC = 1.79 dS/m) indicated moderate salinity, below the critical threshold of 4 dS/m where salinity stress can significantly impair crop growth (FAO/WHO, 2007). Nonetheless, prolonged irrigation with wastewater could gradually increase sodium accumulation, altering soil structure and promoting metal desorption from exchange sites (Abdel-Malek et al., 2024; Qadir et al., 2022). Elevated Na^+ concentrations can disperse clay particles and release adsorbed heavy metals, enhancing their movement toward plant roots. The soil texture comprised 76.28% sand, 16.88% silt, and 6.79% clay, classifying it as sandy loam. This texture type is typical of arid and semi-arid regions and is known for low metal retention capacity due to its small surface area and reduced adsorption potential (El-Hematy et al., 2025). The limited clay fraction and low organic matter content reduce the number of active binding sites for heavy metals, increasing leaching potential and metal mobility. In contrast, fine-textured soils (high in clay or organic colloids) tend to immobilize metals by surface complexation and cation exchange (Zhao et al., 2023).

Exchangeable base analysis revealed the dominance of Ca^{2+} (11.70 cmol/kg), followed by Mg^{2+}, Na^+, and K^+. High calcium levels are characteristic of semi-arid soils and may compete with heavy metals for adsorption sites, thereby reducing metal availability (Lee et al., 2025). However, the relatively elevated Na^+ (1.11 cmol/kg) poses a potential sodicity hazard, particularly under continuous wastewater irrigation, as Na^+ can displace Ca^{2+} and Mg^{2+} on exchange sites and promote dispersion of clay minerals—conditions that enhance metal migration and solubility. The cation exchange capacity (CEC = 1.45 cmol/kg) was very low, far below the benchmark of >10 cmol/kg for fertile soils (Ćirić et al., 2023). Such low CEC reflects a deficiency in negatively charged colloids (clays and humic substances), implying limited adsorption capacity for cationic heavy metals and, consequently, a greater tendency for metal leaching and bioavailability (Roulia, 2024). This low CEC condition helps explain the elevated contamination factors observed for Pb and Fe in later sections of this study.

The organic carbon content (OC = 8.06 g/kg or 0.81%) was also below the 2% minimum threshold for maintaining soil fertility and structural stability (FAO, 2015). Organic matter strongly influences metal behavior through complexation, adsorption, and redox reactions. Low OC implies reduced complexation potential, leading to weak immobilization of metals in the soil matrix (Su et al., 2024). Conversely, dissolved organic compounds from wastewater could form soluble metal–organic complexes, enhancing vertical and lateral mobility of metals in the soil profile. Macronutrient analysis showed total nitrogen (1.33 g/kg) and available phosphorus (77.66 mg/kg), values consistent with nutrient enrichment commonly associated with wastewater irrigation (Singh, 2021; Saleh et al., 2025). While this enrichment enhances soil fertility, excess phosphorus may form insoluble complexes with Fe and Zn, reducing their bioavailability to plants (Yang et al., 2024). Moreover, nutrient–metal interactions could influence competitive uptake dynamics, particularly where Fe–P and Zn–P antagonisms occur in the rhizosphere.

Comparative assessment against international soil quality standards indicates that the study soils were within the acceptable pH and salinity ranges but notably deficient in CEC and organic matter, both of which are critical for heavy metal retention and immobilization. The combination of sandy texture, low CEC, and low organic carbon implies high potential mobility and bioavailability of metals, thereby increasing the risk of transfer from soil to vegetables. These conditions offer a plausible explanation for the high Contamination Factor (CF), Geo-accumulation Index (Igeo), and Pollution Load Index (PLI) values observed for Pb and Fe in this study.

Although the alkaline pH tends to restrict solubility, the dominance of sandy particles, low exchange surfaces, and limited organic matter facilitate enhanced metal migration and uptake by plants.

Hence, the physicochemical characteristics of the soil not only promote heavy metal transfer to edible plant parts but also amplify cumulative ecological and food safety risks, as reflected in the pollution indices discussed in the subsequent sections.

