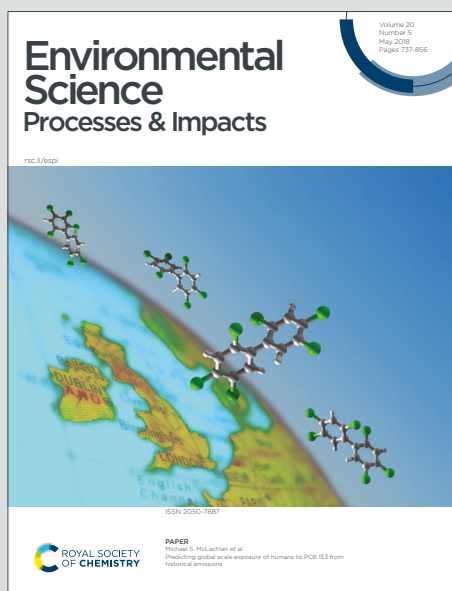


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Environmental significance statement

Heavy metal contamination of vegetables irrigated with wastewater is a critical environmental and public health issue in developing Asian countries. Understanding this problem is crucial for ensuring food safety and sustainable agriculture in water-scarce regions. This review reveals widespread contamination of vegetables with toxic metals like cadmium, lead, and arsenic, often exceeding international safety standards. Leafy vegetables consistently show higher accumulation compared to other types. Health risk assessments indicate potential carcinogenic and non-carcinogenic risks from chronic dietary exposure. These findings highlight the urgent need for improved wastewater treatment, agricultural practices, and regulatory enforcement to mitigate risks. Insights gained can inform integrated policies and interventions to balance water scarcity, agricultural productivity, and public health across developing regions facing similar challenges globally.



Heavy Metal Contamination in Wastewater-Irrigated Vegetables: Assessing the Food Safety Challenges in Developing Asian Countries

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Abstract

Vegetables are crucial for human nutrition, providing essential micronutrients and beneficial compounds. Heavy metal contamination of vegetables irrigated with wastewater poses a significant public health risk in developing Asian countries. This review analyses recent research on Heavy metal accumulation in vegetables across India, Bangladesh, Pakistan, and China. Studies consistently report concerning levels of cadmium, lead, chromium, arsenic, nickel, and mercury in vegetables, often exceeding international safety standards. Leafy vegetables consistently show higher heavy metal accumulation compared to fruit and root vegetables. Within plant structures, roots generally contain higher heavy metal concentrations than edible parts, though this varies by metal and plant species. Many studies report health risk indices exceeding safe limits, indicating potential non-carcinogenic and carcinogenic risks from chronic dietary exposure, with children at higher risk. The review highlights inadequate regulatory frameworks and enforcement mechanisms. A multi-faceted approach is urgently needed, encompassing improved wastewater treatment, best

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agricultural practices, rigorous monitoring, and public awareness campaigns. Future research directions are identified, including long-term health impact studies, development of cost-effective remediation techniques, and exploration of sustainable alternatives to wastewater irrigation. While wastewater irrigation addresses immediate water scarcity, it poses significant long-term food safety and public health risks. Integrated policies balancing water scarcity, agricultural productivity, and health risks are essential. This review underscores the pressing need for coordinated efforts from policymakers, researchers, and health officials to safeguard public health and ensure sustainable agriculture in developing Asian countries facing increasing urbanization and water scarcity.

Keywords: *vegetables, waste water, Heavy metals, irrigation, contamination, Asian countries*

1. Introduction

Vegetables are essential to human nutrition, providing vital micronutrients and other beneficial compounds ¹. These include minerals such as iron, sodium, copper, magnesium, zinc, calcium, iodine, and potassium, as well as vitamins, antioxidants, and important metabolites ^{2,3}. People consume vegetables both in their raw state and after cooking⁴. However, if vegetables contain toxic metals, they may present serious health hazards to consumers ⁵. Research has extensively documented heavy metals (HMs) contamination in food chains worldwide ⁶⁻⁹. Plants can absorb HMs from the soil, often accumulating them at higher concentrations than found in their environment ¹⁰⁻¹². Primary factor contributing to this metal buildup in plants is the presence of HM pollutants in the soil ^{13,14}.

Globally, wastewater production is estimated at 359.4 billion m³ per year, with South Asia contributing approximately 25.6 billion m³ - just 7% of the global total despite hosting around 24% of the world's population ¹⁵. In India, the estimated wastewater generation in 2020–21 was approximately 14.46 billion m³ per year in rural areas and 26.41 billion m³ per year in urban centers, totaling about 40.8 billion m³ per year ^{16,17}. A 2002 report stated that Pakistan produces an estimated 4.369 billion m³ of wastewater annually, comprising 3.060 billion m³ from municipal and 1.309 billion m³ from industrial sources ¹⁸. In Bangladesh, annual domestic and industrial wastewater generation is approximately 4.87 billion m³ and 0.45 billion m³, respectively ¹⁹. China

discharged 55.7 billion m³ of wastewater in 2021, of which 28.7% originated from industrial sources²⁰. While data vary across years and sources, they collectively highlight the substantial and growing volume of wastewater in developing Asian countries. Thus, urbanization and industrialization in many developing Asian nations have led to the proliferation of waste water irrigation for agricultural purposes, particularly in peri-urban areas^{21–26}. This led to the accumulation of HMs in farmlands, which can then be absorbed by vegetable crops, posing a serious health hazard to consumers^{25,27–29}.

Toxicity of food due to HM contamination poses a serious threat to human wellbeing and is a significant food safety problem globally (Rehman et al., 2018). HMs can be classified depending on their toxicity levels into low toxicity (Mo, Mn, Fe)^{31,32}, Average toxicity (Zn, Cr, Cu, W, Co, V, Ni)³³ and high toxicity (As, U, Pb, Sb, Hg, Cd, Ag)³⁴. While some trace elements like iron, manganese, zinc, and copper are vital nutrients for plants and animals with lower health risks at elevated levels, others such as cadmium, nickel, arsenic and lead can be detrimental even in small amounts^{5,35,36}. Ingesting these metals beyond safe thresholds can potentially harm human and animal well-being^{37,38}. Plants, particularly vegetables, absorb these elements through their root systems, leading to accumulation in different tissues³⁹. Excessive intake of such metals by humans and animals can result in various health issues, including disrupted endocrine function, cancer, skeletal damage, and impairment of the circulatory, nervous, excretory and cardiovascular systems^{40,41}. The persistent nature of HMs, their extended biological presence, and high potential for uptake and bioaccumulation make them particularly dangerous to all living organisms, including humans⁴². Prolonged exposure to toxic metals through dietary sources, even in minute quantities, is believed to cause gradual buildup in the hepatic and renal systems of humans, livestock, and bird species^{43,44}.

The quality of irrigation water is a crucial factor, as sewage⁴⁵ or industrial waste water^{46,47} often contains much higher concentrations of HMs, such as mercury, arsenic, chromium, nickel, zinc, lead, copper and cadmium, compared to clean water⁴⁸. Approximately 11% of global cultivated land is irrigated using untreated wastewater⁴⁹. Furthermore, an estimated 10% of the world's population consumes produce grown with wastewater irrigation⁵⁰. Due to its high content of organic matter and nutrients, wastewater is often utilized in agriculture as a method of wastewater management⁵¹.

