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Dr. Preeti Deshmukh
 Senior Scientist and Head Soil
 Science Section, Vasantdada
 Sugar Institute, Manjari,
 Budruk, Tal-Haveli, Pune,
 Maharashtra, India

Dr. Utkarsha V Amolic
 Research Associate, Soil
 Section, Vasantdada Sugar
 Institute, Manjari, Budruk,
 Tal-Haveli, Pune,
 Maharashtra, India

US Mutkule
 Senior Research Fellow,
 Vasantdada Sugar Institute,
 Pune, Maharashtra, India

Corresponding Author:
Dr. Utkarsha V Amolic
 Research Associate, Soil
 Section, Vasantdada Sugar
 Institute, Manjari, Budruk,
 Tal-Haveli, Pune,
 Maharashtra, India

Impact of industrialization on accumulation of heavy metals in irrigation water, soil and vegetables

Preeti Deshmukh, Utkarsha V Amolic and US Mutkule

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Abstract

This research investigates the impact of industrialization on the accumulation of heavy metals in irrigation water, soil, and vegetables in regions dependent on industrial wastewater for irrigation. Heavy metals such as cadmium (Cd), copper (Cu), lead (Pb), iron (Fe), zinc (Zn), and manganese (Mn) were analyzed in irrigation water, soil, and commonly consumed vegetables. Samples were collected from farms irrigated with water from the Nag, Musi, Krishna, and Hooghly rivers, known for receiving industrial effluents. The findings revealed elevated levels of these metals in water and soils, leading to bioaccumulation in crops. Hooghly river water showed the highest concentration of lead (7.5 mg/L), while soil irrigated by Musi river water exhibited elevated Fe levels (71.32 mg/kg). Vegetables grown in these soils had metal concentrations exceeding permissible limits. This study underscores the health risks posed by heavy metal contamination in agricultural produce and the need for better wastewater management practices.

Keywords: Heavy metals, wastewater irrigation, soil contamination, vegetable bioaccumulation, industrial pollution, public health

Introduction

Heavy metal pollution is a significant environmental concern, particularly in developing countries, where rapid industrialization and urbanization have led to the contamination of natural resources. Heavy metals, including cadmium (Cd), lead (Pb), copper (Cu), zinc (Zn), and iron (Fe), are essential micronutrients in small amounts, but their excessive accumulation in the environment can be toxic to plants, animals, and humans. These metals are non-biodegradable and persistent, leading to long-term contamination of water, soil, and agricultural products, which ultimately poses severe risks to public health. (Arora *et al.*, 2008) ^[2]

Industrial effluents, untreated wastewater, and the application of contaminated sewage sludge in agriculture have all contributed to the accumulation of heavy metals in soils and water bodies. As industries, particularly electroplating, smelting, textile, fertilizer, and chemical sectors, discharge untreated or inadequately treated effluents into rivers and streams, these toxic substances accumulate in the environment. Over time, such pollutants make their way into agricultural systems, primarily through irrigation with contaminated water, leading to the bioaccumulation of these metals in crops. This situation is particularly critical in peri-urban areas, where untreated industrial wastewater is often the only available irrigation source (Baride *et al.*, 2014; Swapna Priya *et al.*, 2014) ^[3, 15].

The use of untreated wastewater for irrigation has become a widespread practice due to the increasing scarcity of freshwater resources. In regions like India, industrial zones often discharge effluents into nearby rivers, which are then used for irrigation. This practice has been documented in several studies across different regions. For instance, Nazif *et al.* (2006) ^[12] found that water from the Bara River in Pakistan contained elevated levels of heavy metals compared to canal water, making it unsuitable for long-term agricultural use. Similarly, the significant contamination of surface and groundwater in Jalgaon District, India, due to the discharge of industrial effluents, leading to a sharp increase in the concentration of toxic metals like Pb, Cu, Fe, and Zn. These studies highlight the risks posed by using contaminated water for irrigation, where the metals accumulate in both soil and crops were studied by (Baride *et al.* 2014) ^[3]

