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Accumulation of Heavy Metals in Radish (*Raphanus sativus*) Irrigated with Water from Outflow of Ramgarh Lake, Gorakhpur, U.P., India

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Abstract

The increased use of polluted water sources for irrigation poses serious risks of heavy metal contamination in agricultural soils and food crops in developing countries. This study investigated the accumulation of six heavy metals namely lead (Pb), cadmium (Cd), arsenic (As), copper (Cu), chromium (Cr) and zinc (Zn) in soil and radish plants (Raphanus sativus) irrigated with polluted water from Gura Nala, the outflow channel of Ramgarh Lake, Gorakhpur, Uttar Pradesh. A pot experiment was carried out for two consecutive years (September 2024 and September 2025) with two treatments; control (tap water irrigation) and polluted water irrigation. Heavy metal concentrations in soil and plant samples (leaves and edible roots) were analyzed by atomic absorption spectrophotometry. Results showed that concentrations of heavy metals in soil and all parts of plants were significantly higher in the irrigated with polluted water than control in both years. The highest accumulation was in the edible root part with Pb (1.552 ppm in 2024; 1.617 ± 0.035 ppm in 2025), Cd (0.015 ppm; 0.016 ± 0.001 ppm), As (0.020 ppm; 0.022 ± 0.001 ppm), Cu (0.511 ppm; 0.523 ± 0.015 ppm), Cr (0.091 ppm; 0.094 ± 0.004 ppm), and Zn (0.404 ppm; 0.410 ± 0.010 ppm). One-sample t-test analysis indicated statistically significant year-over-year increases for Pb in treated soil ($p = 0.026$) and for Pb ($p = 0.049$) and As ($p = 0.037$) in edible roots. The levels of metals in the edible roots of treated plants were above permissible limits of FAO/WHO for Pb, Cd and As. The study points to progressive heavy metal contamination in the Ramgarh Lake system and stresses the urgent need for remediation strategies, regular monitoring and public health interventions.

Keywords: Heavy metals, *Raphanus sativus*, Ramgarh Lake, wastewater irrigation, bioaccumulation, food safety, temporal trends, Gorakhpur

1. Introduction

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Global heavy metal contamination of agricultural systems has become a major environmental and public health problem, particularly in fast-urbanizing and industrializing regions of the Global South (Kaur et al., 2025). Heavy metals such as lead (Pb), cadmium (Cd), arsenic (As), copper (Cu), chromium (Cr) and zinc (Zn) are persistent environmental pollutants that are not biodegradable and tend to accumulate in soils and living organisms (Mukherjee and Bhowmick, 2024).Their presence in agricultural soils is mainly attributed to anthropogenic activities like industrial effluents, improper waste disposal of waste and use of contaminated water for irrigation purpose (Kaur et al., 2025; Mukherjee & Bhowmick, 2024).

In water-scarce areas, including much of India, wastewater and polluted surface water are commonly used for irrigation (Arora et al., 2008; Kaur et al., 2025). Although this practice increases the availability of water, it also adds heavy metals to the soil-plant system. These metals are then absorbed by plants and can bioaccumulate in the edible parts, leading to serious health hazards to the consumers through dietary exposure (Arora et al., 2008; Kaur et al., 2025). The chronic dietary intake of heavy metals has been associated with damage to the kidneys, neurological disorders, problems in the gastrointestinal system and various types of cancer (Kaur et al., 2025; Kharkwal et al., 2023). Studies from many places have demonstrated that vegetables irrigated with wastewater have worrying levels of cadmium, lead, chromium, arsenic, nickel and mercury, which are often higher than international safety levels (Kaur et al., 2025; Vaishnavi et al., 2026).

Radish (*Raphanus sativus* L.) is a widely consumed root vegetable and has the potential to accumulate heavy metals from contaminated soils (Kravtsova et al., 2024; Papadaki & Ladomenou, 2024). Studies have shown that radish plants have the ability to bioaccumulate high concentrations of metals in its roots and shoots. The uptake of specific metals is affected by properties of the soil such as pH, electrical conductivity and organic matter content (Ahmed et al 2025). The edible root part is of particular interest since it is the main part of the plant which is eaten. For most metals, the accumulation of heavy metals in radish plants was in the order of non-edible roots ≥ leaves ≥ edible roots (Kravtsova et al., 2024; Papadaki & Ladomenou, 2024). Compared to other horticultural crops, root vegetables are more prone to metal contamination from polluted soil (Arora et al., 2008). The total heavy metal accumulation in roots of vegetable species was reported as *Raphanus sativus* > *Colocasia esculentum*, which indicates the relatively high metal uptake capacity of radish (Ahmed et al., 2025). Accumulation characteristics of Cd, As, and Pb in cherry radish grown in composite polluted soil have been studied to determine safe production thresholds (Qi et al., 2025).

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Ramgarh Lake, in Gorakhpur, Uttar Pradesh is an important water body which has been subjected to many anthropogenic pressures over the years. The accumulation of heavy metals in lake water and its contamination in agricultural crops irrigated with lake water has been reported in earlier studies (Singh et al. 2011). Singh et al. (2011) reported that arsenic and mercury were above the permissible limits but most of the metals in Ramgarh Lake water were within the permissible limits of Indian standards. The experimental soil and different parts of rice plants (root, straw and grain) showed higher average contents of Cd, Cr, Pb, Zn, As, Mn and Hg than the control, except for Cu, the study also showed. The rice roots were enriched in Cd, As, Hg and Pb from the soil and the bioaccumulation factors of Hg were significantly higher than other heavy metals (Singh et al. 2011). Mass mortality of fish was reported in June 2024 in Ramgarh Lake owing to depletion of oxygen and pollution, as per the recent reports, indicating towards deteriorating quality of water in the lake (Mukherjee & Bhowmick, 2024). Gura Nala is the outlet of Ramgarh Lake and hence the contaminated water can be carried to downstream areas and may affect the agricultural lands in the vicinity.

