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Original Article

Impact of treated wastewater irrigation on vegetable growth, yield, and heavy metal bioaccumulation in a semi-arid greenhouse environment: A case study in Neyshabur, Iran

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Abstract

This study investigates the potential of using treated municipal wastewater to irrigate fenugreek, spinach, radish, and carrot crops in Neyshabur, Iran, as a sustainable response to water scarcity in arid regions. Greenhouse experiments were conducted under three irrigation regimes—100% groundwater (control), 50% wastewater blend, and 100% wastewater—to assess growth performance, yield, and soil and plant quality. Irrigation with 100% wastewater significantly enhanced plant growth, biomass, leaf area, and yield, particularly in fenugreek, due to the wastewater's high nutrient content (nitrogen, phosphorus, potassium, and organic matter), which improved soil fertility despite increased salinity and pollution indicators (EC, BOD, COD). Heavy metal analyses revealed elevated concentrations of Pb, Ni, Zn, Cu, Cr, and Cd in soils irrigated with wastewater, yet all remained below international safety standards. Although metal accumulation in plant tissues rose with wastewater use, concentrations were within FAO/WHO permissible limits, except for cadmium (Cd), which showed a transfer factor (TF) greater than 1 in root vegetables, indicating higher mobility from soil to edible parts. Overall, treated wastewater proved to be a promising alternative water and nutrient source for vegetable cultivation in water-limited areas like Neyshabur, enhancing productivity without immediate health risks, though continuous monitoring of cadmium accumulation is essential to prevent potential long-term soil and food safety issues.

Keywords: Wastewater Reuse; Heavy Metals; Soil Contamination; Food Safety; Semi-Arid Agriculture; Neyshabur

1. Introduction

Global climate change and escalating population pressure are placing unprecedented stress on freshwater resources, particularly in arid and semi-arid regions, which constitute a significant portion of the world's landmass (UNESCO, 2021). Iran, with over 65% of its territory classified as arid or semi-arid, faces acute water scarcity, making sustainable water management a cornerstone of national food security and environmental policy

(Madani, 2014). The agricultural sector, being the largest consumer of water in the country, is at the forefront of this challenge, necessitating a paradigm shift from conventional water sources to alternative, non-conventional resources (Ashraf et al., 2017).

The reuse of treated municipal wastewater for agricultural irrigation has emerged as a globally recognized strategy to mitigate water shortages, recycle valuable nutrients, and reduce the pollution load on receiving water bodies (Qadir et al., 2020). Wastewater is a rich source of essential macronutrients (Nitrogen, Phosphorus, Potassium) and micronutrients, which can reduce the reliance on synthetic fertilizers, thereby lowering production costs and the environmental footprint of farming (Jaramillo & Restrepo, 2017). However, the practice is not without significant risks. Wastewater, even after secondary or tertiary treatment, may contain a cocktail of contaminants, including pathogenic microorganisms, emerging contaminants (e.g., pharmaceuticals, microplastics), and, most notably, heavy metals (Sato et al., 2013; Sajjad et al., 2022).

Heavy metals such as Cadmium (Cd), Lead (Pb), Chromium (Cr), Nickel (Ni), Copper (Cu), and Zinc (Zn) are of particular concern due to their non-biodegradable nature and tendency to accumulate in the soil-plant system (e.g., Zhang et al., 2024). Long-term irrigation with metal-laden wastewater can lead to the gradual degradation of soil health and fertility. More critically, these metals can be taken up by crops and enter the human food chain, posing serious health risks, including renal dysfunction, neurological disorders, and various forms of cancer (Mazhari et al., 2019; Tóth et al., 2016; Khan et al., 2024). The rate of metal uptake and translocation within plants is highly variable, depending on the metal's chemical form, soil properties (pH, organic matter, CEC), plant species, and even genotype (Alexander et al., 2006; Kausar et al., 2017).