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While HMs concentration in wastewater is typically low and often within acceptable limits, prolonged irrigation with wastewater has led to an increase in HM levels in soil over time ^{52,53}. Consequently, farmlands irrigated with this contaminated water over extended periods have become heavily polluted with HMs, which are then taken up by the vegetables grown in these soils. HMs uptake by plants from soil is affected by multiple factors ⁴⁵. These include nature of the metal sources, seasonal variations, loading rates, soil pH levels, oxidation-reduction potential, soil composition, organic content, various forms of bioavailable metal fractions, and overall metal concentrations in the soil ^{2,54}

The global context of this issue cannot be overstated. However, the situation in developing Asian countries is particularly acute due to a confluence of factors. Rapid industrialization, coupled with inadequate waste management infrastructure and often lax environmental regulations, has exacerbated the problem in these nations ⁵⁵. The United Nations' Sustainable Development Goals define food security as a state where every individual has consistent access to adequate and safe nutrition for a healthy, active lifestyle ⁵⁶. However, developing countries like India often prioritize increasing food quantity and access in their efforts to achieve food security, often overlooking practices that ensure food quality and safety. These include cultivating crops on polluted land and irrigating with untreated wastewater that could alter food composition. Such practices risk introducing non-essential elements and harmful substances into the food supply ⁵⁷. The production of fruits and vegetables has been on the constant rise as shown in figure 1, but the quality of such vegetables due to the use of wastewater has declined. Addressing HM contamination in vegetables is not just a matter of environmental concern but is crucial for achieving sustainability goals and ensuring food security and public health in developing regions.



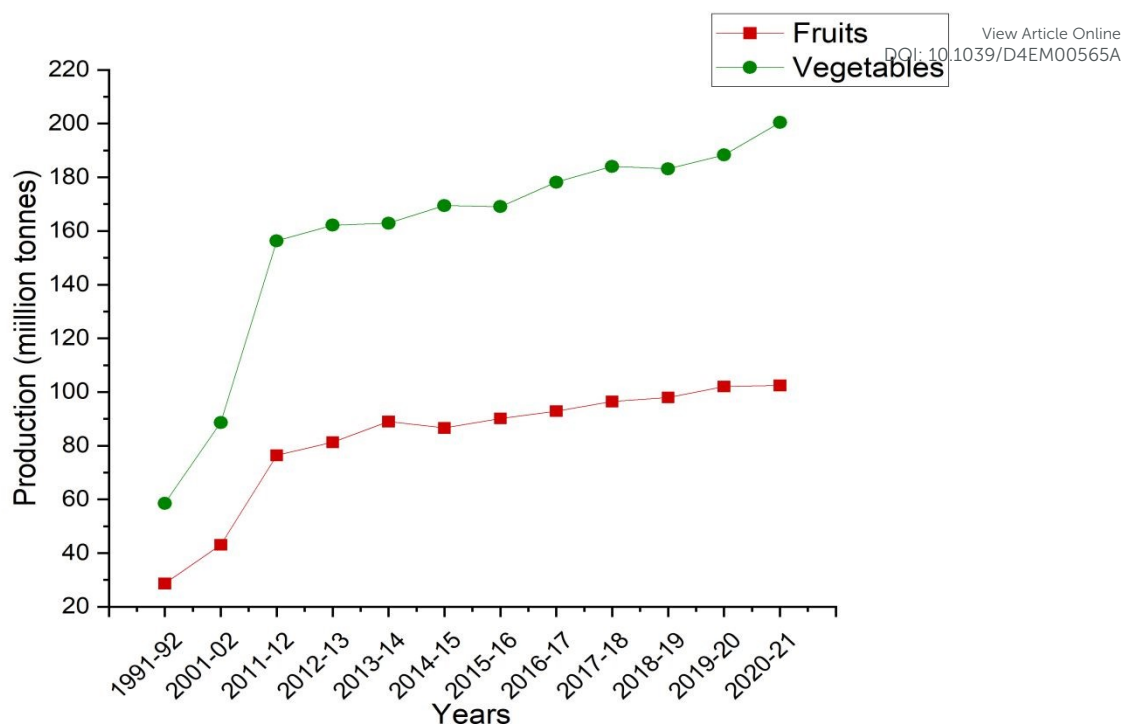


Figure 1: Year Wise Increase in Production of Fruits and Vegetables ⁵⁸

The World Health Organization (WHO) has established safety guidelines for maximum permissible concentration of HMs in various edible items, including vegetables ^{59,60}. These guidelines serve as a global benchmark for food safety. However, numerous studies conducted in wastewater-irrigated areas have reported that vegetables grown in these conditions often exceed these safety limits ^{34,61}. This widespread non-compliance with international safety standards raises serious concerns about the long-term health impacts on consumers who rely on these vegetables as a staple part of their diet.

There are various sources of HM contamination of agricultural fields as shown in figure 2, of which HMs usually enter through irrigation with contaminated water. The use of wastewater for irrigation in developing Asian countries is driven by a complex set of factors that highlight the challenging trade-offs between immediate agricultural needs and long-term health and environmental concerns ^{29,62,63}. Water scarcity is a primary driver, with many regions facing severe shortages that make wastewater an attractive alternative for irrigation. Additionally, wastewater often contains high levels of nutrients, which can enhance crop yields and reduce the need for chemical fertilizers ⁶⁴. Farmers favour wastewater irrigation for its nutrient content and constant availability ⁶⁵. This nutritional benefit makes wastewater irrigation an economically attractive option for many small-scale farmers who view it as a free or low-cost irrigation source. In

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some peri-urban areas, wastewater may be the only readily available water source for irrigation, leaving farmers with little choice but to use it despite the potential risks⁶⁶. While wastewater irrigation offers these apparent benefits, it also presents significant risks, particularly in terms of HM contamination. Balancing these competing interests poses a significant challenge for policymakers and agricultural practitioners in developing Asian countries.

