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Agronomic performance and food safety assessment of radish (*Raphanus sativus* l.) irrigated with polluted water from Ramgarh Lake, India

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Abstract
The use of polluted urban lake water for vegetable irrigation presents a critical trade-off between agronomic benefits and food safety risks. This study evaluated the effects of irrigation with heavy metal-contaminated water from Ramgarh Lake, Gorakhpur, on the growth, yield, and heavy metal accumulation in radish (*Raphanus sativus* L. cv. NRD 45). A two-year pot experiment (2024–2025) compared tap water irrigation (control) with raw wastewater from the lake's outflow channel. Polluted water significantly enhanced seed germination (94.2% vs 81.9% in control), vegetative growth (33.7% increase in plant height), and fresh root yield (36.6% increase). However, substantial heavy metal accumulation occurred in both soil and edible tissues. Lead concentrations in radish roots (1.58 mg/kg) exceeded the FAO/WHO permissible limit of 0.30 mg/kg by over fivefold, while cadmium, arsenic, copper, chromium, and zinc remained within safety thresholds. Bioaccumulation factors ranged from 0.313 (As) to 0.628 (Pb), indicating efficient metal uptake. These findings demonstrate that while Ramgarh Lake water offers agronomic value through nutrient supplementation, its use for radish irrigation poses significant food safety concerns due to lead contamination, necessitating careful management and continuous monitoring.

Keywords: *Raphanus sativus*, wastewater irrigation, heavy metals, bioaccumulation, lead contamination, food safety, Ramgarh Lake

Introduction
Freshwater scarcity has emerged as a critical constraint on agricultural production in developing countries, driving the widespread use of wastewater for irrigation in peri-urban farming systems (Qadir *et al*., 2010; FAO, 2021) [8, 16]. While wastewater provides essential nutrients—nitrogen, phosphorus, potassium, and organic matter—that can enhance soil fertility and crop productivity, it also introduces toxic contaminants, particularly heavy metals, into agricultural ecosystems (Singh *et al*., 2023; Hussain *et al*., 2024) [10, 23]. Unlike organic pollutants, heavy metals are non-biodegradable and persist in soils, gradually accumulating in edible plant tissues and entering the human food chain (Alloway, 2013; Rai *et al*., 2019) [1, 17].

Ramgarh Lake, a natural oxbow lake in Gorakhpur District, Uttar Pradesh, exemplifies the environmental degradation affecting urban water bodies across India. Once spanning 723 hectares with a depth of 4.5 meters, the lake has shrunk to 678 hectares with depths below 3.5 meters, receiving millions of liters of untreated municipal wastewater daily through five major drains (Sharma, 2001; Singh & Sharma, 2022) [20, 21]. Previous investigations have documented hypereutrophic conditions, toxic cyanobacterial blooms dominated by *Microcystis* species, and elevated concentrations of lead, cadmium, arsenic, and chromium in lake water and sediments (Singh *et al*., 2011; Barnwal *et al*., 2015; Pandey & Chandra, 2016) [3, 14, 22]. Despite this contamination, local farmers continue to use lake water for irrigation, creating a potential pathway for heavy metal transfer into food crops.

Radish (*Raphanus sativus* L.) is a widely cultivated root vegetable in the region, valued for its short growing cycle and economic importance. As a root crop, its edible portion develops in direct contact with contaminated soil, making it particularly vulnerable to heavy metal accumulation (Rai *et al*., 2019) [17]. While previous studies have examined heavy metal contamination in paddy crops irrigated with Ramgarh Lake water (Singh *et al*., 2011) [22], limited information exists regarding the effects on vegetable crops and the associated food safety implications.

This study aimed to: (1) evaluate the effects of irrigation with Ramgarh Lake water on radish growth and yield; (2) quantify heavy metal accumulation in soil and plant tissues; (3) assess bioaccumulation and translocation patterns; and (4) compare metal concentrations in edible roots with international food safety standards.