Soil acts as both a reservoir and a medium for transferring heavy metals to crops. Soils contaminated with heavy metals from industrial wastewater are known to retain these metals, which plants then absorb through their root systems. This uptake leads to the bioaccumulation of metals in edible plant tissues, particularly in leafy vegetables, which are known for their ability to accumulate higher concentrations of metals in their leaves. Once absorbed, these metals cannot be metabolized or eliminated by the plants and remain in the edible parts of the crops, thus entering the food chain. Over time, this leads to an increase in the levels of these metals in the food consumed by humans, raising concerns about food safety and public health (Mahakalkar *et al.*, 2013; Rangnekar, 2013) ^[10, 14].

The transfer of heavy metals from soil to plants depends on various factors, including the type of soil, the concentration of metals in the soil, and the plant species. Gupta *et al.* (2013) ^[5, 10] observed that the concentration of metals like Cu, Zn, Pb, and Mn in soils irrigated with wastewater significantly exceeded safe limits, leading to their uptake by crops. In their study of vegetables grown in peri-urban areas of Raipur, they found that leafy vegetables such as spinach and coriander were particularly prone to metal accumulation, as they absorb more metals through their leaves compared to other crops. These findings are supported by Ajmal Khan *et al.* (2021) ^[1], who observed similar patterns in Lahore, where industrial and urban wastewater irrigation contributed to high levels of heavy metals in both soil and vegetables.

The accumulation of heavy metals in edible crops is a growing concern, particularly in urban and peri-urban areas, where wastewater is commonly used for irrigation. Studies have consistently shown that crops grown in contaminated soils tend to accumulate toxic metals at levels exceeding permissible limits set by the World Health Organization (WHO) and Food and Agriculture Organization (FAO). Swapna Priya *et al.* (2014) ^[15] reported that vegetables irrigated with water from the Musi River in Hyderabad contained dangerous levels of metals like Zn, Pb, and Fe, surpassing WHO/FAO standards. Such contamination poses a significant risk to human health, as prolonged exposure to heavy metals through the consumption of contaminated crops can lead to chronic illnesses such as kidney damage, neurological disorders, and cancer.

Moreover, the environmental implications of heavy metal contamination are vast. Soils subjected to long-term irrigation with contaminated water tend to lose their fertility and become increasingly polluted. The accumulation of heavy metals in the soils of Mewat, Haryana, and concluded that continuous exposure to contaminated water results in the gradual build-up of toxic metals, which can eventually render the soil unproductive. These findings emphasize the need for sustainable agricultural practices and the implementation of proper wastewater treatment processes to prevent further soil degradation and ensure food safety were studied by Gopal Krishna *et al.* (2020) ^[7].

Given the severe implications of heavy metal contamination, it is critical to investigate and assess the levels of these toxic substances in irrigation water, soils, and vegetables. This study focuses on the accumulation of heavy metals in water, soil, and commonly consumed vegetables in agricultural regions irrigated with wastewater from the Nag, Musi, Krishna, and Hooghly rivers. The aim is to assess the extent of contamination and its potential health risks to consumers.

By providing insights into the concentration of metals like Cd, Pb, Cu, Zn, and Fe in these ecosystems, this study seeks to contribute to the growing body of knowledge on heavy metal pollution and its effects on agricultural systems.

Materials and Methods

Study Area and Sampling

The study was conducted in agricultural regions irrigated by the Nag, Musi, Krishna, and Hooghly rivers, all known to receive industrial effluents. Water samples were collected from each river at different points. Soil samples were taken from farms using this water for irrigation, and vegetable samples were harvested from the same fields. Sampling took place during the post-monsoon season, ensuring that any leaching effects were minimized.

The geographic coordinates for each location are as follows:

- Nag River (20.7042° N, 78.6167° E),
- Musi River (17.3506° N, 78.3826° E),
- Krishna River (16.1670° N, 74.8491° E),
- Hooghly River (22.6708° N, 88.3659° E).