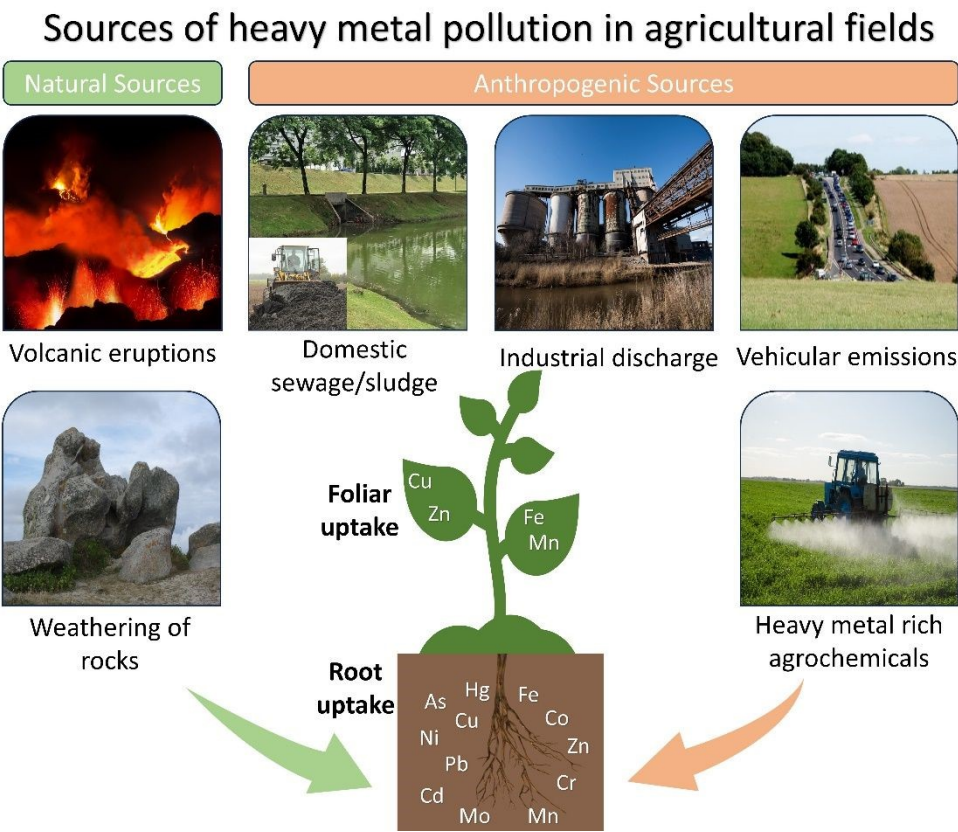


Figure 2: Different sources of HM pollution in agricultural fields. All the images used in the figure are re-used under the terms of creative commons license CC BY 2.0 <https://creativecommons.org/licenses/by/2.0/>^{67–73}

The bioaccumulation of these metals in vegetables is not a straightforward process but depends on a variety of factors. Soil properties play a crucial role, with factors such as clay content, cation exchange capacity, organic matter content, and pH all influencing the bioavailability of HMs⁷⁴. Different vegetable species have varying capacities for uptake of HMs and their translocation. In general, compared to fruit vegetables, leafy vegetables like spinach and lettuce tend to acquire higher quantities of HMs²¹. Vegetables accumulate varying levels of HMs based on agronomic conditions and farming practices. These diverse products converge in common markets across villages,

towns, and cities, potentially exposing unsuspecting consumers to significant health risks⁴²

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The duration of irrigation with wastewater is another critical factor. Long-term usage of wastewater for irrigation leads to increased accumulation of HMs in soils and, consequently, in vegetables⁵⁷. The source of wastewater also plays a significant role, with industrial effluents typically containing higher concentrations of HMs compared to domestic wastewater⁵⁷. Climate and environmental factors, including temperature, rainfall, and atmospheric deposition, can influence HM mobility and uptake⁶⁴. Additionally, agronomic practices such as the use of fertilizers and pesticides can affect HM dynamics in soil-plant systems⁷⁵.

Current status of HM contamination in vegetables due to wastewater irrigation varies across developing Asian countries but they share common challenges, including rapid urbanization, inadequate wastewater treatment infrastructure, and the need to balance food security with environmental and health concerns.

By identifying knowledge gaps and proposing future research directions, this review seeks to enhance our understanding and management of HM contamination in vegetables grown using wastewater irrigation in developing Asian countries. By evaluating the extent of contamination across different vegetables and geographic regions, the review seeks to identify patterns and trends that can inform targeted interventions. Assessing the associated health risks based on reported contamination levels and established safety standards is crucial for prioritizing public health measures. This review holds significant implications for various stakeholders. Policymakers can use the findings to inform the development and refinement of food safety regulations, environmental protection policies, and urban planning strategies to minimize the risks associated with wastewater irrigation. By addressing the critical issue of HM contamination in vegetables grown using wastewater irrigation, this review contributes to the broader goals of ensuring food security, promoting public health, and advancing sustainable agricultural practices in developing Asian countries.

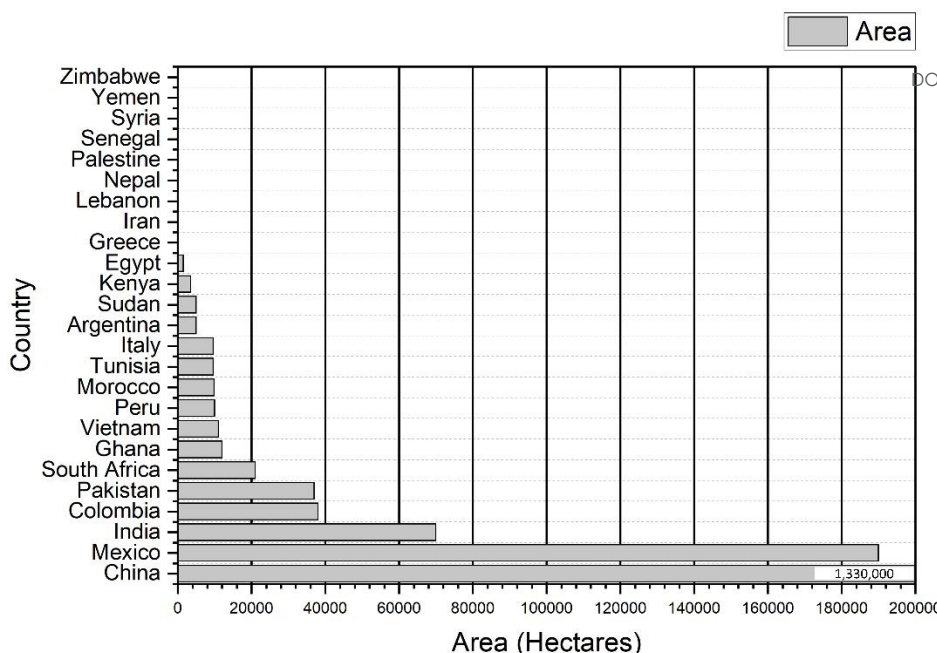


Figure 3: Area Under Waste Water Irrigation in Developing Countries of Asia ⁷⁶

2. Heavy metal determination in various vegetable samples

The determination of HMs in vegetable samples from developing Asian countries has highlighted both the prevalence of these contaminants and the methodologies employed for their detection. Studies conducted in countries such as India, Bangladesh, Pakistan, and China have focused on urban and peri-urban areas, agricultural regions, and industrial zones, reflecting a comprehensive approach to understanding the extent of HM contamination. In these studies, various digestion methods were employed to prepare vegetable samples for analysis. The most commonly used method involved nitric acid (HNO₃), either alone or in combination with other acids like hydrofluoric acid (HF), sulfuric acid (H₂SO₄), perchloric acid (HClO₄), and hydrochloric acid (HCl). The analysis of digested samples predominantly used Atomic Absorption Spectroscopy (AAS), Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) whereas Atomic Fluorescence Spectroscopy (AFS), Atomic Fluorescence Morphological Analyzer (AFMA) and Automatic Mercury Analyzer (AMA) were rarely used. These were used to identify various HMs such as Aluminum (Al), Arsenic (As), Boron (B), Cadmium (Cd), Chromium (Cr), Cobalt (Co), Copper (Cu), Iron (Fe), Lead (Pb), Manganese (Mn), Mercury (Hg), Molybdenum (Mo), Nickel (Ni), Selenium (Se), and Zinc (Zn).