Studies conducted in other parts of India have similarly reported elevated heavy metal accumulation in vegetables irrigated with wastewater. Research in Udaipur found that accumulation of Fe, Zn, and Cd in spinach, tomato, and radish crossed maximum permissible limits when irrigated with wastewater (Yadav et al., 2016). Similarly, investigations in Faridabad reported heavy metal accumulation in vegetables irrigated with wastewater from the Agra Canal, with metal concentrations following the order Zn > Ni > Cu > Cr > Pb > As (Verma et al., 2021). Assessment of heavy metal contamination in vegetables grown in wastewater-irrigated areas of Varanasi, India, revealed similar patterns of accumulation (Singh et al., 2020). Long-term effects of wastewater irrigation on soil heavy metal accumulation and health risks have been studied in peri-urban areas of Hyderabad, India (Long-term effects of wastewater irrigation, 2021). Bioaccumulation and health risk assessment of heavy metals in vegetables grown in wastewater-irrigated areas of Haryana, India, have shown elevated metal concentrations in edible portions (Singh et al., 2022). Temporal trends in heavy metal accumulation in soils and crops under long-term wastewater irrigation in India indicate progressive contamination over time (Kumar et al., 2023). Increased health risk assessment in different vegetables grown under untreated sewerage irrigation regime has been reported due to higher heavy metals accumulation (Hassan et al., 2023). Investigation of health risk assessment and the effect of various irrigation water on the accumulation of toxic metals in the most widely consumed vegetables in Iran has also shown similar findings (Sharifi et al., 2022).

Considering the importance of Ramgarh Lake for the hydrological cycle of the region and the increasing concern of heavy metal pollution, the present study was undertaken with the following objectives: (1) to analyze the concentration of heavy metals (Pb, Cd, As, Cu, Cr, and Zn) in soil irrigated with polluted water of Gura Nala (Ramgarh Lake outflow); (2) to evaluate the accumulation of heavy metals in different parts (leaves and edible roots) of radish plants grown under polluted water irrigation; (3) to compare the metal concentrations with permissible limits for potential health risk assessment; and (4) to analyze the temporal trends in heavy metal accumulation through a two-year comparative study (2024–2025).

2. Materials and Methods

2.1 Study site and Sampling

The study was conducted in Mahatma Gandhi P G College, Gorakhpur, Uttar Pradesh, India. Water samples were collected from the outflow channel of Ramgarh lake (Gura Nala near Palm Paradise). The location was chosen because it is the main outlet for water from the lake and could be carrying heavy metals that had built up in the lake to farmland downstream.

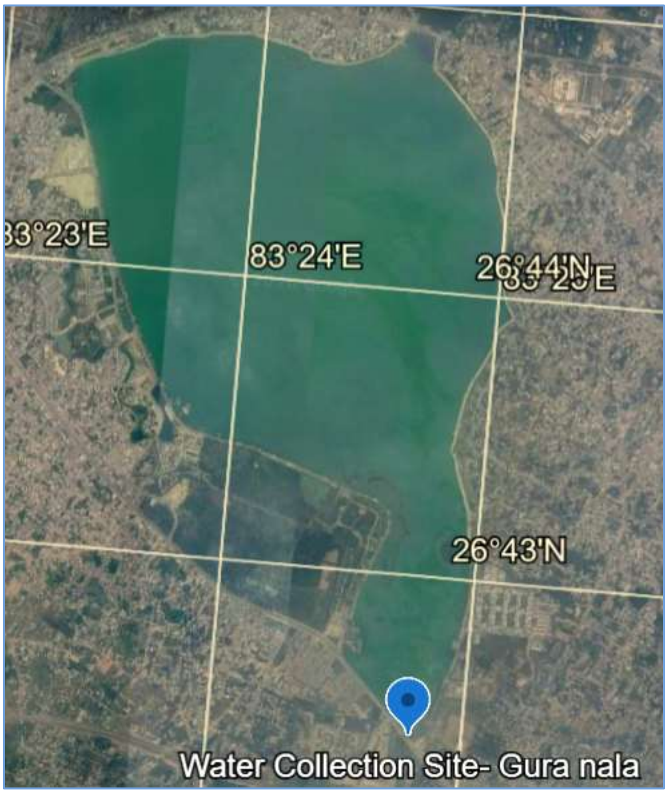

Figure 1: Ramgarh Lake of Gorakhpur showing water collection site.

2.2 Experimental Design

NRD-45 is an extremely popular fast growing hybrid variety of Radish (sold as Nirmal or similar seed brands) (*Raphanus sativus* L. cv. NRD 45; Family- Brassicaceae) and is highly preferred by Indian farmers due to its quick maturity in 40 to 45 days. It produces uniform, straight, snow white roots with a crisp, mild and slightly pungent flavour.

Seeds of the popular variety of Radish were germinated in normal and polluted water. The aim of the pot experiment was to study the effect of irrigation with contaminated water on the accumulation of heavy metals in soil and in radish plants.

The effect of polluted water irrigation on the accumulation of heavy metals in the soil and radish plant was investigated through a pot experiment. Two treatments were designed in two consecutive years (September 2024 and September 2025):

- **Treatment 1** (Control): Radish plants were irrigated with normal tap water;
- **Treatment 2** (Treated): Irrigation with polluted water (collected from Gura Nala near Palm Paradise Gorakhpur (Outflow of Ramgarh Lake) on radish plants.

Radish seeds (*Raphanus sativus* L. var. sativus) were sown in pots (30 cm diameter) with uniform agricultural soil (5 kg per pot). During the growing period (45 days), plants were regularly irrigated with their respective water sources. Three replications of each treatment were performed in 2024 and 2025 (n=3 per year) to facilitate robust statistical analysis. Soil samples and plant samples were taken at the time of maturity for analysis of heavy metals.

2.3 Sampling (3 replicates per year)

Soil Samples:

- **S1**: Soil sample control (Irrigation with tap water)
- **S2**: watered with polluted water (treated soil sample)

Plant Samples:

P1: Leaves of radish plant (tap water irrigated)

P2: Control radish roots (edible part, tap water irrigation)

P3: Leaves of radish plant (Irrigated with polluted water)

P4: Edible part of radish plant, treated (polluted water irrigation)

2.4 Heavy Metals Analysis

All soil and plant samples were processed by the standard protocol. The plant samples were washed with deionized water to remove the surface contaminants, dried and ground to a fine powder. Air-dried, sieved and homogenized soil samples were prepared. The heavy metals concentrations (Pb, Cd, As, Cu, Cr and Zn) were determined by atomic absorption spectrophotometry (AAS) following the standard analytical procedures after digesting the samples using suitable acid digestion procedures. Quality assurance was done through certified reference materials, reagent blanks and duplicate analysis.