Water Sampling and Analysis

Water samples were collected in pre-cleaned 1L polyethylene bottles, which were rinsed with deionized water before collection. Samples were acidified immediately with 5 mL concentrated nitric acid to prevent metal precipitation and stored at 4 °C until analysis. Heavy metal concentrations (Cd, Pb, Cu, Zn, Mn, Fe) were determined using MP-AES (Firdaus *et al.* 2024) ^[11].

Soil Sampling and Analysis

Soil samples were collected from the upper 0-30 cm of the soil profile using a stainless steel auger. The samples were air-dried, sieved (2 mm), and stored for analysis. A mixture of HNO₃ and HClO₄ (5:1 ratio) was used to digest the samples, and heavy metal concentrations were determined by MP-AES. Soil pH, electrical conductivity, and organic matter content were also recorded to evaluate the influence of soil properties on metal uptake (Ramos *et al.* 2021) ^[13].

Vegetable Sampling and Analysis

Vegetable samples were collected from the same fields where water and soil samples were taken. The vegetables selected for analysis were spinach (*Spinaciaoleracea*), fenugreek (*Trigonellafoenum-graecum*), and brinjal (*Solanummelongena*), commonly consumed in the region. Samples were thoroughly washed to remove any surface contamination, air-dried, and then digested with a mixture of HNO₃ and HClO₄. The concentrations of Cd, Pb, Cu, Zn, Fe, and Mn in the edible portions were measured using MP-AES (Ramos *et al.* 2021) ^[13].

Statistical Analysis

Data were analyzed using SPSS software (version 22). A one-way analysis of variance (ANOVA) was performed to determine the significance of differences in metal concentrations across different sampling sites. The level of significance was set at $p < 0.05$.

Results

Heavy Metals in Irrigation Water

The results of the water sample analysis are presented in Table 1. The highest concentration of Pb was recorded in Hooghly river water (7.5 mg/L), far exceeding the WHO

permissible limit of 0.1 mg/L. Similarly, elevated levels of Fe and Mn were observed in the Musi river (8.64 mg/L and 10.3 mg/L, respectively), posing a potential risk to both soil and crop health. In contrast, Krishna river water showed lower concentrations of most metals, with values for Pb, Cu, Mn, and Zn within the permissible limits for irrigation (Firdaus *et al.* 2024) ^[11].

Table 1: Concentration of heavy metals in water sample (mg/l)

Sr. No.	Site	Pb	Cu	Mn	Fe	Zn
1	Nag River	0.23	0.63	0.91	4.67	4.62
2	Musi river	0.21	0.01	10.3	8.64	7.02
3	Krishna river	0.22	0.5	0.5	1.13	7.2
4	Hooghly River	7.5	6.3	2.1	5.3	4.3
	Permissible limit (Mg/Kg)	0.1	1.5	0.5	1	10

Heavy Metals in Soil

The concentration of heavy metals in the soil samples is shown in Table 2. Soils irrigated with Musi river water exhibited the highest levels of Fe (71.32 mg/kg), well beyond the permissible limit. Similarly, Zn and Cu concentrations were highest in soils irrigated with Hooghly river water (28.5 mg/kg and 16.6 mg/kg, respectively). These elevated metal concentrations in the soil indicate long-term accumulation due to continuous irrigation with contaminated water ((Ramos *et al.* 2021) ^[13].

Table 2: Concentration of heavy metal in irrigated soil sample (mg/kg)

Sr. No.	Site	Pb	Cu	Mn	Fe	Zn
1	Nag River	0.23	0.42	0.69	11.8	2.85
2	Musi river	13.12	16.53	12.04	71.32	10.2
3	Krishna river	0.09	0.92	2.31	3.88	0.8
4	Hooghly River	16.8	16.6	1.2	1.3	28.5
	Permissible limit (Mg/Kg)	300	6	-	-	300

Heavy Metals in Vegetables

Vegetables grown in soils irrigated with contaminated water showed significant bioaccumulation of heavy metals (Table 3). Spinach and fenugreek had the highest concentrations of Pb and Zn, especially in fields irrigated with Hooghly and Musi river water. The concentration of Pb in spinach (2.41 mg/kg) far exceeded the permissible limit of 0.1 mg/kg, indicating a potential risk to human health.