A wide variety of vegetables were analyzed across these studies, with spinach, tomato, cabbage, radish, and brinjal being the most frequently tested. These vegetables, commonly consumed in the regions studied, serve as key indicators of HM contamination due to their varying abilities to absorb and accumulate metals from the soil. Results obtained from these studies are listed in Table 2 and discussed in the following sections.

Table 1: Sampling sites and processing methods for HM analysis of vegetables in developing Asian countries.

Country	Sampling Site	Vegetables Analyzed	Digestion	Analysis Method (Metals)	Metals Detected	References
India	Bangalore, Karnataka	Spinach, Coriander	HNO ₃ +H ₂ O ₂ (20:1)	AAS	Pb, Cu, Zn, Cd, Cr, Mn	77
	Nashik, Maharashtra	Coriander, Spinach, Onion, Cauliflower, Brinjal, Cabbage, Tomato, Cucumber, Potato, Carrot	HNO ₃ +H ₂ SO ₄ +HClO ₄ (5:1:1)	AAS	Pb, Cd, As, Cu	78
	Dehradun, Uttarakhand	Beet, French Bean, Spinach, Cauliflower	HNO ₃ +HClO ₄ (2:1)	AAS	Pb, Ni, Zn, Cd, Cu, Cr	79
	Patna, Bihar	Spinach, Red Spinach, Bean, Okra, Cabbage, Cauliflower, Beetroot	HNO ₃	AAS	Hg, Zn, Pb, Cu, Mn	80
	Haridwar, Uttarakhand	Spinach	HNO ₃ +HClO ₄ (4:1)	AAS	Zn, Mn, Fe, Cd, Cr, Cu	81
	Jhansi, Uttar Pradesh	Spinach, Fenugreek, Brinjal, Green Chili	HNO ₃ +HClO ₄ (3:1)	AAS	Zn, Pb, Mn, Ni, Cu, Co, Cd	82
	Lucknow, Uttar Pradesh	Tomato, Spinach, Cucumber, Cabbage, Green Pepper, Mint, Bitter Gourd, Beet Root, Cauliflower	HNO ₃ +HClO ₄ (2:1)	ICP-OES	Cr, Cd, Pb, Ni, Cu, Co, Zn, Mn, Fe	42
	New Delhi (Urban And Peri-Urban Areas)	Spinach, Mustard, Okra, Tomato, Carrot, Potato	HNO ₃ +HClO ₄ (5:1) and HNO ₃ +H ₂ SO ₄ (4:1) for Hg	ICP-OES	As, Cd, Cr, Pb, Hg	63
	Lucknow (Peri-Urban Regions), Uttar Pradesh	Tomato, Spinach	HNO ₃ +HClO ₄ (2:1)	ICP-OES	Ni, Pb, As, Cr, Cd	83
	Faridabad (Agra Canal), Haryana	Spinach, Radish, Coriander, Garlic	HClO ₄ +HNO ₃ +HClO ₄ (5:1:1)	ICP-OES	As, Pb, Cr, Mn, Cu, Zn, Ni	84
	Solapur, Maharashtra	Cabbage, Carrot, Fenugreek, Garlic, Ginger, Potato, Radish, Onions, Sorghum, Sugarcane, Apple, Brinjal, Broad Beans, Chick Pea, Cucumber, Cream Beans, Green Peas, Mung Beans,	HNO ₃ +HCl+H ₂ O ₂	ICP-MS, Automatic Mercury	Pb, Cd, As, Hg	85

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		Okra, Orange, Papaya, Red Gram, Tamarind, Tomatoes		Analyze r		
	Bhadohi, Uttar Pradesh	Spinach, Radish, Garlic, Cabbage, Brinjal	HNO ₃ +HClO ₄ (9:4)	AAS	Zn, Cu, Cd, Ni, Cr	86
	Ladakh	Spinach, Cabbage	HNO ₃ +HClO ₄ +HCl	ICP-OES	Zn, Se, Pb, Fe, Cu, Co, Cd, B, Al, As	87
	Prakasam, Andhra Pradesh	Potato, Amaranthus	HNO ₃ +H ₂ O ₂ (2:1)	ICP-MS	Cr, As, Cd, Hg, Pb	88
	Delhi & Dehradun (Urban And Peri-Urban Areas)	Tomato, Potato, Onion, Okra, Cabbage, Cauliflower, Spinach	HNO ₃ +H ₂ O ₂ (2:1)	ICP-MS, Automatic Mercury Analyzer	Co, Mo, Mn, Cu, Zn, Se, As, Ni, Hg, Cr, Cd, Pb	89
	Lucknow (Peri-Urban Regions), Uttar Pradesh	Tomato, Spinach	HNO ₃ +HClO ₄ (2:1)	ICP-OES	Cu, Fe, Zn, Mn, Co	90
	Bokaro, Jharkhand	Cabbage, Indian Spinach, Tomato, Radish, Carrot, Onion	HNO ₃ +HClO ₄ (5:1)	AAS	Cd, Pb, Hg, As, Cr	91
	Yamuna Floodplain, New Delhi	Radish, Brinjal, Cauliflower, Spinach	HNO ₃ +HF (5:1)	AAS	Zn, Mn, Co, Ni, Pb, Cr	92
	Kolkata, West Bengal	Red spinach, Mustard, Fenugreek, Pok choi, Coriander, Bathua, Spinach, Capsicum, M. spinach, Lettuce, Green amaranthus	HNO ₃ +H ₂ O ₂ +HCl (15:5:1)	ICP-MS	Pb, Cd, Ni	93
Bangladesh	Jessor District	Bottle Ground, Taro, Drumstick Leaf, Stem Amaranth, Brinjal, Ash Gourd, Snake Gourd, Elephant Foot, Potato, Okra, Eddoe, Plantain, Green Papaya, Ghotkol, Indian Spinach	HNO ₃	ICP-AES, ICP-MS	As, Cd, Cu, Pb, Zn	94
	Dhaka Export Processing Zone	Green Cabbage, Brinjal, Chilli, Okra, Tomato	HNO ₃ +H ₂ SO ₄ +HCl O ₄ (5:1:1)	AAS	Zn, Pb, Cr, Cd, Fe, Ni, Cu	95
	Chittagong	Green Arum Leaves, Jute Leaves, Water Spinach, Bottle Gourd, Wax Gourd, Sweet Gourd	HNO ₃ +H ₂ SO ₄ +HCl O ₄ (5:1:1)	AAS	Chromium, Copper, Lead	96
	Pakshi, Pabna	Potato, Red Amaranthus, Spinach, Amaranthus, Carrot, Cabbage, Tomato, Brinjal	HNO ₃	AAS	Ni, Cr, Cd, Co, Cu, Pb, Fe, Zn, Mn, Hg, As	97
	Savar Upazila, Dhaka	Stem Amaranth, Green Papaya, Indian Spinach, Red Amaranth, Radish, Bottle Gourd, Pointed Gourd, Coriander, Jute	HNO ₃ +H ₂ O ₂ (9:1)	AAS	Pb, Ni, As	98