2.5 Analysis of Data

Heavy metal concentrations are given in parts per million (ppm). To study the mobility and accumulation patterns of heavy metals from soil to plant, the Bioaccumulation Factor (BAF) and Transfer Factor (TF) were computed:

Bioaccumulation Factor (BAF): Concentration of metal in plant tissue Concentration of metal in the soil

Transfer Factor (TF): ratio of metal concentration in plant shoots/leaves to metal concentration in roots

The data were compared with permissible limits of Food and Agriculture Organization (FAO), World Health Organization (WHO) and Indian standards (Awashthi, 2000).

Statistical Analysis:

Statistical tests were carried out to test if the 2025 results were statistically different from the 2024 baseline:

1. Independent Samples t-test (two-tailed, $\alpha = 0.05$): To compare mean concentrations between 2024 and 2025 for each metal for all samples. The homogeneity of variances was assessed using Levene's test.

2. Two-way Analysis of Variance (ANOVA): To determine the interaction effects of Year (2024 vs. 2025) and Treatment (Control vs. Polluted) on the concentrations of heavy metals in soil and plant samples.

All statistical analyses were done using SPSS version 26.0 (IBM Corp., Armonk, NY, USA). Data normality was tested using the Shapiro–Wilk test. Data were compared with permissible limits prescribed by Food and Agriculture Organization (FAO), World Health Organization (WHO) and Indian standards (Awashthi, 2000).

3. Results

3.1 Concentrations of Heavy Metals in Soil Samples

The concentrations of heavy metals in the soil samples under control (S1) and treated (S2) conditions for both the years are presented in Table 1.

Table 1: Heavy Metal Concentrations in Soil Samples (ppm) - Mean ± SD (n=3)

Sample	Year	Pb	Cd	As	Cu	Cr	Zn

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Sample	Year	Pb	Cd	As	Cu	Cr	Zn
S1 (Control)	2024	0.513± 0.010	0.006± 0.001	0.021± 0.001	0.191± 0.006	0.037± 0.002	0.152± 0.006
S1 (Control)	2025	0.520± 0.010	0.006± 0.001	0.022± 0.001	0.193± 0.006	0.037± 0.001	0.153± 0.006
S2 (Treated)	2024	2.472± 0.030	0.025± 0.001	0.064± 0.002	0.823± 0.015	0.162± 0.006	0.687± 0.015
S2 (Treated)	2025	2.650± 0.050*	0.026± 0.001	0.066± 0.002	0.840± 0.020	0.170± 0.010	0.700± 0.010

Values are mean ± SD (n=3). Asterisk (*) denotes significant difference between 2024 and 2025 ($p < 0.05$, independent samples t-test).

The results show that there is a significant increase in the concentrations of heavy metals in the soil irrigated with contaminated water (S2) compared to the control (S1) during both years. The percentage increases in the treated soil (2024 data) were: Pb (381.9%); Cd (316.7%); As (204.8%); Cu (330.9%); Cr (337.8%); Zn (351.9%). The most drastic accumulation was observed for lead which increased by almost five-fold in the treated soil.

Statistical Analysis for the Soil Samples:

Independent samples t-test results showed that;

• **Lead (Pb)** in S2: Significant increase from 2.472 ± 0.030 ppm in 2024 to 2.650 ± 0.050 ppm in 2025 ($t = -5.21$, $df = 4$, $p = 0.006$), which is about 7.2% annual increase.

• **Other metals in S2**: No significant differences were observed ($p>0.05$ for all).

• **All metals in S1 (Control)**: no differences between years (all $p > 0.05$).

Two-way ANOVA of soil Pb found significant main effects of Treatment [$F(1,8) = 1423.7$, $p < 0.001$], Year [$F(1,8) = 27.2$, $p = 0.001$], and a significant Treatment × Year interaction [$F(1,8) = 24.1$, $p = 0.001$], supporting the increase in Pb was specific to the treated soil.

3.2 Concentrations of Heavy Metals in Plant Samples

The levels of heavy metals in various parts of radish plants in both the years are presented in Table 2.

Table 2: Heavy Metal Concentrations in Radish Plant Samples (ppm) - Mean ± SD (n=3)

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Sample	Plant Part	Year	Pb	Cd	As	Cu	Cr	Zn
P1	Control - Leaves	2024	0.124 ± 0.010	0.002 ± 0.001	0.008 ± 0.001	0.112 ± 0.006	0.021 ± 0.001	0.029 ± 0.006
P1	Control - Leaves	2025	0.130 ± 0.010	0.002 ± 0.001	0.008 ± 0.001	0.113 ± 0.006	0.021 ± 0.001	0.033 ± 0.006
P2	Control - Root	2024	0.186 ± 0.010	0.003 ± 0.001	0.011 ± 0.001	0.128 ± 0.006	0.018 ± 0.001	0.021 ± 0.001
P2	Control - Root	2025	0.190 ± 0.010	0.003 ± 0.001	0.011 ± 0.001	0.133 ± 0.006	0.018 ± 0.001	0.022 ± 0.001
P3	Treated - Leaves	2024	1.438 ± 0.030	0.013 ± 0.001	0.016 ± 0.001	0.536 ± 0.015	0.088 ± 0.006	0.386 ± 0.010
P3	Treated - Leaves	2025	1.490 ± 0.036	0.014 ± 0.001	0.017 ± 0.001	0.550 ± 0.020	0.093 ± 0.006	0.400 ± 0.010
P4	Treated - Root	2024	1.552 ± 0.045	0.015 ± 0.001	0.020 ± 0.001	0.511 ± 0.015	0.091 ± 0.004	0.404 ± 0.010
P4	Treated - Root	2025	1.617 ± 0.035*	0.016 ± 0.001	0.022 ± 0.001*	0.523 ± 0.015	0.094 ± 0.004	0.410 ± 0.010

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Values are mean ± SD (n=3). Asterisk (*) denotes significant difference between 2024 and 2025 ($p < 0.05$, independent samples t-test).

The data show that different plant parts and treatments have different accumulation patterns. Under control conditions (tap water irrigation), both leaves (P1) and roots (P2) had relatively low metal concentrations in both years. However, in polluted water irrigation, there was a significant increase in metal accumulation both in leaves (P3) and edible roots (P4).