Materials and Methods
1. Study Site and Water Source
The study was conducted at Mahatma Gandhi P.G. College, Gorakhpur, Uttar Pradesh, India (26°45'N, 83°23'E). Polluted water was collected from the Gura Nala outflow channel of Ramgarh Lake (near Palm Paradise), which serves as the primary discharge point used by local farmers for irrigation. Control irrigation used tap water. The region experiences a subtropical monsoon climate with distinct summer, winter, and monsoon seasons.

2. Experimental Design
A pot experiment was conducted over two successive years (September 2024[10] and September 2025) using a completely randomized design with three replications per treatment. Radish seeds (*Raphanus sativus* L. cv. NRD 45) were sown in pots (30 cm diameter) containing 5 kg of uniform agricultural soil per pot. Two treatments were established:

- **Control (C):** Plants irrigated with tap water
- **Treated (T):** Plants irrigated with raw wastewater from Ramgarh Lake

Plants were harvested at maturity (40 days after sowing) for growth, yield, and heavy metal analyses.

3. Growth and Yield Parameters
Growth parameters were recorded at 15, 30, and 40 days after sowing, including plant height, root length, shoot length, number of leaves, fresh and dry biomass of roots and shoots, and net primary productivity. Yield attributes at harvest included fresh root yield, dry root yield, total biological yield, root-to-shoot ratio, and harvest index.

Fig 1: Ramgarh Lake of Gorakhpur showing water collection site for irrigation.

4. Heavy Metal Analysis
Soil and plant samples were processed according to standard protocols. Plant samples were oven-dried at 70°C for 48 hours and ground to a fine powder. Soil samples were air-dried and passed through a 2 mm mesh. Samples were digested using HNO_3:$HClO_4$ (3:1), and heavy metal concentrations (Pb, Cd, As, Cu, Cr, Zn) were determined by atomic absorption spectrophotometry (AAS, Perkin Elmer A Analyst 400) following APHA (2017) protocols.

Bioaccumulation Factor (BAF) was calculated as the ratio of metal concentration in plant tissue to that in soil (Kabata-Pendias, 2011) [12]. Transfer Factor (TF) was calculated as the ratio of metal concentration in leaves to that in roots (Alloway, 2013) [1].

5. Statistical Analysis
Data were expressed as mean ± standard deviation (SD) of three replicates. One-way ANOVA and independent samples t-tests were performed using SPSS version 20.0. Statistical significance was set at $p < 0.05$ and $p < 0.01$.

Results
1. Seed Germination and Seedling Establishment
Polluted water irrigation significantly enhanced seed germination compared to the control (Table 1). By the 9th day after sowing, average germination reached 94.2% in treated seeds compared to 81.9% in controls. Mean germination time was marginally extended under treatment, while seedling survival remained high but showed a slight decline under treatment (94.5% vs 98.8% in controls).

Table 1: Effect of polluted water irrigation on seed germination and seedling survival of radish (mean ± SD, n=6; average of two years).

Parameter	Control	Treated	Change (%)
Germination (%) – Day 9	81.87 ± 1.22	94.17 ± 2.10**	+15.02
Seedling survival (%) – Day 9	98.81 ± 0.96	94.54 ± 0.52**	-4.32
Mean germination time (days)	8.01 ± 0.18	8.17 ± 0.13*	+2.00

- $p < 0.05$, ** $p < 0.01$ vs control.

2. Vegetative Growth
Plants irrigated with polluted water consistently outperformed controls throughout the growth period. At final harvest (40 DAS), significant increases were observed across all vegetative parameters (Table 2). Plant height increased by 33.7%, root length showed a dramatic increase of 53.9%, and leaf production increased by 33.3%. Both fresh and dry biomass showed substantial enhancement, with fresh root weight increasing by 36.6% and dry root weight by 36.8%.

Table 2: Vegetative growth parameters of radish at harvest (40 DAS) (mean ± SD, n=6; average of two years).