Numerous studies have documented the dual effect of wastewater irrigation: enhanced crop productivity due to its fertilizing effect, and the concurrent risk of heavy metal contamination. For instance, Sharma et al. (2007) in India and Mapanda et al. (2005) in Zimbabwe reported significant build-up of heavy metals in soils and vegetables under long-term wastewater irrigation. Conversely, studies by Faizan et al. (2014) and Tamoutsidis et al. (2009) highlighted the substantial improvements in growth and yield of various crops. This dichotomy underscores the need for region-specific and crop-specific assessments to develop safe and sustainable wastewater reuse guidelines.

The region of Neyshabur, located in the semi-arid province of Razavi Khorasan, Iran, is characterized by low precipitation, high evaporation rates, and a heavy reliance on dwindling groundwater reserves for its vibrant agricultural economy. While the use of treated wastewater is being promoted as a sustainable alternative, there is a significant gap in local scientific data regarding its long-term impacts, particularly in controlled greenhouse environments where high-value vegetable crops are cultivated. The structure of the study by Kausar et al. (2017), which systematically evaluated growth, yield, and metal accumulation in both leafy and root vegetables, provides an excellent framework for such an investigation.

This study, therefore, aims to adapt and apply that framework to the specific context of Neyshabur. The primary objectives were: (1) to assess the physico-chemical and biological quality of treated wastewater from the Neyshabur municipal plant and its suitability for irrigation; (2) to evaluate the effect of different concentrations of wastewater on the growth and yield of four economically important vegetables (fenugreek, spinach, radish, and carrot); (3) to determine the accumulation patterns of Cd, Cr, Cu, Ni, Pb, and Zn in the irrigated soil and in the edible parts of the vegetables; and (4) to calculate the soil-to-plant transfer factor (TF) for each metal to assess their mobility and potential risk to the food chain. By providing robust, localized data, this research seeks to inform best practices for the safe and productive use of treated wastewater in the semi-arid agricultural systems of Iran.

2. Materials and Methods

2.1. Study Site and Experimental Design

The experiment was conducted from October 2023 to February 2024 in a climate-controlled greenhouse at the Kian Kesht Company of Neyshabur, Razavi Khorasan Province, Iran (36°12' N, 58°47' E). The region has a semi-arid climate with cold winters and hot, dry summers. The experiment was laid out in a randomized complete block design (RCBD) with three replications. The treatments consisted of three different irrigation water qualities: (a) Control (GW), irrigated with local groundwater; (b) 50% Wastewater (50% WW), a 1:1 mixture of treated wastewater and groundwater; and (c) 100% Wastewater (100% WW), irrigated solely with treated wastewater.

Earthen pots (25 cm diameter, 30 cm height) were filled with 8 kg of air-dried, sieved (2 mm) soil. The soil was a calcareous loam, typical of the Neyshabur plain, mixed with 5% (w/w) well-decomposed farmyard manure to improve its physical properties, following the methodology of Tadesse et al. (2013)..

2.2. Plant Material and Wastewater Source

Four vegetable species were selected for the study: two leafy vegetables, fenugreek (Trigonella foenum-graecum L. cv. 'Esfahani') and spinach (Spinacia oleracea L. cv. 'Viroflay'), and two root vegetables, radish (Raphanus sativus L. cv. 'Cherry Belle') and carrot (Daucus carota L. cv. 'Nantes'). Seeds were surface-sterilized with a 1% sodium hypochlorite solution for 5 minutes, followed by thorough rinsing with deionized water (Sauer & Burroughs, 1986). Seeds were sown at an appropriate depth in the pots and thinned to a uniform number of plants per pot after germination.

The treated wastewater (WW) was collected biweekly from the outlet of the Neyshabur Municipal Wastewater Treatment Plant, which employs an activated sludge process. The groundwater (GW) was sourced from a deep well at the research center. Water samples were collected in sterile polyethylene bottles and stored at 4°C for analysis.

2.3. Analysis of Water and Soil Samples

Water samples were analyzed for their physico-chemical properties, including pH, electrical conductivity (EC), total dissolved solids (TDS), total suspended solids (TSS), biological oxygen demand (BOD), and chemical oxygen demand (COD), following the standard methods outlined by APHA (1998). Concentrations of major cations (Ca2+, Mg2+, K+) and anions (Cl-, HCO3-, CO32-) were also determined. Soil samples were collected before the experiment and after the final harvest from each treatment. Soil pH and EC were measured in a 1:5 soil-water extract. Other properties, like cation exchange capacity (CEC), were determined according to Jackson (1973).