Table 1. Physicochemical properties of the rhizosphere soil in the study area

Parameters	Values/class
pH	7.76
EC (dS\ cm)	1.79
Sand (%)	76.28
Silt (%)	16.88
Clay (%)	6.79
Textural class	Sandy-loam
Ca	11.70
Mg	2.85
K	0.79
Na	1.11
CEC	1.45
OC (g/kg)	8.06
TN (g/kg)	1.33
AP (mg/kg)	77.66

Note: EC–electrical conductivity; Ca–calcium; Mg– magnesium; K–potassium; Na–sodium; CEC–cation exchange capacity; OC–organic carbon; TN–total nitrogen; AP–available phosphorus.

Heavy metal concentrations in vegetable samples

Heavy metals including Copper (Cu), Chromium (Cr), Iron (Fe), Lead (Pb), and Zinc (Zn) were detected in the edible components of the five vegetables analyzed in this study (Table 2). The concentration of Cu ranged from 3.61 mg/kg in spinach shoots to 7.63 mg/kg in spinach leaves, with most values exceeding the FAO/WHO (2007) permissible limit of 3.0 mg/kg. Chromium was found at levels between 11.11 mg/kg in cabbage shoots and 24.45 mg/kg in onion bulbs, significantly higher than the safe threshold of 2.3 mg/kg. Iron concentrations varied widely, from 75.4 mg/kg in spinach shoots to 1046.5 mg/kg in onion leaves, all surpassing the FAO/WHO limit of 425 mg/kg. Lead was detected only in cabbage leaves (4.33 mg/kg) and carrot shoots (23.0 mg/kg), far above the maximum limit of 0.3 mg/kg. Zinc concentrations ranged from 5.88 mg/kg in spinach shoots to 32.66 mg/kg in carrot shoots, remaining below the FAO/WHO limit of 60 mg/kg. Statistically significant differences ($p < 0.05$) were observed for Cr, Fe, Pb, and Zn, reflecting crop-specific variations in heavy metal uptake. The elevated levels of these metals can be explained by several interacting mechanisms.

Wastewater used for irrigation often contains industrial and domestic effluents rich in heavy metals such as Cr and Pb, which are non-biodegradable and highly persistent (Abdullahi et al., 2025; Ugya et al., 2019).

Soil physicochemical properties, including sandy texture, low organic carbon, and low cation exchange capacity, reduce metal adsorption and retention, making them more mobile and bioavailable to plants (Alloway, 2013; Kabata-Pendias, 2011). Alkaline pH may partially limit solubility; however, in soils with low buffering capacity, metals remain available for plant uptake. Additionally, differences in metal accumulation among crops can be attributed to plant-specific factors such as root morphology, transpiration rate, and leaf surface area, which influence both root absorption and foliar deposition of metals (Woldetsadik et al., 2023; Chen et al., 2023). For example, the high Pb content in carrot roots likely reflects the strong adsorption of Pb onto root surfaces and its limited translocation to shoots (Mthembu et al., 2024 4).

Table 2. Heavy metals concentrations (mg/kg) in wastewater irrigated vegetables.

Sample	Cu (3.0)	Cr (2.3)	Fe (425)	Pb (0.3)	Zn (60)
Cabbage Shoot	4.52 ± 0.11^{a}	11.11 ± 0.45a	102.6 ± 5.2^{a}	N.D	8.46 ± 0.27^{d}
Cabbage Leaves	3.67 ± 0.10^{b}	18.33 ± 0.56^{b}	156.5 ± 7.4^{e}	4.33 ± 0.18^{a}	7.82 ± 0.33^{d}
Carrot Shoot	6.33 ± 0.13^{a}	18.33 ± 0.56^{b}	770.6 ± 34.2^{c}	23.00 ± 1.00^{b}	32.66 ± 1.20^{a}
Carrot Taproot	7.23 ± 0.14^{a}	13.89 ± 0.45^{b}	296.9 ± 14.6^{d}	N.D	11.22 ± 0.44^{b}
Lettuce Shoot	4.18 ± 0.11^{b}	23.89 ± 0.60^{c}	908.5 ± 41.3^{c}	N.D	11.80 ± 0.39^{b}
Lettuce Leaves	4.58 ± 0.12^{b}	22.22 ± 0.55^{c}	495.0 ± 20.5^{d}	N.D	12.49 ± 0.46^{b}
Onion Leaves	6.67 ± 0.18^{a}	23.89 ± 0.58^{c}	1046.5 ± 48.3^{b}	N.D	16.98 ± 0.55^{a}
Onion Bulb	5.93 ± 0.17^{a}	24.45 ± 0.60^{c}	788.7 ± 35.2^{c}	N.D	19.32 ± 0.63^{a}
Spinach Shoot	3.61 ± 0.10^{b}	19.44 ± 0.47^{b}	75.4 ± 3.3^{a}	N.D	5.88 ± 0.19^{c}
Spinach Leaves	7.63 ± 0.20^{a}	23.89 ± 0.59^{c}	369.1 ± 18.0^{d}	N.D	12.86 ± 0.45^{b}