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Pakistan	Dhaka Metropolitan City Area	Lettuce, Cucumber, Tomato, Coriander	HNO ₃	AAS	Pb, Cd, Cr	99 View Article Online DOI: 10.1039/D4EM00565A
	Tangail	Indian Spinach, Sponge Gourd, Bitter Gourd, Bottle Gourd, Okra, Papaya, Bean, Brinjal, Chili, Cucumber	HNO ₃ +H ₂ O ₂ (3:1)	ICP-MS	Pb, Cd, As, Cu, Ni, Cr	100
	Dhaka (Buriganga River)	Red Amaranth, Spinach, Jute, Bottle Gourd, Mustard Green, Water Spinach	HNO ₃ +H ₂ O ₂ (3:1)	AAS	Cd, Cr, Cu, Ni, Pb, Zn	101
	Savar Upazila, Dhaka	Brinjal, Lady's Finger, Water Spinach, Red Spinach, Green Spinach	HNO ₃ +H ₂ SO ₄ +HCl O ₄ (5:1:1)	AAS	As, Mn, Ni, Cd, Pb, Fe, Cu	102
	Dhaka-Mymensingh Highway	Bottle Gourd, Esculent, Papaya	HNO ₃ +HClO ₄ (5:1)	AAS	Fe, Mn, Cu, Zn, Cd, Pb, Cr, Ni	103
	Gujranwala	Cauliflower, Bitter Gourd, Radish, Pumpkin, Applegourd	HNO ₃ +HClO ₄ +HCl	AAS	Cd, Ni, Cr, Pb, Mn, Fe, Cu, Zn	104
	Sargodha District	Spinach, Mustard, Coriander, Mint, Fenugreek, Lettuce, Chenopodium, Carrot, Radish, Beetroot, Turnip	Wet Digestion	AAS	Fe	105
	Mingora Swat	Okra, Onion, Green Pepper, Pumpkin	HNO ₃ +HCl (1:3)	AAS	Fe, Pb, Cr, Ni, Mn, Co	106
	Khyber Pakhtunkhwa Region	Cauliflower, Tinda, Spinach, Cabbages, Carrot, Taro, Radish, Turnip, Lettuce	HNO ₃ +H ₂ SO ₄ +HClO ₄ (5:1:1)	AAS	Pb, Cu, Zn, Ni, Cd, Cr, Fe, Mn	107
	Lahore	Spinach, Mustard, Radish, Green Bean, Carrot, Potato	HNO ₃ +HCl (3:1)	ICP-OES	As, Cd, Pb	108
Pakistan	Vehari	Cauliflower, Round Gourd, Fenugreek, Lucerne, Carrot, Spinach, Radish, Turnip, Mustard, Cabbage, Pea, Coriander, Onion, Brinjal	HNO ₃ +HClO ₄	AAS	As, Cr, Cd, Cu, Fe, Ni, Mn, Pb, Zn	109
	Punjab	Spinach, Mustard Leaves, Lettuce, Tomato, Radish, Cabbage, Okra, Onion, Chilli, Brinjal, Bottle Gourd (Round), Garlic, Fenugreek, Cauliflower, Zucchini, Mint, Coriander, Potato, Sugarbeet, Turnip	HNO ₃ +H ₂ SO ₄ +HCl O ₄ (10:1:4)	AAS	Ni, Cd, Pb, Cr	110
	Bhakkar	Spinach, Cabbage, Cauliflower, Turnip, Radish, Taro, Wax Gourd, Carrot, Lettuce	HNO ₃ +H ₂ SO ₄ +HClO ₄ (5:1:1)	AAS	Fe, Pb, Mn, Ni, Cd, Co	111
	Kirri Shamozai	Lettuce, Carrot, Tinda, Radish, Turnip, Cabbage, Spinach	HNO ₃ +H ₂ SO ₄ +HClO ₄ (5:1:1)	AAS	Zn, Mn, Cu, Fe, Pb, Cd, Ni, Cr	112
	Dera Ghazi Khan, Punjab	Brinjal, Red Corn, White Corn, Tomato, Luffa, Apple Gourd, Cabbage, Spinach	HNO ₃ +H ₂ SO ₄ +HClO ₄ (5:1:1)	AAS	Cu, Fe, Zn, Ni, As, Cd, Cr, Mn, Pb	113
	Layyah, Punjab	Radish, Turnip, Spinach, Fenugreek, Carrot	Wet Digestion	AAS	Cd, Zn, Fe	114

	Sargodha District	Cauliflower	HNO ₃ +H ₂ O ₂	AAS	Pb, Cu, Co, Mn, Ni, Cd, Cr, Zn, Fe	115
	Faisalabad And Multan	Spinach, Lettuce, Cabbage, Cauliflower, Okra	HNO ₃ +HClO ₄ (3:1)	AAS	Cd, Pb	116
	Sargodha	Carrot, Cauliflower, Pea, Potato, Radish, Spinach	HNO ₃ +Aqua regia (70% Conc. HNO ₃ and 65% HClO ₄ ; 2:1) (1:3)	AAS	Pb	117
	Bahawalpur	Cauliflower, Cabbage, Brinjal, Green Chilli, Turnip, Spinach, Potato, Radish, Carrot, Radish Pods	HNO ₃ +H ₂ SO ₄ + HClO ₄ (5:1:1)	AAS	As, Cd, Cr, Pb, Ni	118
China	Pearl River Delta, South China	Chinese Leaf Mustard, Loose-Leaf Lettuce, Pakchoi, Chinese Cabbage, Lettuce	HNO ₃ +HClO ₄ +H ₂ O ₂ (87:13:10)	AFMA, AAS	Hg, As, Pb, Cr, Cd	119
	Chenzhou City, Suxian District	White Radish, Carrot, Sweet Potato, White Caitai, Red Caitai, Brinjal, Red Pepper, Tomato, Bitter Gourd, Towel Gourd, Cucumber, Pumpkin, Mater Convolvulus, Edible Amaranth, Cabbage, Pai-Tsai, Chinese Cabbage, Spinach, Caraway, Lettuce, Asparagus Bean, Kidney Bean	Dry Ashing Method	ICP-OES, AFS	As, Zn, Cu, Cd, Pb	36
	Xi River, Shenyang City, Northern China	Cabbage, Coriander, Chlorella, Lettuce, Chinese Lettuce, Asparagus Leaves, Celery, Spinach, Radish, Tomato	Boiled With HNO ₃	ICP	Cd, Cu, Pb, Zn	120
	Baiyin City, Gansu Province	Carrot, Potato, Chinese Cabbage, Spinach, Shallot, Chinese Chives, Cabbage, Celery, Chinese Lettuce, Garland Chrysanthemum, Coriander, Leafy Lettuce, Rape, Cucumber, Kidney Bean, Pepper, Winged Bean, Brinjal, Zucchini, Tomato	HNO ₃ +H ₂ O ₂ (8:1)	ICP-MS	Zn, Pb, Cu, Cr, Cd, As	121