For heavy metal analysis, water samples were acidified and digested according to Ademoroti (1996). Soil samples were air-dried, ground, and digested using a di-acid mixture (HNO3-HClO4) following the DTPA extraction method of Lindsay and Norvell (1978). The concentrations of Cadmium (Cd), Chromium (Cr), Copper (Cu), Nickel (Ni), Lead (Pb), and Zinc (Zn) in the digested solutions were determined using an Atomic Absorption Spectrophotometer (AAS, Varian AA240).

2.4. Plant Growth, Yield, and Heavy Metal Analysis

Plant growth parameters were measured at 30, 60, and 90 days after sowing (DAS). Three plants per pot were carefully uprooted, washed, and measured for plant length, leaf number, and leaf area (using a leaf area meter, LI-COR LI-3100C). Fresh weight was recorded, after which samples were oven-dried at 75°C for 48 hours to determine the dry weight.

At final harvest (90 DAS for leafy vegetables, 120 DAS for root vegetables), yield attributes including seed number, 1000-seed weight, and seed yield per plant were recorded. For root vegetables, the fresh weight of the edible root was the primary yield parameter.

For heavy metal analysis, the edible parts of the plants (leaves for fenugreek and spinach, roots for radish and carrot) were harvested, washed thoroughly with deionized water, and oven-dried. The dried samples were ground into a fine powder and digested using a wet digestion procedure. Heavy metal analysis was conducted using an aqua regia digestion technique, in which a solution was prepared by combining three volumes of concentrated hydrochloric acid (HCl) with one volume of concentrated nitric acid (HNO_3) (USGS, 2019). Metal concentrations in the digested plant samples were analyzed using AAS.

2.5. Data Indices and Statistical Analysis

To evaluate the extent of soil and plant contamination, three indices were calculated:

• Pollution Load Index (PLI): Calculated for soil to assess the degree of pollution from each metal relative to the control soil (Liu et al., 2005).

$$PLI=C_{contaminated} / C_{control} \quad (1)$$

• Enrichment Factor (EF): Calculated for plants to determine the degree of metal accumulation in wastewater-irrigated plants compared to control plants (Barman et al., 2000).

$$EF=C_{plant\_contaminated} / C_{plant\_control} \quad (2)$$

• Transfer Factor (TF): Calculated to assess the mobility of metals from soil to the plant (Chamberlin, 1983).

$$TF = C_{plant} / C_{soil} \quad (3)$$

All collected data were subjected to Analysis of Variance (ANOVA) using R statistical software (Version 4.3.1). Treatment means were compared using Tukey's Honestly Significant Difference (HSD) test at a significance level of $p < 0.05$

3. Results and Discussion

3.1. Physico-chemical and Heavy Metal Quality of Irrigation Waters

The average characteristics of the groundwater (GW) and treated wastewater (WW) used for irrigation are presented in Table 1. The wastewater exhibited a slightly alkaline pH (8.1), which is favorable for agricultural use and falls within the FAO guidelines (Ayers & Westcot, 1994). As expected, the WW had significantly higher values for EC, TDS, TSS, BOD, and COD compared to GW, indicating a much higher load of dissolved salts and organic matter. The high nutrient content, particularly Nitrate-Nitrogen (1.35 mg/L), Phosphorus (0.92 mg/L), and Potassium (11.5 mg/L), highlights the fertilizing potential of the wastewater, which can supplement crop nutrient requirements and reduce the need for synthetic fertilizers (Jaramillo & Restrepo, 2017).

Heavy metal analysis showed that concentrations of all six metals (Cd, Cr, Cu, Ni, Pb, Zn) were higher in WW than in GW. However, the levels of all metals in the treated wastewater were well below the maximum permissible limits for irrigation water recommended by the FAO (Pescod, 1992). For instance, the concentration of Pb in WW was 3.31 mg/L, exceeding the limit of 5.0 mg/L, and Cd was 0.009 mg/L, exceeding the limit of 0.01 mg/L. This suggests that, from a quality perspective, the treated wastewater from the Neyshabur plant is suitable for agricultural irrigation. However, the potential for long-term accumulation in soil remains a concern.