Parameter	Control	Treated	Increase (%)
Plant height (cm)	27.22 ± 0.85	36.39 ± 0.95**	33.69
Root length (cm)	13.73 ± 0.20	21.12 ± 0.72**	53.82
Shoot length (cm)	20.72 ± 0.30	26.36 ± 1.04**	27.22
No. of leaves/plant	8.50 ± 0.55	11.33 ± 0.52**	33.29
Fresh root weight (g)	63.24 ± 1.50	86.33 ± 2.43**	36.51
Dry root weight (g)	12.48 ± 0.27	17.08 ± 0.34**	36.82

Fresh shoot weight (g)	64.45 ± 0.86	82.73 ± 0.54**	28.37
Dry shoot weight (g)	11.52 ± 0.30	14.89 ± 0.33**	29.25
Total dry weight (g)	24.00 ± 0.42	31.97 ± 0.59**	33.21
NPP (g/plant/day)	0.60 ± 0.01	0.80 ± 0.01**	33.33

** p < 0.01 vs control.

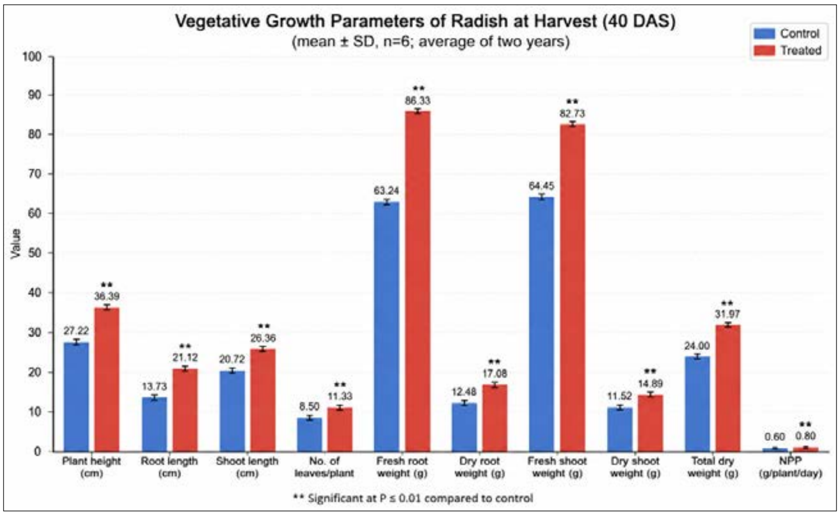

Fig 2: Vegetative growth parameters of radish at harvest (40 DAS). (Bar chart showing plant height, root length, shoot length, and number of leaves for control and treated plants).

3. Yield and Reproductive Performance

All yield attributes were significantly enhanced under polluted water irrigation (Table 3). Fresh root yield increased by 36.5%, while dry root yield and total biological yield showed improvements of 36.8% and 33.2%, respectively. Reproductive development was accelerated, with flowering occurring approximately 6 days earlier in treated plants. The number of fruits per plant increased from 41.7 to 57.6 (38.1% increase), and seed yield per plant showed a 56.5% enhancement.

Table 3: Yield and reproductive attributes of radish (mean ± SD, n=6; average of two years).

Parameter	Control	Treated	Change (%)
Fresh root yield (g/plant)	63.24 ± 1.50	86.33 ± 2.43**	+36.51
Dry root yield (g/plant)	12.48 ± 0.27	17.08 ± 0.34**	+36.82
Biological yield (g/plant)	24.00 ± 0.42	31.97 ± 0.59**	+33.21
Harvest index	0.520 ± 0.008	0.534 ± 0.011*	+2.69
Days to first flowering	64.22 ± 2.00	59.12 ± 1.76**	-7.94
Days to first fruiting	73.26 ± 1.00	67.34 ± 0.75**	-8.08
Days to first fruit maturation	94.65 ± 1.15	86.26 ± 1.42**	-8.86
Fruits per plant	41.7 ± 1.5	57.6 ± 1.3**	+38.13
Fruit length (cm)	4.74 ± 0.18	6.27 ± 0.16**	+32.28
Seed yield per plant (g)	8.20 ± 0.21	12.69 ± 0.50**	+54.76
100 seed weight (g)	0.64 ± 0.01	0.81 ± 0.02**	+26.56

- p < 0.05, ** p < 0.01 vs control.