3. Contamination of vegetables irrigated with waste water in India

Several recent studies have highlighted the concerning levels of HM pollution in vegetables that are irrigated with wastewater in different parts of India. A study conducted in Jhansi, North India found that vegetables irrigated with wastewater/grown near industrial area, particularly leafy varieties: spinach and fenugreek, accumulated hazardous levels of cadmium, manganese, and lead. The target hazard quotients for these metals exceeded unity, indicating significant non-carcinogenic health risks for regular consumers⁸². Research in peri-urban and urban areas of Delhi analyzed six vegetables for 5 HMs (Pb, Hg, Cr, Cd and As). The study found that Cd concentrations exceeded permissible levels in most vegetables, with spinach and okra showing the

highest metal pollution index and transfer factor values ⁶³. Similarly, another Research in peri-urban and urban areas of Delhi and Dehradun revealed ubiquitous presence of toxic elements like cadmium and lead in vegetables, often exceeding permissible limits set by World Health Organization (WHO) and the Food and Agriculture Organization (FAO). Vegetables, especially spinach and okra, were identified as major contributors to dietary exposure of HMs. Cadmium and lead levels in vegetables, particularly in spinach samples, were found to be dangerously high. The health risk assessments concluded that children are at a higher risk compared to adults, with vegetables being the primary contributors to this risk ⁸⁹. Another research conducted in peri-urban regions of Lucknow city found that while HM levels in irrigation water and agricultural soil were within permissible limits, they exceeded these limits in vegetables. Iron levels were particularly high, being 5 to 60 times above permissible limits in almost all samples. The hazard index values for vegetables from all studied peri-urban areas were found to be more than 1 (threshold level), indicating probable adverse non-carcinogenic health hazards ⁹⁰.

Vegetables watered with untreated wastewater had a notable buildup of HMs, according to a study conducted on the Agra Canal in Faridabad. The metals were ranked according to the extent of accumulation as $Mn > Zn > Ni > Cu > Cr > Pb > As$. Metal bioaccumulation varied considerably between leafy and non-leafy vegetables. The health risk index for manganese, nickel, and lead was above 1, indicating significant health hazards for consumers of these wastewater-irrigated vegetables ⁸⁴. A study found that vegetables in the Yamuna River floodplain in Delhi had varying degrees of trace element contamination; leafy vegetables had higher concentrations of Mn, Co and Ni, while fruit and inflorescence vegetables had higher levels of Pb, Zn and Cr. It also found that the highest translocation efficiency from soil to vegetables was for Cr. Most significantly, the research indicated potential carcinogenic risks due to consumption of all studied vegetables, with higher carcinogenic and non-carcinogenic risks for cauliflower and brinjal ⁹². Significant HM contamination was found in the soil, vegetables, and grain crops near the Bokaro thermal power station in Jharkhand. The study discovered that the levels of Cd and Pb in every vegetable and grain crop sampled were higher than allowed. Cd had the highest transfer factor for HMs due to its great mobility. Adults were at significant risk for non-carcinogenic health problems due to high concentrations of Cr, Cd and Pb in grain crops and vegetables. Moreover,

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carcinogenic risks for adults were identified due to Pb and Cr ⁹¹. A study focusing on areas receiving untreated wastewater from carpet industries in northern India revealed high concentrations of HMs in irrigation water, crops and soils. Notably, Cd levels in all tested vegetables exceeded both national and international safety limits ⁸⁶.

A study carried out in the industrialised city of Solapur, Maharashtra, examined the presence of HMs in twenty-four distinct varieties of fruits and vegetables. Varying levels of Pb, Cd, As, and Hg were found, with vegetables generally showing higher metal accumulations than fruits. Garlic and potato were identified as having the highest HM accumulation. Concerningly high human health risk index values were found in several vegetables, indicating possible negative health impacts from their consumption ⁸⁵. A comprehensive study conducted across a 100 km radius around Lucknow, India, revealed significant contamination of toxic HMs (Cd, Cr, Pb, Ni) and metalloid (As) in vegetables. Notably, the edible parts of vegetables contained significantly higher levels of these elements than the maximum allowable concentration. The study highlighted a high bioaccumulation factor for Cd and Ni, indicating their entry into the food chain primarily through contaminated irrigation water. Although ecological risk indices showed moderate risk, As, Ni, Cd and Cr showed high carcinogenic risk factors, suggesting potential long-term health hazards for consumers ⁸³. A study in Haridwar, India, focused on the impact of integrated industrial wastewater irrigation on spinach cultivation. While integrated industrial wastewater irrigation increased crop yield and growth, it also led to greater build-up of HMs in spinach tissues. Prediction models based on soil characteristics were developed to evaluate HM uptake by spinach, which could be valuable for policymakers in formulating guidelines for controlled irrigation using industrial effluents ⁸¹.

Another study in Kolkata revealed high levels of Pb, Cd, and Ni in commercially grown vegetables from 8 zones irrigated with wastewater and affected by solid waste dumping. Leafy vegetables—particularly red spinach, bathua, coriander, and mustard—showed higher HM accumulation (Pb: up to 1.3 mg/kg; Cd: up to 0.2 mg/kg; Ni: up to 0.3 mg/kg) compared to fruit vegetables. Spinach, capsicum, and Malabar spinach from several zones demonstrated TF values >1 for Cd and Pb, suggesting their potential as hyperaccumulators and their role in enhancing dietary exposure to toxic metals. Health risk assessments identified Dhapa and Chelegualia as regions of greatest concern, with

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red spinach, mustard and coriander showing hazard index values greater than 1. Notably, the roots of most vegetables retained more heavy metals than shoots or fruits, although exceptions were observed where shoot concentrations surpassed root levels, particularly for Pb in coriander and spinach⁹³.

These studies collectively emphasize the widespread issue of HM contamination in vegetables due to wastewater irrigation in India. They highlight the variability in metal accumulation across different vegetables, with leafy vegetables generally showing higher levels of contamination. These findings underscore the urgent need for regular monitoring of soil, water, and vegetables in areas using wastewater for irrigation, as well as the implementation of proper wastewater treatment methods before agricultural application to mitigate potential health hazards.

4. Contamination of vegetables irrigated with waste water in Bangladesh

Like many developing countries, Bangladesh is facing significant issues related to the problem of HM pollution in crops that are irrigated with wastewater. This problem stems from the widespread use of untreated or partially treated wastewater for crop irrigation, a practice that has far-reaching implications for food safety and public health. Numerous studies have delved into this matter, revealing alarming levels of HM accumulation in various vegetables across different regions of Bangladesh.