Table 1. Average physicochemical characteristics of groundwater (GW) and treated wastewater (WW) used for irrigation in Neyshabur. All values in mg/L unless specified.

Parameter	Groundwater (GW)	Wastewater (WW)	FAO Guideline Limit[a]
Physical Characteristics			
PH	7.6	8.1	6.5-8.4
EC (dS/m)	0.78	1.35	< 3.0
Chemical Characteristics			
Total Dissolved Solids (TDS)	550	1455	< 2000
Total Suspended Solids (TSS)	442	710	-
Biological Oxygen Demand (BOD)	17.2	54.5	-
Chemical Oxygen Demand (COD)	64.1	148.3	-
Calcium (Ca2+)	20.1	43.5	-
(Mg2+)	Magnesium 27.5	135.2	-
Potassium (K+)	5.2	11.5	-
Nitrate-Nitrogen (NO3-N)	0.65	1.35	< 10
Phosphorus (PO43-)	0.08	0.92	-
Heavy Metals			
Cadmium (Cd)	0.004	0.009	0.01
Chromium (Cr)	0.10	0.16	0.1
Copper (Cu)	0.140	0.215	0.2
Nickel (Ni)	0.095	0.210	0.2
Lead (Pb)	2.15	3.31	5.0
Zinc (Zn)	0.53	0.70	2.0

[a] Ayers and Westcot (1994); Pescod (1992). Data represent mean values (n=5).

3.2. Effect of Wastewater Irrigation on Soil Properties

The analysis of soil characteristics after the final harvest (Table 2) revealed a significant build-up of heavy metals in plots irrigated with wastewater compared to the groundwater control. The Pollution Load Index (PLI), which indicates the relative increase, showed the highest enrichment for Ni (PLI = 3.15), followed by Pb (2.62), Cd (2.38), Zn (2.21), Cu (1.68), and Cr (1.06). This sequence (Ni > Pb > Cd > Zn > Cu > Cr) is consistent with findings from other studies (Kausar et al., 2017; Liu et al., 2005; Alam et al., 2025), suggesting that even low concentrations of metals in irrigation water can accumulate substantially in the soil over time. This phenomenon is attributed to the complexation of metals with soil organic matter and clay particles, reducing their leachability. Despite this accumulation, the absolute concentrations of all metals in the WW-irrigated soil remained within the safe limits for agricultural soils proposed by international bodies. For example, Pb concentration was 133.5 mg/kg, well below the typical threshold of 250-500 mg/kg. However, the high PLI for metals like Ni and Cd signals a potential long-term risk that requires continuous monitoring.

Table 2. Average physico-chemical characteristics of soil after harvest, irrigated with groundwater (GW) and 100% wastewater (WW).

Parameter	GW-irrigated Soil	WW-irrigated Soil	Permissible Range*
pH	7.81	8.15	-
EC (dS/m)	0.85	1.02	-
CEC (meq/100g)	3.35	4.05	-
Nitrate-Nitrogen (g/kg)	0.36	0.45	-
Phosphorus (g/kg)	0.12	0.30	-
Heavy Metals (mg/kg)			
Cadmium (Cd)	2.18	5.18	3-6
Chromium (Cr)	27.8	29.5	-
Copper (Cu)	29.1	48.9	135-270
Nickel (Ni)	32.8	103.3	75-150
Lead (Pb)	51.0	133.5	250-500
Zinc (Zn)	46.2	102.1	300-600

***Pescod (1992). Data represent mean values (n=5).**

3.3. Effect on Plant Growth Characteristics

Irrigation with treated wastewater had a significantly positive effect on the growth of all four vegetable species at all sampling stages (30, 60, and 9 DAS). As shown in Figures 1-4, plants irrigated with 100% WW consistently exhibited the greatest plant length, fresh weight, dry weight, leaf number, and leaf area, followed by the 50% WW treatment, with the control (GW) group showing the least growth. This stimulatory effect is directly attributable to the higher concentration of essential nutrients (N, P, K) and organic matter in the wastewater, which acted as a liquid fertilizer, promoting vigorous vegetative growth (Soumare et al., 2003).