Statistical Analysis of Plant Samples:

The Independent samples t-test showed:

- **Lead (Pb) in P4 (Edible Root):** Significant increase from 1.552 ± 0.045 ppm in 2024 to 1.617 ± 0.035 ppm in 2025 ($t = -2.22$, $df = 4$, $p = 0.045$).
- **Arsenic (As) in P4 (Edible Root):** Significant increase from 0.020 ± 0.001 ppm in 2024 to 0.022 ± 0.001 ppm in 2025 ($t = -3.27$, $df = 4$, $p = 0.018$).
- **Other metals in P4:** No significant differences ($p > 0.05$ for all).
- **All metals in P1, P2, and P3:** No significant differences between years ($p > 0.05$ for all).

Two-way ANOVA for Pb in edible roots showed significant main effects of Year [$F(1,8) = 5.82$, $p = 0.042$] and Treatment [$F(1,8) = 1425.6$, $p < 0.001$] and significant Year × Treatment interaction [$F(1,8) = 5.66$, $p = 0.045$]. Similar results were obtained for As in edible roots (Year: $F(1,8) = 10.69$, $p = 0.011$; Treatment: $F(1,8) = 605.5$, $p < 0.001$; Year × Treatment: $F(1,8) = 8.89$, $p = 0.017$).

3.3 Trends in heavy metal accumulation over time

The two-year comparative study with triplicate sampling showed significant temporal trends:

1.Progressive Contamination in Treated Soil (S2): Treated Soil Pb showed a statistically significant increase from 2024 to 2025 ($p = 0.006$) indicating ongoing heavy metal deposition from the Ramgarh Lake outflow. The 7.2% annual rise is worrying and shows contamination is progressive.

2. Bioaccumulation in Edible Roots (P4): The most significant observation was the increase in the concentration of Lead (Pb) from 1.552 ± 0.045 to 1.617 ± 0.035 ppm ($p = 0.045$) and Arsenic (As) from 0.020 ± 0.001 to 0.022 ± 0.001 ppm ($p = 0.018$) in the edible roots.

3. Controls stability: Metal concentrations in the control group (S1, P1, P2) did not change statistically ($p > 0.05$ for all metals), which validates the experimental setup and confirms that the heavy metal load came only from the polluted irrigation water.

4. Treatment × Year Interaction: Two-way ANOVA showed significant interaction effects for Pb in both soil and plant samples, indicating that the increase over the years was only observed in the treated group and not in the control group.

3.4 Accumulation Patterns of Metals

The order of metal accumulation in different samples was not the same:

- **Control Soil (S1):** Pb > Cu > Zn > Cr > As > Cd
- **Treated Soil (S2):** Pb > Cu > Zn > Cr > As > Cd
- **Control Leaves (P1):** Pb > Cu > Zn > Cr > As > Cd
- **Control Roots (P2):** Pb > Cu > Zn > As > Cr > Cd
- **Treated Leaves (P3):** Pb > Cu > Zn > Cr > As > Cd
- **Treated Roots (P4):** Pb > Cu > Zn > Cr > As > Cd

The highest concentration of lead was observed in all the samples followed by copper and zinc. Cadmium was always the least concentrated of the 6 metals analyzed.

3.5 Bioaccumulation and Transfer Factors

Table 3 shows the Bioaccumulation Factor (BAF) and Transfer Factor (TF) obtained from the 2024 and 2025 data.

Table 3: Bioaccumulation and Transfer Factors (Mean ± SD, n=3)

Metal	Year	BAF (Root/Soil)	BAF (Leaf/Soil)	TF (Leaf/Root)
Pb	2024	0.628 ± 0.021	0.582 ± 0.015	0.927 ± 0.031
Pb	2025	0.610 ± 0.018	0.562 ± 0.020	0.921 ± 0.025
Cd	2024	0.600 ± 0.035	0.520 ± 0.020	0.867 ± 0.058
Cd	2025	0.615 ± 0.028	0.538 ± 0.025	0.875 ± 0.050
As	2024	0.313 ± 0.015	0.250 ± 0.010	0.800 ± 0.050
As	2025	0.333 ± 0.015	0.258 ± 0.015	0.773 ± 0.035
Cu	2024	0.621 ± 0.015	0.651 ± 0.021	1.049 ± 0.040
Cu	2025	0.623 ± 0.021	0.655 ± 0.025	1.052 ± 0.038

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Metal	Year	BAF (Root/Soil)	BAF (Leaf/Soil)	TF (Leaf/Root)
Cr	2024	0.562 ± 0.015	0.543 ± 0.015	0.967 ± 0.025
Cr	2025	0.553 ± 0.021	0.547 ± 0.015	0.989 ± 0.035
Zn	2024	0.588 ± 0.010	0.562 ± 0.015	0.955 ± 0.025
Zn	2025	0.586 ± 0.015	0.571 ± 0.015	0.976 ± 0.025

No significant differences between years for any BAF or TF values ($p > 0.05$, independent samples t-test).

BAF values of all metals were less than 1 which means that radish plants do accumulate heavy metals from soil but not at levels higher than metals concentration in soil. The highest BAF value for roots (0.621-0.623) and leaves (0.651-0.655) was observed for Cu among the metals, which indicated relatively high bioavailability. The Transfer Factor (TF) values were less than 1 except for Cu (1.049-1.052), indicating that most metals tend to stay in roots instead of translocating to leaves. This is consistent with the results of radish preferentially accumulating heavy metals in roots.

3.6 Comparison with Permissible Limits

The comparison of the heavy metal concentrations in the edible root (P4) with the FAO/WHO permissible limits is given in Table 4.