Note: Values are expressed as mean ± SE (n = 3); WHO/FAO permissible limits in the parentheses. N.D = Not Detected. Superscript a-e indicate statistical differences (*$P < 0.05$*, DMRT)

Nutrient-metal interactions may further influence heavy metal dynamics. High phosphorus levels from wastewater irrigation can alter Fe and Zn solubility and uptake, whereas cationic metals such as Ca^{2+} and Mg^{2+} compete with Cu^{2+}, Pb^{2+}, and Zn^{2+} for binding sites in soil and plant tissues (Kabata-Pendias, 2011). Furthermore, industrial Fe and Cr discharged into irrigation water, combined with sediment transport, contribute to excessive metal accumulation in the rhizosphere and edible plant parts (Abbas et al., 2023).

Overall, vegetables grown under wastewater irrigation in Tamburawa exhibit elevated levels of toxic metals, especially Cr, Pb, and Cu, with statistically significant variations across crops. The combination of wastewater contamination, soil characteristics, and plant-specific uptake mechanisms underlies the observed accumulation patterns. These findings highlight the urgent need for wastewater treatment, regular monitoring of heavy metals in vegetables, and implementation of mitigation strategies to ensure food safety and sustainable urban agriculture.

Heavy metal concentrations in the rhizosphere soil of vegetables

Heavy metals including Cu, Cr, Fe,Pb, and Zn were detected in the rhizosphere soils of all five vegetables cultivated under wastewater irrigation in Tamburawa (Table 3). Cu concentrations ranged from 1.21 mg/kg in cabbage soil (RSPC) to 3.30 mg/kg in carrot soil (RSPCR), with the carrot rhizosphere slightly exceeding the FAO/WHO permissible limit of 3.0 mg/kg. Chromium levels varied from undetectable in cabbage and carrot soils to 8.89 mg/kg in spinach rhizosphere (RSPS), exceeding the FAO/WHO limit of 2.3 mg/kg for all detected samples. Iron showed the highest accumulation, ranging from 1338.0 mg/kg in cabbage to 5106.5 mg/kg in carrot soil, while Pb concentrations varied between 13.83 mg/kg in onion rhizosphere (RSPO) and 76.83 mg/kg in carrot (RSPCR), all far above the safe threshold of 0.3 mg/kg. Zn ranged from 1.82 mg/kg in cabbage soil to 9.83 mg/kg in onion soil, remaining below the FAO/WHO limit of 60 mg/kg. Statistically significant differences ($p < 0.05$) were observed for Fe, Pb, and Zn, reflecting differential accumulation across vegetable types.

Table 3. Heavy Metals Concentrations (mg/kg) in the Rhizsophere of the soil employed for planting vegetables.

Sample	Cu (mg/kg)	Cr (mg/kg)	Fe (mg/kg)	Pb (mg/kg)	Zn (mg/kg)
RSPC	12.1 ± 0.05^{a}	ND	1338.0 ± 65.1^{a}	29.67 ± 1.33a	1.82 ± 0.08a
RSPCR	3.30 ± 0.12^{b}	ND	5106.5 ± 221.7^{b}	76.83 ± 2.88b	8.46 ± 0.32^{b}
RSPL	2.88 ± 0.09^{a}	2.78 ± 0.08^{a}	4263.9 ± 192.0^{b}	21.00 ± 1.21a	8.15 ± 0.28^{c}
RSPO	2.88 ± 0.10^{a}	6.11 ± 0.21^{b}	3564.8 ± 170.2^{b}	13.83 ± 0.95c	9.83 ± 0.34^{d}
RSPS	3.05 ± 0.11^{a}	8.89 ± 0.31^{b}	3893.5 ± 178^{b}	16.83 ± 1.01c	6.99 ± 0.23^{c}