The response varied among the plant species. The pattern of increase in growth parameters was generally in the order of fenugreek > radish > spinach > carrot. For example, at 90 DAS, 100% WW irrigation increased the plant length of fenugreek by approximately 48% over the control, while the increase for carrot was around 34%. This differential response is likely due to inherent genetic differences in nutrient uptake efficiency and growth habits among the species. Fenugreek, a legume, may have benefited synergistically from the available nitrogen. Because the nitrogen content in wastewater is very high, it inhibits biological nitrogen fixation, unless the nodules are specifically analyzed. The consistent increase in fresh and dry weight throughout the growing period indicates continuous biomass accumulation, underscoring the sustained nutrient supply from the wastewater.

3.4. Effect on Yield Characteristics

The positive effects on vegetative growth translated directly into significantly higher yields for all four vegetables (Fig. 5). Irrigation with 100% WW resulted in the maximum yield, followed by 50% WW. The order of performance for yield enhancement was fenugreek > radish > spinach > carrot, mirroring the trend observed for growth characteristics. For fenugreek, 100% WW irrigation led to a remarkable increase in seed number (approx. 69%), 1000-seed weight (approx. 69%), and seed yield (approx. 71%) compared to the control. Similarly, radish roots were substantially larger and heavier in the wastewater treatments. These results are in strong agreement with previous research demonstrating that the nutrient-rich nature of wastewater can significantly boost crop productivity, especially in nutrient-limited soils (Heckman et al., 1986; Segura et al., 2004). The balanced supply of macro- and micronutrients from wastewater likely improved photosynthetic efficiency and resource allocation to the economic parts of the plants, leading to higher yields.

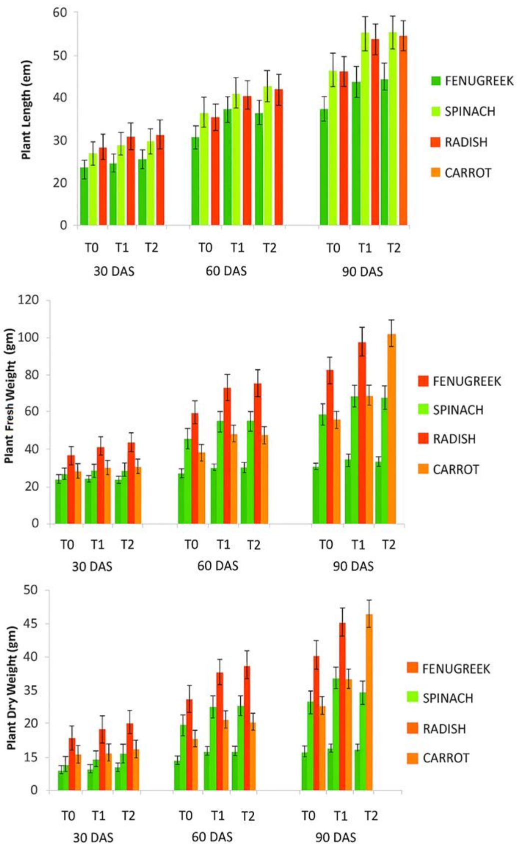

Fig. 1 Effect of GW (T0), 50% WW (T1), and 100% WW (T2) on Plant Length, Fresh Weight, and Dry Weight of Vegetables at 30, 60, and 90 DAS. Error bars denote standard deviation.