A comprehensive investigation in the Tangail district of Bangladesh evaluated the concentrations of Pb, Cu, Ni, Cr, As and Cd in rice and vegetable crops irrigated with industrial effluents. The analysis yielded mean concentrations of 16.26, 16.11, 13.99, 2.28, 1.86, and 7.93 mg/kg for Cr, Ni, Cu, As, Cd, and Pb respectively in the examined samples. The study identified differential accumulation patterns among crop species, with okra exhibiting the highest metal concentrations, followed by chili, bitter gourd, papaya, brinjal, bean, bottle gourd, rice, cucumber, sponge gourd, and Indian spinach, in descending order of accumulation. Estimated daily intake values were calculated for the analyzed metals. With the exception of Cu, all metals examined exceeded the maximum tolerable daily intake, indicating potential consumer health risks. Furthermore, target hazard quotients for Pb, Cd, As, Cu and Ni were determined to be greater than 1, suggesting significant non-carcinogenic problem for both children and adult populations consuming these vegetables. The study also evaluated the target carcinogenic risk for As and Pb, which exceeded the United States Environmental

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Protection Agency (USEPA) threshold level of 10^{-4} ^{122,123}, indicating a heightened cancer risk linked with eating these contaminated vegetables ¹⁰⁰.

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Another study focused on the translocation and bioaccumulation of trace metals from industrial effluents to locally grown vegetables in the heavily industrialized area along the river bank of the river Buriganga in Dhaka. This research analyzed soil samples and various vegetables, including red amaranth, spinach, jute leaf, bottle gourd, mustard green, and water spinach. In the vegetables, chromium and lead concentrations were found to be around 20 mg/kg and 0.5 mg/kg respectively, significantly exceeding the permissible limits set by WHO/FAO (Cr) levels at 2.3 mg/kg and lead (Pb) at 0.3 mg/kg ⁶⁰. The investigation revealed that metal concentrations in the analyzed vegetables exceeded established safety thresholds, with chromium. These findings provide evidence for the translocation of HMs from contaminated agricultural land to the edible portions of the vegetables. Hazard index calculations were performed for all vegetables in the study, yielding values exceeding 1, which indicates severe health risks associated with their consumption. Moreover, the total cancer risk values for Cr, nickel (Ni), and Pb in the vegetables were approximately 1×10^{-3} , surpassing the USEPA threshold of 1×10^{-6} . This suggests a significant carcinogenic risk linked to the consumption of these contaminated vegetables ¹⁰¹. A separate study examined HM contamination in vegetables cultivated in industrially polluted regions across Bangladesh. This research quantified the concentrations of Fe, Ni, As, Cd, Cu, Mn and Pb in various crops and vegetables. The metal concentrations were found to be in the following consistent order: Fe > Mn > Ni > Cu > Pb > Cd > As. Target hazard quotient and target carcinogenic risk approaches were used in health risk assessments, and the results showed that consumption of these metal-contaminated vegetables could increase carcinogenic and non-carcinogenic risks for both adult and children populations ¹⁰².

The level of HM pollution in vegetables grown along Bangladesh's main traffic route, the Dhaka-Mymensingh Highway was evaluated in a recent study. 45 vegetable samples were analysed and collected from five distinct sampling sites with varied land use patterns adjacent to the highway. The analysis revealed the following average concentrations (in mg/kg) for bottle gourd: Cu (14.9), Fe (281.2), Mn (387.6), Zn (49.0), Cr (10.1), and Ni (2.92). Esculent exhibited concentrations of Cu (17.6), Fe (183.4), Mn (107.2), Zn (80.7), Cr (7.98), and Ni (2.34). Average concentrations of Mn, Cr and Zn in these vegetables exceeded established acceptable limits. Target hazard

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quotient for Cr in bottle gourd was found to be 9.52, suggesting a substantial non-carcinogenic risk. Target carcinogenic risk was highest for Cr in bottle gourd at 0.014¹⁰³. A separate study focused on industrial areas of Dhaka, examining water, soil, and vegetables for HM contamination. The investigation determined that the order of metal contents in contaminated irrigation water was Fe > Cu > Zn > Cr > Pb > Ni > Cd, with a similar pattern observed in arable soils. Notably, mean concentrations of Cu, Fe, and Cd in irrigation water and Cd content in soil significantly exceeded recommended thresholds. Although majority of the vegetables under investigation showed HM buildup below the Joint FAO/WHO Expert Committee on Food Additives' (1999) maximum allowable threshold, cadmium levels were higher⁹⁵.

These investigations collectively underscore the critical issue of HM contamination in vegetables irrigated with wastewater in Bangladesh. The consistent findings of elevated contamination of toxic metals such as cadmium, chromium, lead, and arsenic in various vegetables cultivated across different regions of the country raise significant concerns regarding food safety and public health.

5. Contamination of vegetables irrigated with waste water in Pakistan

Recent investigations into HM accumulation in vegetables due to wastewater irrigation have been conducted across diverse regions of Pakistan. These studies have revealed concerning contamination levels and potential health risks associated with this practice.

A survey experiment implemented in Multan and Faisalabad identified significant levels of Cd and Pb in soils subjected to wastewater irrigation. However, the contamination remained below the established allowable limits in both soil and water values. Among the plant species examined, Cd and Pb accumulation was highest in *Zea mays*. The study quantified the translocation factor from soil to root, with *Brassica oleracea* demonstrating the highest factor for Cd (7.037) and *Zea mays* for Pb (6.383). For Cd, target hazard quotient values exceeded non-carcinogenic thresholds in the majority of vegetables analyzed, with *Allium cepa* exhibiting the highest value (5.256). In contrast, target hazard quotient levels for Pb were generally below non-carcinogenic limits, with exceptions observed in *Allium cepa*, *Solanum lycopersicum*, and *Solanum tuberosum*¹¹⁶.

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Another study near a sugar mill in Sargodha district examined HM contents in water-soil-coriander samples. Mean concentrations of all metals except manganese exceeded permissible limits in sugar mill wastewater. In coriander specimens, only Cd had higher mean levels in both groundwater and sugar mill wastewater irrigated sites. Health risk index values indicated high risks from Ni, Cu, Fe, Mn, Zn and Cd in coriander irrigated with wastewater ¹²⁵. Research in Chenab Nagar, Chiniot found that Cr and Co concentrations in crops irrigated with wastewater exceeded WHO recommended levels. All studied vegetables had unsafe Cd concentrations compared to FAO limits. Coriander, sponge gourd, and cauliflower also had unsafe Cr levels, while cauliflower showed unsafe Pb concentration. The highest health risk index values were associated with Cd and Cr for all vegetable samples ¹²⁶. A study in Faisalabad analyzing samples of okra, pumpkin, Brinjal, spinach, tomato, potato and cabbage found that 27% of samples had Cd levels, 50% had Pb levels, and 63% had Hg levels above European Commission standards. This indicates widespread HM contamination in vegetables from this region ¹²⁷.