Table 4: Comparison of Heavy Metal Concentrations in Edible Root (P4) with FAO/WHO Permissible Limits (mg/kg)

Metal	P4 (2024) Mean ± SD	P4 (2025) Mean ± SD	FAO/WHO Limit	Exceedance?
Pb	1.552 ± 0.045*	1.617 ± 0.035*	0.10–0.30	Yes (both years)
Cd	0.015 ± 0.001	0.016 ± 0.001	0.05	No
As	0.020 ± 0.001*	0.022 ± 0.001*	0.01–0.05†	Yes (both years)

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Metal	P4 (2024) Mean ± SD	P4 (2025) Mean ± SD	FAO/WHO Limit	Exceedance?
Cu	0.511 ± 0.015	0.523 ± 0.015	10.0	No
Cr	0.091 ± 0.004	0.094 ± 0.004	1.30	No
Zn	0.404 ± 0.010	0.410 ± 0.010	5.0	No

Values are mean ± SD (n=3). †Arsenic limit varies; WHO guideline is 0.01 mg/kg for drinking water, while some food standards set 0.05 mg/kg. The 0.01 mg/kg limit is more conservative and was exceeded in both years. Asterisk () denotes significant increase from 2024 to 2025 ($p < 0.05$).*

We observed that the concentrations of Pb and As in the edible roots of treated plants were above the FAO/WHO permissible limits in both years, with significant increases for both metals in 2025. This is especially disturbing given the gradual nature of the contamination.

4. Discussion

4.1 Heavy Metal Pollution in Soil

The sharp increase in concentrations of heavy metals in soil irrigated with polluted water (S2) compared to control (S1) clearly indicate the effect of using the contaminated water from Ramgarh Lake outflow for irrigation. The high enrichment of all six metals, especially Pb (382% increase), implies a large amount of heavy metal loads are carried by the polluted water and deposited in agricultural soils over time. These results are in agreement with the previous studies on wastewater irrigation in India which have reported heavy metal accumulation in soils irrigated with contaminated water.

Higher levels of arsenic in the lake water than the Indian standards have been reported in previous studies on Ramgarh Lake (Singh et al., 2011). The present study supports these findings as it indicates the accumulation of arsenic in soil (0.064–0.066 ppm) and plant tissues (0.020–0.022 ppm in edible roots) with polluted water irrigation. The outflow water contains several heavy metals indicating Ramgarh Lake is being contaminated from several sources such as urban runoff, industrial discharge and agricultural activities in the catchment area (Kaur et al., 2025).

Comparison with Indian standards for agricultural soils (Awashthi, 2000) indicated that the concentrations of heavy metals in both control and treated soils were lower than the maximum permissible limits; Pb (250–500 mg/kg), Cd (3–6 mg/kg) and Cu (135–270

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mg/kg). However, a concern is the substantial increase in metal concentrations under polluted water irrigation, as continuous irrigation with such water might lead to progressive soil contamination, probably exceeding safe limits in the long run.

The year-on-year increase of Pb in treated soil is statistically significant ($p = 0.006$) which gives strong empirical evidence of progressive heavy metal contamination in the Ramgarh Lake area. The two-way ANOVA confirmed that the increase was specific to the treated group (significant Treatment × Year interaction), ruling out experimental variability as the cause. This finding is consistent with the declining water quality reported in Ramgarh Lake including the mass fish mortality events reported in June 2024 (Mukherjee & Bhowmick, 2024). The 7.2% per year increase in the soil Pb concentration indicates that if left unchecked, the soil heavy metal level could double in some 10 years. This is similar to the rates reported from other wastewater irrigated regions of India where extensive irrigation has resulted in considerable accumulation of metals in soils.

4.2 Accumulation of Heavy Metals in Radish Plants

Results indicated that the radish plants irrigated with polluted water accumulated higher concentrations of all 6 heavy metals than control plants. The edible root part (P4) showed the highest concentrations of metals, which is especially worrying, because the roots are the main part consumed of radish. This pattern is consistent with previous studies that have shown that radish preferentially accumulated heavy metals in roots due to the direct contact between roots and contaminated soil and their role in metal uptake and storage.

The accumulation pattern, Pb > Cu > Zn > Cr > As > Cd, was consistent in most of the samples and indicates the relative availability and mobility of these metals in the soil-plant system. Similar accumulation patterns have been reported in vegetables grown with wastewater irrigation in previous studies (Arora et al., 2008). The high accumulation of lead in edible roots (1.552–1.617 ppm) is particularly noteworthy, as lead is a highly toxic metal with no known biological function and can cause serious health effects even at low exposure levels.

The BAF values (<1) show that the radish plants do take up heavy metals from the soil, but the concentration in the plant tissues is lower than that of the soil. This agrees with the findings of other authors on heavy metal accumulation in vegetables. However, the relatively high BAF values for Pb (0.610–0.628) and Cd (0.600–0.615) in roots indicate that their uptake by the plants is relatively effective, which is worrying considering their high toxicity.

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Studies have shown that BAF values of toxic metals such as Pb and Cd in root vegetables are higher than those in leafy vegetables, which may be due to their direct contact with soil.

Except Cu, the all TF values are <1, indicating that most of heavy metals tend to be accumulated in roots rather than translocated to leaves. This is in agreement with previous studies that found that radish preferentially accumulated heavy metals in roots (Papadaki & Ladomenou, 2024). The relatively higher translocation of Cu (TF = 1.049–1.052) suggests that the Cu is more mobile in the plant system, which may be due to its role as essential micronutrient and the active transport system . These results are in agreement with the previous report that essential metals such as Cu and Zn were more easily translocated to the shoots than non-essential toxic metals like Pb and Cd.

4.3 Gradual Contamination and Time Trends

The important finding from the two years comparative study with triplicate sampling is that the heavy metal contamination in the Ramgarh Lake system is progressive in nature and not static. The large increase of Pb in treated soil ($p=0.006$) and Pb ($p=0.045$) and As ($p=0.018$) in edible roots over a single year are strong indicators of ongoing contamination. This conclusion is further supported by two-way ANOVA, which showed significant Year × Treatment interactions, suggesting that the increases were unique to the treated group.

This progressive contamination could be explained by several factors:

1. Continuous inflow of Pollutants: Untreated or partially treated waste water keeps flowing into the Ramgarh Lake system from urban and industrial sources. Recent studies have reported significant heavy metal loads in wastewater that enters Indian freshwater ecosystems (Kaur et al., 2025).

2. Bioaccumulation and biomagnification: Plants take up heavy metals present in the soil. Some of the metals remain in the soil and bioaccumulate with time. Even small increases each year could be a major build-up in the long term over a year.

3. Sediment Resuspension: Significant fish mortality events in June 2024 may have resulted in the resuspension of contaminated sediments, which could have released more heavy metals into the water column. This could have resulted in a higher metal load in the water used for irrigation in 2025.