Note: Values are expressed as mean ± SE (n = 3); WHO/FAO permissible limits in the parentheses. N.D = Not Detected. Superscript a-e indicate statistical differences ($P < 0.05$, DMRT), RSPC= Rhizosphere of the soil employed for planting cabbage, RSPCR= Rhizosphere of the soil employed for planting, RSPL= Rhizosphere of the soil employed for planting lettuce, RSPO= Rhizosphere of the soil employed for planting onion
RSPS= Rhizosphere of the soil employed for planting spinach

The elevated metal concentrations can be attributed to prolonged wastewater irrigation containing industrial and domestic effluents, which introduce heavy metals into the soil environment (Abdullahi et al., 2025; Ugya et al., 2019). Soil properties such as sandy loam texture, low cation exchange capacity, and low organic carbon reduce metal retention, enhancing mobility and bioavailability to plant roots (Alloway, 2013). The selective accumulation of Cr in certain rhizospheres may be influenced by crop-specific root exudates and localized inputs from nearby tanneries or paint industries (Kabata-Pendias, 2011). High Fe concentrations are likely driven by iron-rich sediments and industrial discharges, while elevated Pb reflects contamination from vehicular emissions, batteries, and metal wastes along irrigation channels (Mthembu et al., 2024). Zn accumulation patterns are consistent with long-term wastewater application and crop-specific uptake mechanisms (Woldetsadik et al., 2023). Thus these results indicated that the rhizosphere soils of wastewater-irrigated vegetables in Tamburawa exhibit persistent and crop-dependent heavy metal contamination, particularly for Fe and Pb. The interplay between wastewater composition, soil physicochemical characteristics, and plant-specific uptake drives metal accumulation, highlighting the critical need for regular monitoring, proper irrigation water treatment, and management interventions to mitigate ecological and food safety risks (Bellanthudawa et al., 2023).

Contamination factor and pollution load index

The Contamination Factor (CF) values for heavy metals in the rhizosphere soils of wastewater-irrigated vegetables are presented in Table 4, providing an assessment of contamination relative to baseline or background levels. According to Hakanson (1980), CF values are classified as: <1 (low contamination), 1–3 (moderate contamination), 3–6 (considerable contamination), and ≥6 (very high contamination). In this study, Pb exhibited exceedingly high CF values, with 256.10 in carrot soil (RSPCR) and 98.90 in cabbage soil (RSPC), indicating extreme contamination. These values are substantially higher than reported in other industrially impacted agricultural areas in Nigeria (Sulaiman et al., 2021). Fe also showed high CF values across all rhizosphere soils, reflecting long-term accumulation from wastewater carrying sediment and iron-rich effluents (Soleimani et al., 2023; Tayo, 2021).

In contrast, Cu and Zn CFs in cabbage (RSPC) and spinach (RSPS) rhizospheres were below 1, indicating low contamination, consistent with observations in similar wastewater-irrigated farmlands (Abdullahi et al., 2025; Ugya et al., 2019). The carrot rhizosphere (RSPCR) showed moderate Cu contamination (CF = 1.10), likely due to its proximity to industrial drainage channels (Darma et al., 2024). Chromium, though undetected in RSPC and RSPCR, exhibited a high CF (3.87) in spinach rhizosphere (RSPS), suggesting localized contamination from tannery and metal-processing effluents (Tripathi et al., 2025). These patterns indicate that CF values are strongly influenced by wastewater composition, proximity to industrial sources, and crop-specific soil interactions.

The Pollution Load Index (PLI), which provides an overall measure of cumulative heavy metal pollution, further underscores these risks. PLI values for lettuce, onion, and spinach rhizospheres were 2.56, 2.76, and 2.98, respectively, exceeding the critical threshold of 1 and signaling poor soil quality and cumulative heavy metal stress (Elechi et al., 2023; Nasir et al., 2023). The rhizospheres of carrot and cabbage showed PLI values of zero, likely because undetectable Cr concentrations were excluded from the geometric mean calculation, a phenomenon reported in similar studies (Chen et al., 2023).

Overall, these results highlight that Pb and Fe are the primary contributors to soil contamination, while Cu, Zn, and Cr show variable, crop-specific accumulation patterns. The combination of CF and PLI data underscores the urgent need for monitoring, wastewater treatment, and remediation measures to mitigate heavy metal pollution in urban agricultural soils.