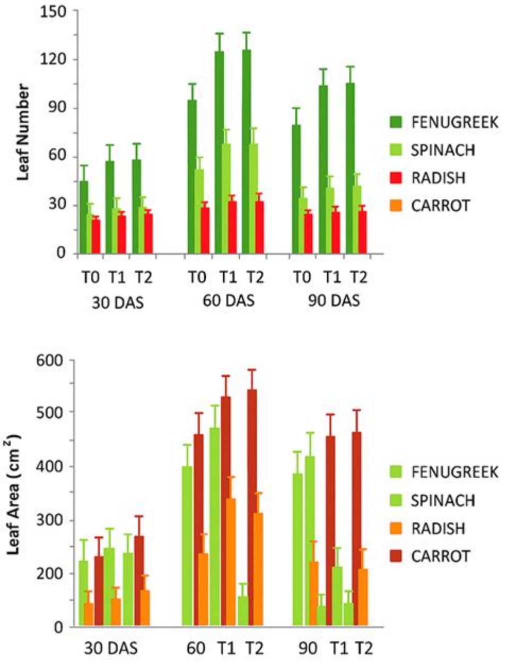

Fig. 2 Effect of GW (T0), 50% WW (T1), and 100% WW (T2) on Leaf number and Leaf area of Vegetables at 30, 60, and 90 DAS. Error bars denote standard deviation.

3.5. Heavy Metal Accumulation in Plants and Transfer from Soil

While wastewater irrigation proved beneficial for growth and yield, it also led to a significant increase in the concentration of heavy metals in the edible plant tissues (Table 3). For all four vegetables, plants grown with 100% WW had the highest metal content, followed by 50% WW and then the GW control. This is a direct consequence of the higher metal load in the wastewater and the subsequent accumulation in the soil, making them more available for plant uptake (Sharma et al., 2007; Gupta et al., 2010; Mazhari et al., 2013; Mazhari et al., 2017; Maleknia et al., 2025). The Enrichment Factor (EF) in plants (Table 4) was particularly high for Cr in fenugreek (EF ≈ 187) and for Zn in radish (EF ≈ 103), indicating a strong tendency for these plants to accumulate these specific metals from the contaminated soil.

Despite this increase, the concentrations of all heavy metals in the edible parts of the vegetables irrigated with 100% WW were found to be within the safe permissible limits for human consumption as recommended by the Joint FAO/WHO Expert Committee on Food Additives (1992) and Kabata-Pendias and Pendias (2010). For example, the Pb concentration in spinach leaves was 3.02 mg/kg, below the toxic level of 5 mg/kg. This suggests that, under the conditions of this short-term study, the use of treated wastewater from Neyshabur does not pose an immediate food safety risk.

The most critical finding of this study relates to the soil-to-plant Transfer Factor (TF), which indicates the mobility of metals (Table 4). For most metals (Cu, Ni, Pb), the TF was less than 1, indicating that the soil acted as a barrier, limiting their translocation into the plants. Pb, in particular, had a very low TF (0.013-0.041), confirming its low bioavailability and mobility in the soil matrix (Berg et al., 1995). However, a striking exception was observed for Cadmium (Cd). In both root vegetables, radish (TF = 1.65) and carrot (TF = 2.07), the TF for Cd was significantly greater than 1. This indicates that these plants readily absorb Cd from the soil and accumulate it in their edible roots at concentrations higher than those in the surrounding soil. This high mobility of Cd is a well-documented phenomenon, as it is easily absorbed by plant roots, often through calcium channels (e.g., Gupta et al., 2010). This finding is of paramount importance for food safety in the Neyshabur region. Although the absolute concentration of Cd in the vegetables was within safe limits in this short-term study, its high transfer factor suggests that with continuous, long-term wastewater irrigation, Cd could accumulate in the soil to a point where its concentration in crops exceeds safe consumption levels. This highlights Cd as the metal of primary concern for any wastewater reuse program in this region.

Table 3. Heavy metal content (mg/kg dry weight) in edible parts of vegetables irrigated with groundwater (T0), 50% wastewater (T1), and 100% wastewater (T2).

Plant (Part)	Treatment	Cd	Cu	Ni	Cr	Zn	Pb
	T0	0.05	0.83	7.04	0.11	1.05	0.056
Fenugreek (Leaf)	T1	0.73	1.75	24.17	14.43	53.17	0.53
	T2	1.25	2.91	32.69	20.57	68.49	1.73
	T0	0.38	1.36	8.00	0.72	1.24	0.098
Spinach (Leaf)	T1	1.04	2.83	30.22	18.06	61.49	1.62
	T2	2.52	5.17	40.93	25.11	75.93	3.02
	T0	0.96	3.65	8.96	0.45	1.43	0.12
Radish (Root)	T1	3.47	8.22	58.85	20.36	138.26	2.15
	T2	8.39	12.36	90.14	29.41	147.13	4.01
	T0	1.37	5.36	10.11	0.94	1.94	0.18
Carrot (Root)	T1	4.21	11.92	65.03	21.19	141.19	2.97
	T2	10.47	16.28	93.38	30.67	160.29	4.41
Permissible Limit [b]		**5-30**	**20-100**	**10-100**	**5-30**	**100-400**	**5-30**

Data represent mean values (n=5). [b] Range of excessive/toxicant levels in plants (Kabata-Pendias & Pendias, 2010; FAO/WHO, 1992).