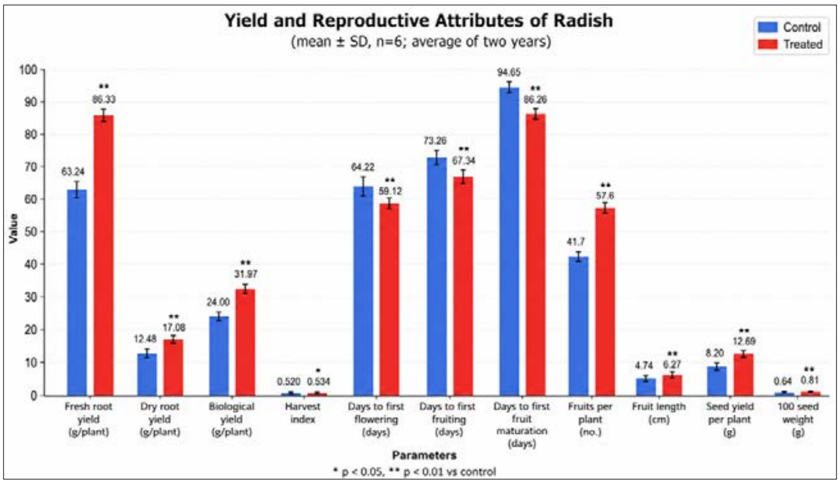

Fig 3: Yield attributes of radish under control and treated conditions. (Bar chart showing fresh root yield, dry root yield, and biological yield).

4. Heavy Metal Accumulation in Soil

Soils irrigated with polluted water showed substantial enrichment of all analyzed heavy metals (Table 4). Lead increased by 395.8% compared to controls, while cadmium, copper, chromium, and zinc showed increases of 325.0%, 397.9%, 348.6%, and 362.5%, respectively. Arsenic showed the lowest enrichment at 209.5% increase.

Table 4: Heavy metal concentrations in soil (ppm, mean ± SD, n=6; average of two years).

Metal	Control	Treated	Increase (%)
Pb	0.517 ± 0.010	2.561 ± 0.090**	+395.8
Cd	0.006 ± 0.001	0.026 ± 0.001**	+325.0
As	0.021 ± 0.001	0.065 ± 0.002**	+209.5
Cu	0.192 ± 0.005	0.832 ± 0.020**	+333.3
Cr	0.037 ± 0.002	0.166 ± 0.006**	+348.6
Zn	0.153 ± 0.005	0.693 ± 0.015**	+362.5

** $p < 0.01$ vs control.

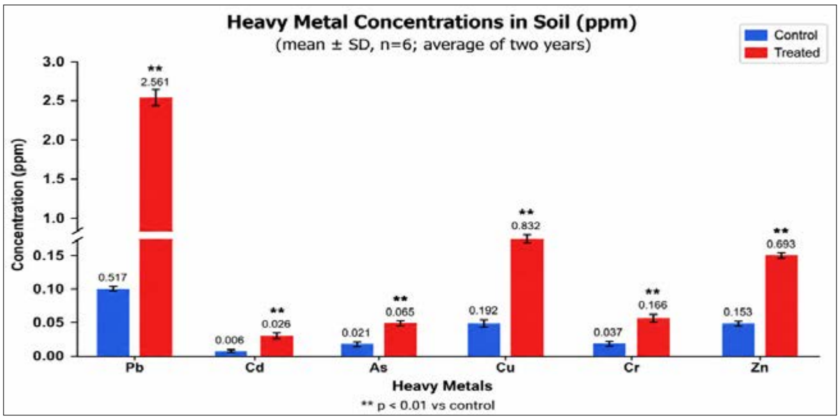

Fig 4: Heavy metal concentrations in soil under control and treated conditions. (Bar chart showing Pb, Cd, As, Cu, Cr, and Zn concentrations).

5. Heavy Metal Accumulation in Plant Tissues

Table 5: Heavy metal concentrations in radish tissues (ppm, mean ± SD, n=6; average of two years).