Table 4. Contamination Factor and Pollution Load Index for Rhizosphere of the soil employed for planting vegetables.

Sample	CF-Cu	CF-Cr	CF-Fe	CF-Pb	CF-Zn	PLI
RSPC	0.40	0.00	3.15	98.90	0.03	0.00
RSPCR	1.10	0.00	12.02	256.10	0.14	0.00
RSPL	0.96	1.21	10.03	70.00	0.14	2.56
RSPO	0.96	2.66	8.39	46.10	0.16	2.76
RSPS	1.02	3.87	9.16	56.10	0.12	2.98

Note: CF > 1 indicates contamination; PLI > 1 indicates soil deterioration; RSPC= Rhizosphere of the soil employed for planting cabbage; RSPCR= Rhizosphere of the soil employed for planting; RSPL= Rhizosphere of the soil employed for planting lettuce; RSPO= Rhizosphere of the soil employed for planting onion; RSPS= Rhizosphere of the soil employed for planting spinach.

Geo-accumulation index (Igeo)

The results of Geo-accumulation Index (Igeo) which are depicted in Table 5 therein presenting another indicator of the intensive contamination of heavy metals in the rhizosphere of the soil employed in cultivating the studied vegetables. Going by the classification of Muller (1969), Igeo 5 and above Implies that there is extreme pollution. The detection of Pb in the rhizosphere soil indicate serious pollution with maximum values of 7.42 in carrot, 6.04 in cabbage, which is congruent with the CF findings and a sign of the threat of Pb buildup in agricultural land (Onwuka et al., 2024).

Fe concentrations were at medium and fair pollution levels, with Igeo values ranging between 1.07 (RSPC) and 3.00 (RSPCR) in agreement with other researchers that indicated the enrichment of iron in raw sewage effluents (Abubakar et al., 2025). The Igeo values of Zn and Cu were mostly < 0 which is indicative of background or non-polluted conditions and this is supported by their low CFs (Hasheem et al., 2020). The fact that the highest Igeo Cr (1.37) obtained in RSPS contributes to moderate contamination to the fact that Cr is well known to persist in wastewater-affected sites (Elechi et al., 2023).

The results in this study highlight Pb and Fe to be crucial pollutants of concern in the-Tamburawa irrigation ecosystem. Therefore, proper and continuous monitoring coupled with long-term soil-remediation activity are required with a view to curbing bio-accumulation and human contact of heavy metals through food chains.

Table 5. Geo-accumulation Index for Heavy Metals in Rhizosphere Soil

Soil Type	Igeo-Cu	Igeo-Cr	Igeo-Fe	Igeo-Pb	Igeo-Zn
RSPC	-1.89	-∞	1.07	6.04	-5.63
RSPCR	-0.45	-∞	3.00	7.42	-3.41
RSPL	-0.64	-0.31	2.74	5.54	-3.47
RSPO	-0.64	0.82	2.48	4.94	-3.19
RSPS	-0.56	1.37	2.61	5.22	-3.69

Note: Igeo > 1 indicates pollution. RSPC= Rhizosphere of the soil employed for planting cabbage; RSPCR= Rhizosphere of the soil employed for planting; RSPL= Rhizosphere of the soil employed for planting lettuce; RSPO= Rhizosphere of the soil employed for planting onion; RSPS= Rhizosphere of the soil employed for planting spinach.

Conclusion

This study demonstrated that wastewater-irrigated soils and vegetables in Tamburawa are heavily contaminated with Pb and Fe, with levels exceeding FAO/WHO limits and classified as extreme pollution by CF, PLI, and Igeo indices. The sandy texture, low organic matter, and low cation exchange capacity of the soils facilitated metal mobility and bioavailability, explaining the observed accumulation in edible crops. Crop-specific differences in metal uptake were evident, with carrot, lettuce, onion, and spinach showing the highest bioaccumulation of Pb and Fe.

These findings underscore the urgent need for monitoring and regulation of wastewater use in urban agriculture. Treatment of irrigation water before application, coupled with strategies such as phytoremediation or soil amendments, can mitigate heavy metal risks. Further research is recommended to evaluate human health hazards, bioaccumulation in crops, and seasonal variations, enhancing food safety and the sustainability of urban vegetable production.

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