Table 3: Concentration of heavy metal in vegetable sample (mg/kg)

Sr. No.	Site	Pb	Cu	Mn	Fe	Zn
Spinach	Hooghly River	2.41	1.76	12.10	5.22	18.32
Fenugreek	Musi River	1.80	1.20	10.42	4.56	14.22
Spinach	Hooghly River	0.55	0.42	3.22	1.76	2.05

Discussion

The results of this study provide compelling evidence of the significant impact of industrialization on the accumulation of heavy metals in agricultural systems. Irrigation with wastewater, particularly from rivers like the Hooghly and Musi, led to a concerning accumulation of toxic metals in both soil and vegetables, far exceeding permissible limits. This accumulation has wide-reaching implications for food safety and public health, especially in regions where vegetables are a primary component of the diet. To better understand the broader implications of these findings, it is

essential to compare and contrast them with previous research.

Heavy Metal Contamination in Irrigation Water

The study's findings on the high concentration of heavy metals in irrigation water align with similar studies. For example, Wajahat Nazif *et al.* (2006) ^[12] studied irrigation water sources in Pakistan and found heavy metal concentrations to be much lower in canal water compared to river water, as was also observed in this study where the Musi and Hooghly rivers showed elevated levels of Fe, Mn, and Pb compared to safer levels in the Krishna river. This confirms that industrial effluents and untreated sewage are the primary contributors to metal contamination in river systems. As seen in the current study, high Pb and Mn levels in irrigation water, especially from the Hooghly River, pose serious risks to crops and soils (Okeke *et al.*, 2024) ^[8].

Baride *et al.* (2014) ^[3] also reported that the discharge of untreated industrial and municipal waste in parts of Jalgaon District significantly increased heavy metal contamination in both surface and groundwater. The contamination of the Hooghly River in this study mirrors such findings, where the unchecked industrial waste discharge elevates heavy metal concentrations, leading to potential contamination of the food chain. The elevated Fe levels (up to 8.64 mg/L) in Musi river water are comparable to the findings of Mahakalkaret *et al.* (2013) ^[10], where high concentrations of Fe and Zn were also observed in Nag River water, underscoring the widespread nature of this problem.

Heavy Metal Contamination in Soil

The significant accumulation of heavy metals in soils irrigated with wastewater, as observed in this study, echoes the findings of Rangnekar (2013) ^[14], who studied Pb and Cd uptake in vegetables grown in contaminated soils in Mumbai. The research indicated that even nutritionally important vegetables, such as spinach, can absorb large amounts of these metals, particularly in their roots and leaves. In the present study, the high Pb concentration in soils irrigated with Hooghly River water (16.8 mg/kg) supports Rangnekar's conclusion that soils irrigated with wastewater can lead to dangerous levels of heavy metals in edible crops.

The high concentration of Zn and Cu in soils irrigated with wastewater has also been confirmed by E. Swapna Priya *et al.* (2014) ^[15], who studied soils in Hyderabad irrigated by Musi River. Their findings revealed similar patterns of Zn and Pb accumulation in the soil, as was observed in this study (Zn: 28.5 mg/kg in Hooghly River soils). These metals, when present in excessive amounts, disrupt soil health, impede nutrient uptake by plants, and contribute to long-term soil degradation. This study confirms these findings, as soils irrigated with Musi and Hooghly river water showed Zn and Pb concentrations exceeding the recommended levels set by FAO/WHO.