Tissue	Pb	Cd	As	Cu	Cr	Zn
Control leaves	0.127 ± 0.009	0.002 ± 0.001	0.008 ± 0.001	0.113 ± 0.006	0.021 ± 0.001	0.031 ± 0.005
Control root	0.188 ± 0.009	0.003 ± 0.001	0.011 ± 0.001	0.131 ± 0.006	0.018 ± 0.001	0.022 ± 0.001
Treated leaves	1.464 ± 0.038**	0.014 ± 0.001**	0.017 ± 0.001**	0.543 ± 0.018**	0.091 ± 0.005**	0.393 ± 0.011**
Treated root	1.584 ± 0.046**	0.016 ± 0.001**	0.021 ± 0.001**	0.517 ± 0.014**	0.093 ± 0.004**	0.407 ± 0.011**

** $p < 0.01$ vs control.

Heavy metal concentrations in radish tissues were substantially higher in treated plants than in controls (Table 5). Edible roots accumulated lead (1.58 ppm), cadmium (0.016 ppm), arsenic (0.021 ppm), copper (0.517 ppm), chromium (0.093 ppm), and zinc (0.407 ppm). Lead showed the highest concentration among all metals in both leaves and roots.

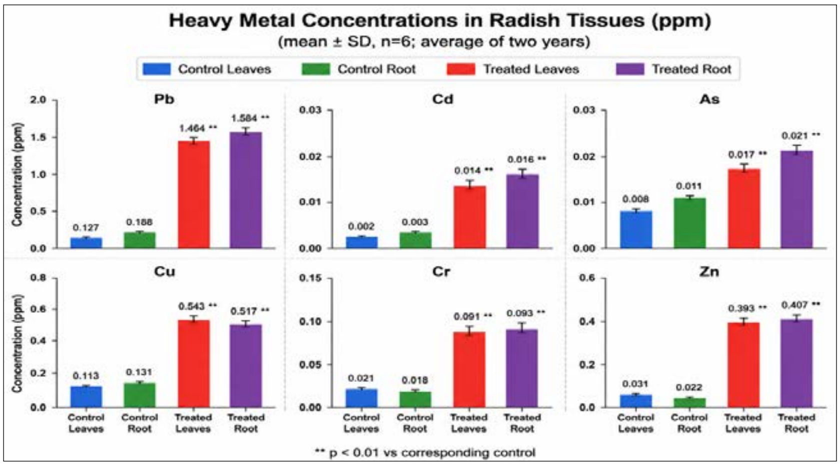

Fig 5: Heavy metal concentrations in radish tissues. (Bar chart comparing metal concentrations in control leaves, control roots, treated leaves, and treated roots).

The distribution pattern showed that edible roots contained higher concentrations of lead, arsenic, and cadmium than leaves, while copper showed slightly higher accumulation in leaves. This reflects the different translocation efficiencies of various metals and the physiological barriers that regulate metal movement from roots to shoots.

6. Bioaccumulation and Transfer Factors

Bioaccumulation factors (BAF) varied among metals (Table 6). Lead showed the highest root-to-soil BAF (0.619), followed by copper (0.622) and cadmium (0.608). Arsenic exhibited the lowest BAF (0.323). Transfer factors from roots to leaves remained below unity for most metals, indicating preferential retention in root tissues. Lead showed a TF of 0.924, while copper exhibited the highest TF (1.051), suggesting greater mobility.

Table 6: Bioaccumulation and transfer factors (mean ± SD, n=6; average of two years).

Metal	BAF (Root/Soil)	BAF (Leaf/Soil)	TF (Leaf/Root)
Pb	0.619 ± 0.020	0.572 ± 0.018	0.924 ± 0.030
Cd	0.608 ± 0.032	0.529 ± 0.022	0.871 ± 0.054
As	0.323 ± 0.015	0.254 ± 0.012	0.787 ± 0.042
Cu	0.622 ± 0.018	0.653 ± 0.023	1.051 ± 0.039
Cr	0.558 ± 0.018	0.545 ± 0.015	0.978 ± 0.030
Zn	0.587 ± 0.012	0.567 ± 0.015	0.966 ± 0.025

7. Comparison with FAO/WHO Permissible Limits

Comparison of heavy metal concentrations in edible radish roots with FAO/WHO permissible limits revealed a critical food safety concern (Table 7). Lead concentrations (1.58 mg/kg) exceeded the recommended limit of 0.30 mg/kg by over fivefold. Cadmium, arsenic, copper, chromium, and zinc remained within permissible limits.