Table 4. Enrichment Factor (EF) and Transfer Factor (TF) for heavy metals in vegetables grown in 100% wastewater-irrigated soil

Plant	Index	Cd	Cu	Ni	Cr	Zn	Pb
Fenugreek	EF	25.00	3.51	4.64	187.00	65.23	30.89
	TF	0.241	0.060	0.316	0.697	0.671	0.013
Spinach	EF	6.63	3.80	5.12	34.88	61.23	30.82
	TF	0.486	0.106	0.396	0.851	0.744	0.023
Radish	EF	8.74	3.39	10.06	65.36	102.89	33.42
	TF	1.650	0.253	0.873	0.997	1.441	0.030
Carrot	EF	7.64	3.04	9.24	32.63	82.62	30.06
	TF	2.070	0.333	0.904	1.040	1.570	0.041

4. Conclusion

This study demonstrates that the use of treated municipal wastewater for irrigation in the semi-arid environment of Neyshabur, Iran, presents a classic case of dual effects. On one hand, it is an unequivocally valuable resource that significantly enhances the growth and yield of key vegetable crops, acting as a reliable source of both water and essential plant nutrients. This can contribute to improving agricultural productivity and farmer livelihoods in a region grappling with severe water scarcity. The increase in yield for all four tested vegetables—fenugreek, spinach, radish, and carrot—confirms the fertilizing value of the wastewater.

On the other hand, the practice leads to the inevitable accumulation of heavy metals in the soil and their subsequent uptake by plants. While the concentrations of Cd, Cr, Cu, Ni, Pb, and Zn in the edible portions of the vegetables remained within the internationally accepted safe limits for human consumption in this short-term greenhouse study, the long-term implications cannot be overlooked. The high soil-to-plant transfer factor (TF > 1) observed for Cadmium (Cd) in root vegetables is a significant red flag. It indicates that Cd is highly mobile and readily bioaccumulated, posing a potential future risk to food safety if wastewater irrigation continues unabated without proper management.

Based on these findings, we conclude that treated wastewater can be used profitably for vegetable cultivation in Neyshabur, but this practice must be coupled with a robust and vigilant management strategy. We recommend the following:

1. Regular Monitoring: A long-term monitoring program for heavy metals in irrigation water, soil, and crops is essential. Special attention should be paid to Cadmium levels.

2. Crop Selection: Farmers should be encouraged to cultivate crops with low heavy metal uptake potential. Our results suggest leafy vegetables like fenugreek and spinach may be safer choices than root vegetables like carrots and radishes, which showed high Cd accumulation.

3. Soil Amelioration: The application of soil amendments such as biochar or compost, which can immobilize heavy metals and reduce their bioavailability, should be investigated as a risk mitigation strategy.

Future research should focus on long-term field trials to validate these greenhouse findings, investigate the accumulation of emerging contaminants, and explore cost-effective methods for reducing metal mobility in the soil. By adopting a scientifically informed and cautious approach, Neyshabur and other semi-arid regions can harness the benefits of wastewater reuse while safeguarding environmental health and food security for generations to come.