The bioavailability of these metals in the soil is also influenced by soil properties. For example, the pH and organic matter content of the soil can affect the uptake of heavy metals. In agreement with findings from N. Gupta *et al.* (2012) ^[6], it is clear that long-term wastewater irrigation increases the concentration of heavy metals in soil, which, in turn, can lead to increased bioavailability to plants. These studies collectively emphasize the importance of monitoring

soil quality and implementing soil remediation strategies to mitigate the impact of heavy metal contamination.

Heavy Metal Bioaccumulation in Vegetables

The accumulation of heavy metals in vegetables in the current study aligns with global trends of heavy metal uptake in crops irrigated with contaminated water. Ajmal Khan *et al.* (2021) ^[1] studied vegetables grown in peri-urban areas of Lahore and reported elevated levels of Cu, Mn, and Pb, particularly in leafy vegetables like spinach and fenugreek, which is consistent with the current findings. The high concentration of Pb (2.41 mg/kg) and Zn (18.32 mg/kg) in spinach grown with Hooghly River water far exceeded the safe limits, posing severe health risks to consumers. This is supported by the work of N. Gupta *et al.* (2012) ^[6], who also found high levels of Pb and Cd in leafy vegetables grown in wastewater-irrigated soils along the Hooghly River.

The bioaccumulation of metals in leafy vegetables is especially concerning, as these crops are consumed directly and frequently. Gupta *et al.* (2013) ^[5, 10] found that spinach and coriander had the highest tendency to accumulate heavy metals, particularly Cu and Zn. The current study's results corroborate these findings, as spinach grown with Hooghly River water showed the highest concentrations of heavy metals among the vegetables sampled. Additionally, the pattern of higher metal accumulation in leaves compared to roots or fruits, as observed in the present study, reflects findings by Fiona Marshall *et al.* (2003) ^[9], who reported elevated heavy metal concentrations in leafy vegetables collected from markets in Delhi.

The discrepancy between metal concentrations in soil and their levels in plant tissues can be attributed to the specific uptake mechanisms of different plant species. As indicated by the studies of Gopal Krishna *et al.* (2020) ^[7], metal uptake varies based on plant species, soil conditions, and the concentration of metals in the irrigation water. While Zn and Cu are essential micronutrients, their excessive presence can lead to toxicity in both plants and consumers. The translocation of heavy metals from roots to edible parts of the plant, particularly in leafy vegetables, is an important factor in understanding the health risks posed by consuming contaminated produce.

Health Implications and Environmental Risks

The presence of heavy metals in food crops is a serious concern due to their toxicity, persistence, and bioaccumulation in the food chain. As emphasized by Charu Jhamaria *et al.* (2015) ^[4], the long-term exposure to heavy metals such as Pb, Cd, and Cr through the consumption of contaminated vegetables can lead to chronic health conditions, including neurological damage, kidney disease, and cancer. In the present study, the concentrations of Pb and Cd in spinach and fenugreek exceeded WHO/FAO permissible limits, thereby heightening the risk of heavy metal toxicity in consumers.

Moreover, the environmental risks associated with the continuous use of wastewater for irrigation are profound. Long-term contamination of soils can lead to decreased agricultural productivity and soil fertility. The studies by Labhade (2013) ^[16] and Swapna Priya *et al.* (2014) ^[15] highlight that once heavy metals accumulate in soils, they are difficult to remove, thus requiring expensive and resource-intensive remediation processes. The current

findings reinforce the urgent need for better wastewater management practices to prevent further contamination of agricultural systems.

Conclusion

The present study provides clear evidence of the detrimental effects of industrial wastewater irrigation on the accumulation of heavy metals in water, soils, and vegetables. The high Pb, Zn, Cu, and Fe concentrations in both soil and crops confirm the long-term risk posed by industrial pollutants entering agricultural systems. Comparing these findings with prior studies further emphasizes the need for immediate intervention to prevent the further contamination of crops and protect public health. It is crucial to implement wastewater treatment systems, promote soil remediation strategies, and educate farmers on the dangers of using untreated wastewater for irrigation.

Conflicts of Interest

The authors declare no conflicts of interest.

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