Table 7: Comparison of heavy metal concentrations in radish roots with FAO/WHO permissible limits (mg/kg).

Heavy Metal	FAO/WHO Limit	Radish Root	Status
Pb	0.30	1.584 ± 0.046	Exceeded
Cd	0.20	0.016 ± 0.001	Within limit
As	0.10	0.021 ± 0.001	Within limit
Cu	40.00	0.517 ± 0.014	Within limit
Cr	2.30	0.093 ± 0.004	Within limit
Zn	60.00	0.407 ± 0.011	Within limit

Discussion

1. Agronomic Benefits of Wastewater Irrigation

The significant improvements in seed germination, vegetative growth, and yield observed in this study demonstrate the agronomic value of Ramgarh Lake water. Enhanced germination from 81.9% to 94.2% can be attributed to the readily available nitrogen, phosphorus, and potassium in wastewater, which accelerate metabolic activation and reserve mobilization during germination (Marschner, 2012; Bewley *et al*., 2013) [4, 13]. The 33.7% increase in plant height and 53.8% increase in root length reflect improved nutrient availability stimulating cell division, elongation, and overall biomass production.

The substantial increases in root yield (36.5%) and seed production (54.8%) represent significant economic benefits for farmers. Early flowering and fruiting (approximately 6 days earlier) suggest that improved nutritional status accelerated reproductive development, while increased fruit and seed production reflect enhanced assimilate partitioning to reproductive structures (Taiz *et al*., 2018) [25]. These findings align with Qadir *et al*. (2020) and Hussain *et al*. (2024) [10, 15], who emphasized that appropriately managed wastewater can substitute for chemical fertilizers and improve crop productivity in water-scarce regions.

The enhanced growth responses observed across both experimental years confirm that the nutrient content of Ramgarh Lake water consistently supported radish cultivation. The availability of nitrogen, phosphorus, and potassium in wastewater promoted vigorous vegetative development, increased leaf production, and enhanced biomass accumulation, ultimately translating to higher marketable yield (Singh *et al*., 2023) [23].

2. Heavy Metal Accumulation and Food Safety Concerns

Despite the agronomic benefits, the progressive accumulation of heavy metals—particularly lead—raises serious food safety concerns. Lead concentrations in radish roots (1.58 mg/kg) exceeded the FAO/WHO permissible limit of 0.30 mg/kg by more than fivefold, indicating that regular consumption of these radishes could contribute to chronic lead exposure. Lead has no known biological function in humans and is associated with neurological impairment, renal dysfunction, and cardiovascular disease even at low exposure levels (WHO, 2021; Tchounwou *et al*., 2012 [26]; EFSA, 2010).

The high bioaccumulation factor for lead (0.619) reflects efficient uptake from contaminated soil, consistent with radish's growth habit as a root vegetable with prolonged contact with the rhizosphere. Similar findings have been reported by Rai *et al*. (2019) and Zhou *et al*. (2020) [17, 30], who demonstrated that root vegetables accumulate greater heavy metal concentrations than fruit vegetables under comparable conditions. The transfer factor for lead (0.924) indicates that most absorbed lead remained sequestered in root tissues rather than translocating to shoots, consistent with lead's strong adsorption to cell wall components and precipitation as insoluble phosphates (Alloway, 2013; Kabata-Pendias, 2011) [1, 12].

The high concentrations of lead in edible roots represent a significant health risk, particularly for children and pregnant women who are more susceptible to lead toxicity (WHO, 2021). Chronic lead exposure has been associated with impaired cognitive development, reduced intelligence quotient, and behavioural disorders in children (EFSA, 2010). In adults, long-term lead exposure contributes to hypertension, renal dysfunction, and cardiovascular disease (Tchounwou *et al*., 2012) [26].