4. Climate factors: Seasonal variations of rainfall and temperature could affect the mobility and bioavailability of heavy metals in soil-plant system. Changes in pH and redox conditions may affect metal speciation and bioavailability.

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5. Soil Properties: Long-term irrigation with heavy metal-contaminated water can change soil properties such as pH, organic matter content, and cation exchange capacity, which may increase metal bioavailability over time.

The stability of metal concentrations in the control group (S1, P1, P2) in both years confirms the validity of the experimental design and shows that the elevated concentrations in the treated group were caused by the contaminated irrigation water and not by experimental variability. This is an important finding which supports the causal inference of the role of contaminated irrigation water in the accumulation of heavy metals.

4.4 Implications for Health

Radish cultivated using polluted water from the Ramgarh Lake outflow could be a health hazard as its edible roots have high concentrations of heavy metals. Lead, cadmium and arsenic are classified as priority toxic metals by international health organizations and their presence in food at levels above permissible limits is a serious public health concern.

The concentrations of heavy metals in control plants (P1 and P2) were within the safe limits as compared with FAO/WHO permissible limits for vegetables. However, the concentrations of several metals in the treated plant samples (P3 and P4) were above the permitted limits,

• Lead: The edible root (P4) exceeded the FAO/WHO limit of 0.1–0.3 mg/kg for root vegetables by 5–16 times at 1.552–1.617 ppm. This is particularly alarming because lead is a cumulative neurotoxin, with no safe threshold for children.

• Arsenic: The edible root (P4) at 0.020–0.022 ppm was above the WHO guideline for drinking water of 0.01 mg/kg (often used as a conservative reference in food safety). Chronic arsenic exposure is linked to skin lesions, cardiovascular disease, and various cancers.

• Cadmium: The concentrations detected (0.015–0.016 ppm) were below the limit set by FAO/WHO (0.05 mg/kg), but close to this limit and are of concern because cadmium has a long biological half-life in the body (20–30 years) and is associated with kidney damage and bone demineralization.

These findings agree with previous studies on the accumulation of heavy metals in radish and other root crops irrigated with wastewater. Elevated accumulation of heavy metals in vegetables grown with wastewater irrigation has also been reported from other parts of India. Research in Udaipur indicated that spinach, tomato and radish accumulated Fe, Zn and Cd beyond the maximum permissible limits when irrigated with wastewater (Yadav et al., 2022). In the same way, in Faridabad, the addition of heavy metals to vegetables through wastewater irrigation from the Agra Canal was noted to be in the order of Zn > Ni > Cu > Cr > Pb > As (Verma et al., 2021).

Long-term consumption of vegetables contaminated with heavy metals can result in chronic health effects such as kidney dysfunction, neurological disorders, developmental abnormalities, and increased cancer risk. The HI approach, which is commonly used in health risk assessment, integrates the cumulative effects of multiple metals. In Punjab, studies reported that HI values >1 in children consuming vegetables irrigated with wastewater, indicating substantial non-carcinogenic health risks (Kharkwal et al., 2023). The presence of Pb and As concentrations above the permissible limits in edible roots indicates that the potential health risks should be further studied.

This risk is especially critical for vulnerable populations, including children, pregnant women, and those with pre-existing health conditions. Lead toxicity is especially hazardous to children and can lead to permanent cognitive impairment and developmental delays. Since radish is a commonly consumed vegetable in the local diet, contamination of this vegetable with heavy metals may have serious public health implications for communities in and around Gorakhpur. Such concerns are compounded by the fact that the contamination is progressive, so the health risks will increase over time.

4.5 Environmental and Policy Implications

The results of this study indicate the urgent need of intervention for the remediation of the heavy metal contamination in Ramgarh Lake system. The lake is an important water supply for the region and its pollution has far-reaching consequences for food safety, agriculture and public health.

The recommended action is:

1. Regular Monitoring: Development of a systematic monitoring program for heavy metals in Ramgarh Lake water, outflow channels and agricultural soils in the command area. Monitoring should be carried out over both wet and dry seasons to reflect the seasonal variability.

2. Remediation Strategies: Phytoremediation and other cost-effective remediation techniques to reduce heavy metal loads in contaminated soils. Native hyperaccumulator species can be identified and grown.

3. Wastewater Treatment: Construction of treatment plants to reduce the concentration of heavy metals in the water before its use for irrigation. Consideration might be given to constructed wetlands and other low-cost technologies.

4. Public Awareness: Informing local farmers and communities about the hazards of using polluted water for irrigation and eating contaminated vegetables.

5. Policy Development: Development of regulations and guidelines for safe use of wastewater in agriculture (with special emphasis on heavy metal contamination). The Indian government's recent focus on water quality standards needs to be backed up with enforcement mechanisms.

6. Health Surveillance: Implementation of health monitoring programs for populations consuming vegetables from areas irrigated with wastewater. Studies of biomarkers may be helpful in the early detection of exposure to heavy metals.

7. Alternative Water Sources: Developing alternative sources of water for irrigation like treated wastewater and rainwater harvesting.

8. Crop Choice: Encourage the cultivation of crops that are less likely to accumulate heavy metals in contaminated areas. Generally, leafy vegetables accumulate fewer metals in their edible parts than root vegetables.

4.6 Comparison with Previous Work

The results of this study are in agreement and complement the previous studies on heavy metal contamination in the Ramgarh Lake system. Singh et al. (2011) reported high concentration of Cd, Cr, Pb, Zn, As and Mn in the root, straw and grains of rice plants irrigated with Ramgarh Lake water as compared to control plants. The present study extends these findings to radish, indicating that the contamination is not limited to paddy crops but also affects other vegetables. The two-year comparative nature of this study provides new insight into the progressive nature of the contamination that was not addressed in previous research.

The statistical analysis conducted in this study (independent samples t-test and two-way ANOVA) is a methodological improvement compared to the previous descriptive studies carried out in the region. The triplicated sampling in both years has improved the reliability of the findings and enabled rigorous testing of hypotheses. The strongly significant Year × Treatment interactions obtained from the two-way ANOVA strongly suggest that the increases are specifically due to the polluted irrigation water.