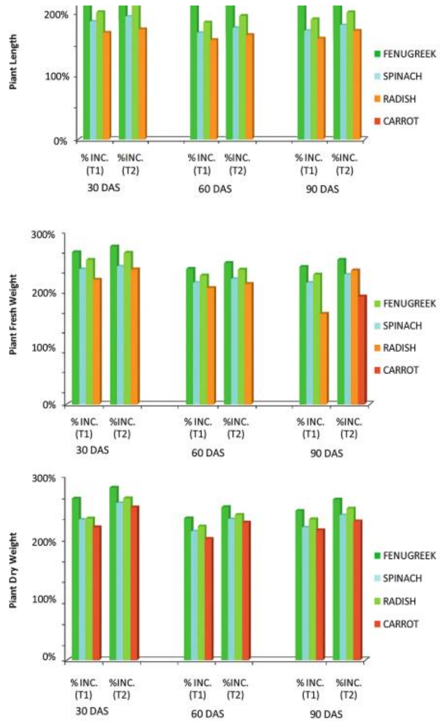

Fig. 3 Percent increase of Plant Length, Fresh Weight, and Dry Weight of Vegetables at 30, 60, and 90 DAS due to 50% WW (T1) and 100% WW (T2) over groundwater.

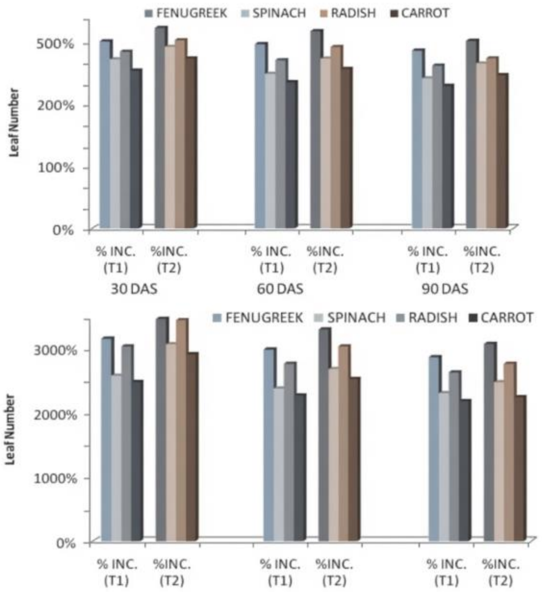

Fig. 4 Percent increase of Leaf Number and Leaf Area of Vegetables at 30, 60, and 90 DAS due to 50%WW (T1) and 100%WW (T2) over groundwater.

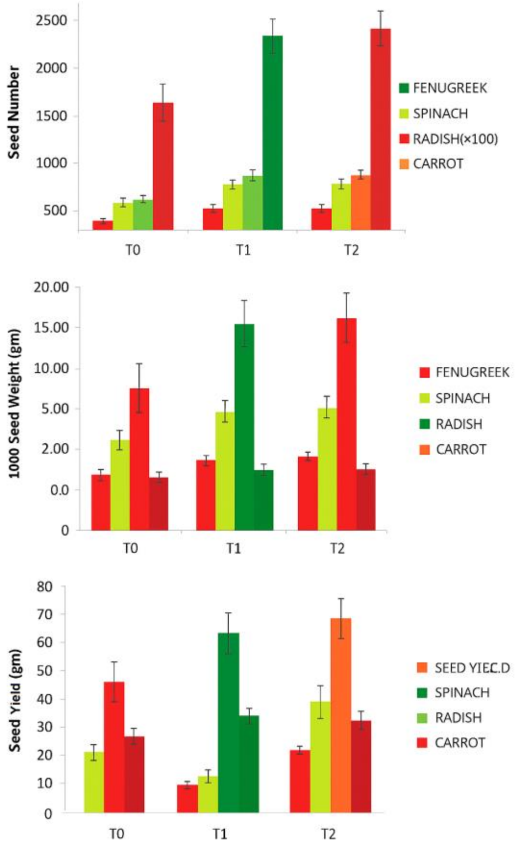

Fig. 5 Effect of GW (T0), 50% WW (T1), and 100% WW (T2) on Seed number, 1000 Seed weight, and Seed yield of Vegetables at harvest. Error bars denote standard deviation.

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Declarations

Data and code availability

All data generated or analyzed during this study are available from the corresponding author upon reasonable request. No computational code was used in this study.

Conflicts of interest

The authors announced that they have no known conflicts of interest or personal relationships that could have appeared to influence the work reported in this manuscript.

Ethical approval

The authors declare no ethical issues; the research was carried out in full agreement with ethical standards. Also, this paper is neither under Review nor published elsewhere.

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