Cadmium, arsenic, copper, chromium, and zinc remained within permissible limits, though their progressive accumulation warrants monitoring. Cadmium is particularly concerning due to its high mobility and long biological half-life in humans (Clemens & Ma, 2016 [6]; JECFA, 2011), while arsenic's presence reflects contamination from both geogenic and anthropogenic sources (Smedley & Kinniburgh, 2002) [24].

3. Soil Contamination and Long-term Implications

The substantial enrichment of all analyzed heavy metals in soils irrigated with polluted water represents a significant environmental concern. Lead concentrations in treated soils (2.56 ppm) were 395.8% higher than controls, while cadmium, copper, and zinc showed similar levels of enrichment. These elevated concentrations reflect continuous metal loading from wastewater irrigation and the persistent nature of heavy metals in agricultural soils (Alloway, 2013; Bolan *et al*., 2023) [1, 5].

Unlike organic pollutants, heavy metals cannot be degraded biologically and therefore accumulate progressively with repeated irrigation (Kabata-Pendias, 2011) [12]. Their retention in soil depends on factors such as pH, organic matter content, clay mineral composition, and cation exchange capacity (Bolan *et al*., 2023) [5]. In the present study, the observed accumulation indicates that adsorption sites in the soil may be approaching saturation, increasing the bioavailable fraction available for plant uptake.

The long-term implications of soil contamination are particularly concerning. Heavy metals in soils can persist for decades and may continue to accumulate even if wastewater irrigation is discontinued (Alloway, 2013) [1]. This persistence poses ongoing risks to crop quality, groundwater quality, and ecosystem health (Hussain *et al*., 2024) [10]. Regular monitoring of soil metal concentrations is therefore essential for assessing the sustainability of wastewater irrigation practices.

4. Comparative Metal Accumulation and Translocation

The distribution of heavy metals within radish plants revealed important patterns. Edible roots consistently contained higher concentrations of lead, arsenic, and cadmium than leaves, while copper showed slightly higher accumulation in leaves. This pattern reflects the different translocation efficiencies of various metals and the physiological barriers that regulate metal movement from roots to shoots (White & Broadley, 2009) [27].

Lead's strong retention in root tissues (BAF root 0.619 vs leaf 0.572) is consistent with its low phloem mobility and efficient sequestration mechanisms. Lead is strongly adsorbed to cell wall components, precipitated as insoluble phosphate complexes, and sequestered within root vacuoles (Alloway, 2013; Seregin & Kozhevnikova, 2008) [1, 19]. Cadmium showed similar retention patterns, while copper exhibited greater translocation to leaves (TF 1.051), reflecting its role as an essential micronutrient with active transport systems (Marschner, 2012) [13]. Arsenic displayed the lowest bioaccumulation and translocation, suggesting efficient detoxification mechanisms in root tissues (Zhao *et al*., 2010) [29].

These patterns have important food safety implications. For root vegetables like radish, the edible organ is also the primary site of metal accumulation, making these crops particularly vulnerable to soil contamination (Rai *et al*., 2019) [17]. In contrast, fruit vegetables typically show lower metal concentrations in edible tissues due to physiological barriers restricting metal translocation to reproductive organs (Zhou *et al*., 2020; Singh *et al*., 2023) [23, 30].

5. Comparison with Previous Studies

The findings of this study are consistent with previous investigations on wastewater irrigation in vegetable crops. Singh *et al*. (2011) [22] reported heavy metal accumulation in paddy crops irrigated with Ramgarh Lake water, with bioaccumulation of mercury being particularly significant. However, the present study extends these findings by documenting the specific risks to radish cultivation and quantifying the extent of lead contamination in edible tissues.

Global studies have similarly demonstrated that wastewater irrigation enhances crop productivity while increasing heavy metal accumulation. Gupta *et al*. (2024) [9] reported significant enrichment of Pb, Cd, and As in wastewater-irrigated vegetables, with lead frequently exceeding food safety limits. Hussain *et al*. (2024) [10] emphasized that crop species, irrigation duration, and soil properties are the principal determinants of heavy metal accumulation. Zhou *et al*. (2020) [30], in a global meta-analysis, concluded that root vegetables consistently accumulate higher concentrations of heavy metals than fruit vegetables under wastewater irrigation.