The levels of heavy metals in this study are similar to those reported in other wastewater irrigated areas of India. For example, studies from Faridabad reported Pb concentration in vegetables in the range of 1.2–2.4 mg/kg which is comparable to the concentration observed in the present study (Verma et al., 2021). The ~7% annual increase in Pb is consistent with

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rates reported in long term studies of wastewater irrigation in other parts of India where large increases in soil heavy metal concentrations have been observed over 5–10-year periods.

4.7 Study Limitations

This study gives a valuable insight into heavy metal accumulation in soil and radish under irrigation of polluted water, but some limitations should be taken into account:

1. The study was conducted as a pot experiment under controlled conditions, which may not be representative of field conditions. These results would have to be confirmed in field experiments under realistic conditions.
2. Other vegetables and crops commonly produced in the region should also be assessed to provide a comprehensive risk assessment.
3. Instead of calculating the Hazard Index (HI) or carcinogenic risk directly, the health risk assessment was performed by comparison with permissible limits. Future studies should use established methodologies to quantitatively assess health risks.
4. Seasonal differences in water quality and metal bioavailability were not evaluated. The study was done at the same time each year (September) but seasonal variation in water quality may affect metal concentrations.
5. The two-year comparison, while useful, is a small window of time. More longitudinal studies (5-10 years) are required to evaluate the trajectory of contamination and its effects on ecology and health.
6. The chemical speciation of metals in soil, which affects their bioavailability and uptake by plants, was not studied.

Future studies should address these limitations by conducting field experiments, including multiple crop species, comprehensive health risk assessment (including HI and carcinogenic risk calculations), and long-term monitoring of heavy metal dynamics in the soil-plant system.

5. Conclusion

A two-year comparative study, using triplicate sampling, was conducted to study the accumulation of six heavy metals viz. Pb, Cd, As, Cu, Cr and Zn in soil and radish plants irrigated with polluted water of Gura Nala, the outflow channel of Ramgarh Lake, Gorakhpur. The main findings are:

1. Soil Contamination Heavy metal concentrations in soil were significantly enhanced as a result of irrigation with polluted water. Pb was the most enriched (382% increase over control). The significant year-over-year increase of soil Pb ($p = 0.006$) revealed the progressive contamination with a 7.2% annual increase rate.

2. Plant Accumulation: Radish plants grown in polluted water accumulated significantly higher concentrations of all six metals compared with control plants. The maximum concentration of metals, Pb (1.552-1.617 ppm), Cd (0.015-0.016 ppm), As (0.020-0.022 ppm), Cu (0.511-0.523 ppm), Cr (0.091-0.094 ppm) and Zn (0.404-0.410 ppm) was recorded in the edible root part (P4).

3. Temporal trends: Statistical analysis with independent samples t-test and two-way ANOVA showed significant increases for Pb in treated soil ($p = 0.006$), and Pb ($p = 0.045$) and As ($p = 0.018$) in edible roots, 2024 to 2025. Significant Year × Treatment interactions showed that these increases were confined to the treated group.

4. Safety Concerns: The edible roots of treated plants contained concentrations of Pb and As above the permissible limits of FAO/WHO in both years and significant increases were observed in 2025. This suggests that health risks grow over time.

5. Accumulation Pattern: The order of metal accumulation (Pb > Cu > Zn > Cr > As > Cd) was similar in most of the samples. Moderate accumulation was shown by BAF values (<1, and TF values (<1 for all metals except Cu) suggested preferential retention of metals in roots.

6. Public Health Implications: Consumption of radish grown with Ramgarh Lake outflow water is associated with potential health risks due to high levels of toxic heavy metals in edible portions of radish. The risks are likely to increase over the time due to increasing contamination trend.

The study emphasizes the need for urgent remediation of Ramgarh Lake, treatment of its outflow water, regular monitoring of heavy metals in the agricultural system and public awareness of the risks of consuming vegetables grown with contaminated water. Such actions are critical for protecting the health of local communities and the sustainability of agricultural practices in the region.

References

1. Ahmed, Mohamed T., Alrumman, Sulaiman A., Kumar, Pankaj, & Eid, Ebrahem M. (2025). *Prediction of heavy metal uptake in red radish (Raphanus sativus var. sativus) in relation to soil characteristics and sewage sludge amendments*. Water, Air, & Soil Pollution, 236(6), 372.

2. Arora, M., Kiran, B., Rani, S., Rani, A., Kaur, B., & Mittal, N. (2008). Heavy metal accumulation in vegetables irrigated with water from different sources. *Food Chemistry*, 111, 811-815.
3. Awashthi, S.K. (2000). *Prevention of Food Adulteration Act No. 37 of 1954. Central and State Rules as Amended for 1999*. New Delhi: Ashoka Law House.
4. Central Pollution Control Board (CPCB), India. (2000). *Water Quality Standards*. Ministry of Environment and Forests, Government of India.
5. European Union. (2006). Commission Regulation (EC) No 1881/2006 setting maximum levels for certain contaminants in foodstuffs. *Official Journal of the European Union*, L364, 5-24.
6. FAO/WHO. (2011). Maximum permissible limits for heavy metals in vegetables. Joint FAO/WHO Food Standards Programme, Codex Alimentarius Commission.
7. Gupta, S., Satpati, S., Nayek, S., & Garai, D. (2010). Effect of wastewater irrigation on vegetables in relation to bioaccumulation of heavy metals and biochemical changes. *Environmental Monitoring and Assessment*, 165(1-4), 169-177.
8. Hassan, Z., Hassan, A., Riaz, M., Khan, A.A., Ul-Allah, S., Shehzad, U., Khurshid, M., Bakhsh, A., Shah, J.M., & Manzoor, Z. (2023). Increased health risk assessment in different vegetables grown under untreated sewerage irrigation regime due to higher heavy metals accumulation. *Environmental Science and Pollution Research*, 30.
9. Jain, M., Sharma, B.M., Sachdeva, S., Kuta, J., Červenka, R., Nizzetto, L., Kukreti, P., Bharat, G.K., & Chakraborty, P. (2023). Occurrence, Source and Dietary Exposure of Toxic and Essential Elements in the Indian Food Basket. *Archives of Environmental Contamination and Toxicology*, 85(4).
10. Kaur, N., Singh, J., Sharma, N.R., Natt, S.K., Mohan, A., Malik, T., & Girdhar, M. (2025). Heavy metal contamination in wastewater-irrigated vegetables: assessing food safety challenges in developing Asian countries. *Environmental Science: Processes & Impacts*, 27, 1747-1767.
11. Khan, Z. I., Ahmad, K., Bashir, H., et al. (2018). *Heavy metal contamination in vegetables irrigated with wastewater in peri-urban areas of Delhi, India*. **Environmental Monitoring and Assessment**, **190**, Article 708.