The present study adds to this body of knowledge by providing site-specific evidence from the Indo-Gangetic plains, where wastewater irrigation is increasingly practiced due to water scarcity. The findings reinforce the need for context-specific management strategies that consider local water quality, soil conditions, and cropping patterns (Singh *et al*., 2023; Bolan *et al*., 2023) [5, 23].

6. Implications for Sustainable Agriculture

The findings highlight a critical trade-off between agricultural productivity and food safety when using polluted water for irrigation. While Ramgarh Lake water offers substantial agronomic benefits—enhanced germination, growth, yield, and reduced fertilizer requirements—the lead contamination in edible roots poses unacceptable health risks. This trade-off is particularly concerning for root vegetables, which accumulate higher metal concentrations than fruit vegetables due to direct soil contact (Rai *et al*., 2019) [17].

Several strategies could mitigate these risks:

Wastewater Treatment: Installing functional municipal wastewater treatment plants would be the most effective solution, though it requires significant investment. Even primary treatment to remove suspended solids and reduce heavy metal concentrations would substantially improve water quality (FAO, 2021; WHO, 2021) [28].

Water Management: Blending wastewater with freshwater could reduce contaminant concentrations. Seasonal irrigation scheduling that minimizes heavy metal exposure during critical growth periods may also reduce accumulation in edible tissues (Hussain *et al*., 2024) [10].

Crop Selection: Cultivating low-accumulating crop varieties or switching to fruit vegetables in wastewater-irrigated areas could reduce dietary exposure. Selection of radish varieties with lower lead uptake potential should be explored (Singh *et al*., 2023) [23].

Soil Amendments: Application of organic amendments (compost, manure), biochar, lime, and phosphate fertilizers can immobilize heavy metals through adsorption, precipitation, and complexation, reducing bioavailability and plant uptake (Bolan *et al*., 2023; Rinklebe *et al*., 2019) [5, 18].

Phytoremediation: Cultivating hyperaccumulator species in rotation with food crops could gradually remove heavy metals from contaminated soils, though this approach requires long-term commitment (Alloway, 2013) [1].

Monitoring: Regular monitoring of irrigation water, soil, and crop metal concentrations is essential for risk assessment and management. Establishing threshold levels and early warning systems would enable timely interventions (FAO, 2021; WHO, 2021) [8].

Conclusion

This study demonstrates that irrigation with polluted water from Ramgarh Lake produces a dual response in radish cultivation. The nutrient-rich wastewater significantly enhances germination (15.0% increase), vegetative growth (33.7% increase in plant height), and yield (36.5% increase in root yield), offering substantial agronomic benefits. However, continuous irrigation leads to progressive accumulation of heavy metals—particularly lead—in both soil and edible roots. Lead concentrations exceeding FAO/WHO permissible limits by over fivefold indicate serious food safety concerns.

The high bioaccumulation factor for lead (0.619) and the substantial soil enrichment (395.8% increase) highlight the cumulative nature of contamination. While radish plants demonstrate efficient nutrient utilization and yield enhancement under wastewater irrigation, the trade-off between productivity and food safety cannot be ignored.

Sustainable utilization of this resource requires integrated management approaches that balance agricultural productivity with environmental protection and public health. Regular monitoring of irrigation water, soil, and crop metal concentrations is essential. Where lead concentrations exceed safety limits, appropriate mitigation measures—including wastewater treatment, blending with freshwater, soil amendments, and cultivation of low-accumulating varieties—should be implemented.

The findings contribute to a better understanding of the ecological and agricultural consequences of urban wastewater reuse and provide scientific evidence for developing safer irrigation practices in peri-urban farming systems. Future research should focus on long-term field experiments, human health risk assessment, and development of cost-effective remediation strategies to ensure sustainable wastewater utilization in agriculture.

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