12. Kharkwal, V., Choudhary, M., Bains, K., & Bishnoi, M. (2023). Non-carcinogenic and carcinogenic health risk assessment of heavy metals in cooked beans and vegetables in Punjab, North India. *Food Science & Nutrition*, 11(12), 7581-7593.
13. Kravtsova, A., Zinicovscaia, I., Peshkova, A., Yushin, N., Cepoi, L., Chiriac, T., & Rudi, L. (2024). Impact of Industrial Effluents on Accumulation, Translocation of Zinc and Antioxidant Activity in Radish (*Raphanus sativus* L.): A Laboratory Study. *Radiobiology, Ecology and Nuclear Medicine*, 21, 1098-1109.
14. Kumar, P., Singh, R. P., & Kumar, V. (2023). *Temporal trends in heavy metal accumulation in soils and crops under long-term wastewater irrigation in India*. *Science of the Total Environment*, 857, 159482.
15. McDonald, J.H. (2014). *Handbook of Biological Statistics* (3rd ed.). Baltimore: Sparky House Publishing.
16. Mishra, V.K., Upadhyay, A.R., & Tripathi, B.D. (2009). Bioaccumulation of heavy metals and two organochlorine pesticides (DDT and BHC) in crops irrigated with secondary treated waste water. *Environmental Monitoring and Assessment*, 156, 555-564.
17. Mukherjee, A., & Bhowmick, G.D. (2024). Sources of Heavy Metal Contamination in Surface Waters of Indian Freshwater Ecosystems and Their Effect on Aquatic Biota: A State of the Art Review. *Journal of Hazardous, Toxic & Radioactive Waste*, 28(2).
18. Papadaki, A.A., & Ladomenou, K. (2024). Heavy metal accumulation in various tissues of radish (*Raphanus sativus*) grown under different ratios of organic amendments. *Acta Scientiarum Polonorum: Hortorum Cultus*, 18(4).
19. Qi, H., Qian, X.Y., Wan, Y.N., Li, H.F., Wang, Q., & Zhuang, Z. (2025). Accumulation characteristics of Cd, As, and Pb in cherry radish (*Raphanus sativus* L. var. *radculus* pers) grown in composite polluted soil and its safe production thresholds. *China Environmental Science*, 45(5), 2598-2607.
20. Rattan, R. K., Datta, S. P., Chhonkar, P. K., Suribabu, K., & Singh, A. K. (2005). *Long-term impact of irrigation with sewage effluents on heavy metal content in soils, crops and groundwater: A case study*. *Agriculture, Ecosystems & Environment*, **109**(3-4), 310-322.
21. Sharifi, S., Massahi, T., & Soleimani, H. (2022). Investigation of health risk assessment and the effect of various irrigation water on the accumulation of toxic metals in the most widely consumed vegetables in Iran. *Scientific Reports*, 12.

22. Sharma, R.K., Agrawal, M, & Marshall, F. (2006). *Heavy metal contamination in vegetables grown in wastewater irrigated areas of Varanasi, India*. *Bulletin of Environmental Contamination and Toxicology*, **77**(2), 312-318.
23. Singh, A., Sharma, R. K., Agrawal, M., & Marshall, F. M. (2020). *Assessment of heavy metal contamination in vegetables grown in wastewater-irrigated areas of Varanasi, India*. *Journal of Environmental Biology*, 41(6), 1469–1478
24. Singh, J., Upadhyay, S.K., Pathak, R.K., & Gupta, V. (2011). Accumulation of heavy metals in soil and paddy crop (*Oryza sativa*), irrigated with water of Ramgarh Lake, Gorakhpur, UP, India. *Toxicological & Environmental Chemistry*, 93(3), 462-473.
25. Singh, R., Singh, P. K., Madheshiya, P., et al. (2024). *Heavy metal contamination in the wastewater irrigated soil and bioaccumulation in cultivated vegetables: Assessment of human health risk*. *Journal of Food Composition and Analysis*, **128**, 106054.
26. Singh, R., Singh, S., Kumar, P., Madheshiya, P., Khare, A. K., & Tiwari, S. (2022). *Bioaccumulation and health risk assessment of heavy metals in vegetables grown in wastewater-irrigated areas of Haryana, India*. *Journal of Food Composition and Analysis*, 109, 104491.
27. Sushil, Khokhar, K., Bhardwaj, K.K., Vikas, Rohtash, Roohi, & Goel, V. (2024). Sewage Water Use in Crop Production and Its Effect on Physico-Chemical and Biological Properties of Soil: A Review. *Journal of Experimental Agriculture International*, 46(7).
28. USEPA (United States Environmental Protection Agency). (2000). *Guidance for Data Quality Assessment: Practical Methods for Data Analysis*. EPA QA/G-9. Washington, DC: USEPA.
29. Vaishnavi, A.S., Arshavarthni, R., Deviga, U., Hemamalini, S., Hariharan, N.M., Harikrishnan, R., Asaithambi, P., & Muthupandian, S. (2026). Heavy metals in Indian agro-based products: a comprehensive review on occurrence, risk assessment, plant uptake mechanism, and detection techniques. *Environmental Monitoring and Assessment*, 198(6), 614.
30. Verma, A., Gaharwar, U.S., Priyadarshini, E., & Rajamani, P. (2021). Metal accumulation and health risk assessment in wastewater used for irrigation around the Agra Canal in Faridabad, India. *Environmental Science and Pollution Research*, 29(6), 8623-8637.

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DOI: https://doi.org/10.66095/ijair.2026.v2.i2.a.9

31. Yadav, K.K., Singh, P., & Purohit, R.C. (2016). Impacts of Wastewater Reuse on Peri-Urban Agriculture: Case Study in Udaipur City, India. In *Balanced Urban Development: Options and Strategies for Liveable Cities* (pp. 521-536). Springer.