In Vehari district, a study found that soil samples exceeded limit values for several potentially toxic elements, including arsenic, cadmium, copper, chromium, manganese, iron, and zinc. Analysis of soil risk indices, specifically the potential ecological risk index and pollution load index, demonstrated severe contamination levels within the investigated area. These indices provide quantitative measures of the environmental impact and cumulative effects of multiple HMs in the soil ecosystem. Some vegetables exhibited high metal accumulation indices, signifying potential health hazards ¹⁰⁹. Research in Sargodha district focused on iron (Fe) contamination in leafy and root crops irrigated with wastewater, canal water, and tube well water. While Fe concentrations in crops were within WHO permissible limits, the pollution load index indicated soil contamination. This study emphasized the need for regular monitoring to prevent excessive Fe accumulation in the food chain ¹⁰⁵.

A comprehensive study conducted in Dera Ghazi Khan investigated the presence of HMs in wastewater, soil, and diverse plant species. The findings revealed a predominance of chromium (Cr) and lead (Pb) contamination in soil samples. Analysis of plant tissues indicated that concentrations of Cr, nickel (Ni), manganese (Mn), and Pb surpassed the safety thresholds established by WHO/FAO. Health risk index

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calculations were performed to assess potential consumer exposure. The results indicated elevated risk levels associated with the consumption of several crops, notably spinach, wheat, brinjal, tomato, and red corn. For the adult population, copper (Cu), zinc (Zn), and Cr were identified as presenting heightened risk factors ¹¹³. An investigation was conducted in Mingora, located in the Swat region, to compare the accumulation of HMs in both soil and vegetable samples under two distinct irrigation conditions. The study contrasted the effects of industrial wastewater irrigation with those of tube well water irrigation. Soil and vegetables irrigated with IWW showed higher concentrations of HMs, often exceeding WHO limits. The metal transfer factor was particularly high for lead in lady finger and green pepper, and for manganese in pumpkin. Health index values indicated that long-term consumption of these vegetables poses a greater threat to adults than children ¹⁰⁶. Another study conducted in Punjab, Pakistan from 2016-2019 examined contamination of nickel, cadmium, lead, and chromium levels in vegetables irrigated with wastewater across eight districts. The results indicated varying concentrations of chromium, with the highest levels observed in contamination were found in Gujranwala district, with 44% of vegetable samples contaminated with nickel, 87% with cadmium, 97% with lead, and 88% with chromium. Analysis showed that leafy vegetables like mustard leaves, spinach, and lettuce accumulated higher levels of HMs compared to other vegetables. The study concluded that cultivation of vegetables with untreated wastewater should be prohibited due to the significant contamination levels observed ¹¹⁰.

An investigation was conducted in the peri-urban regions of Bhakkar, Pakistan, to assess the accumulation of HMs in vegetables irrigated with wastewater. The study's findings revealed significant concentrations of cadmium, cobalt, nickel, manganese, lead, and iron in both the soil and the vegetable samples. Although the HM content in the vegetables did not exceed the limits recommended by the WHO, the data suggests potential environmental and health concerns that warrant further examination. The daily intake of these metals through vegetable consumption was considerable for both adults and children. Lead and cadmium were identified as posing the highest health risks, with the study concluding that regular consumption of wastewater-irrigated vegetables may present significant health hazards ¹¹¹. Research conducted in Kirri Shamoza, Pakistan, investigated eight harmful metals (copper, iron, zinc, manganese, lead, cadmium, nickel, and chromium) in water, soil, and vegetable samples. Results

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showed that vegetables grown on wastewater-irrigated land had significantly higher HM concentrations compared to those grown with freshwater irrigation, often exceeding USEPA and WHO limits. Principal component analysis identified lead, copper, and chromium as the main contaminants affecting water quality and posing health risks. The study found that leafy vegetables accumulated higher quantities of HMs compared to root and fruit vegetables, with some vegetables deemed harmful for human consumption due to high health risk index values ¹¹².

Results reported in a study conducted near Multan found levels of lead and cadmium are higher than FAO/WHO standards in okra and brinjal samples ¹²⁸. Similarly, research in Dera Ismail Khan reported high lead accumulation in two varieties of *Raphanus sativus* irrigated with sewage water, with the local variety showing higher bioaccumulation than the exotic one ¹²⁹.

A health risk assessment in Bahawalpur’s urban and peri-urban areas found elevated levels of Cd, Cr, Pb, and Ni in wastewater used for irrigation, despite compliant pH and total dissolved solids levels. Vegetables grown in sandy clay loam soils showed metal accumulation factors >1 for Ni, Cd, and Cr. Although Health Risk Index values ranged between 0.313 and 0.515—within safe limits—target hazard quotient (THQ) values exceeded 1 for all vegetables, indicating potential non-carcinogenic health risks ¹¹⁸. A field study evaluating wastewater irrigation with organic and mineral fertilizers found significantly elevated Pb levels in soils and six vegetables irrigated solely with wastewater, often exceeding WHO limits. However, combining wastewater with organic (e.g., cow and poultry manure, leaf litter, sugarcane bagasse ash) or mineral fertilizers reduced Pb accumulation in soil and crops. Manure was particularly effective, lowering Pb bioavailability by complexing with organic matter and raising soil pH. Daily Pb intake and health risk index were highest in wastewater-only treatments, with spinach (1.022) exceeding the safe threshold. All other treatments remained below the HRI limit of 1, indicating health risks only under unamended wastewater use. The study underscores the effectiveness of integrated nutrient management, especially organic amendments, in mitigating Pb uptake and improving food safety in wastewater-irrigated systems ¹¹⁷.

These investigations collectively demonstrate the pervasive HM accumulation in wastewater-irrigated vegetables across diverse Pakistani regions. Findings consistently

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indicate that leafy vegetables exhibit elevated HM concentrations relative to other vegetable categories. While some studies found contamination levels below permissible limits, others reported alarming concentrations of toxic metals, particularly lead and cadmium. The variation in results across different regions underscores the need for localized assessments and targeted interventions to reduce health hazards linked to ingestion of wastewater-irrigated produce in Pakistan.

6. Contamination of vegetables irrigated with waste water in China

Over the past two decades, researchers have been delving into the issue of HM contamination in vegetables irrigated with wastewater across various Chinese regions. These studies have provided crucial insights into pollution levels, potential health risks, and strategies for mitigation.

In the early 2000s, a study examined copper toxicity in vegetables grown in polluted environments. The research found that *Brassica chinensis* (cabbage), *Brassica chinensis* (pichkoi), and *Apium graveolens* var. dulce had copper bioaccumulation levels of 19.4, 5.5, and 30.9 mg/kg respectively, far exceeding what's considered safe¹³⁰. A decade later, researchers investigated HM accumulation of cadmium, lead, mercury, chromium and arsenic in six different leafy vegetables near the Pearl River in South China. Their findings showed that among the vegetables studied, lettuce, Chinese cabbage, pakshi, and Chinese leaf mustard pakshi were less prone to absorbing HMs compared to other leafy varieties¹¹⁹. Further research in 2016 looked at 22 different vegetable species grown in contaminated fields in Suxian district. The study revealed a clear pattern of HM accumulation, with leafy vegetables showing the highest levels, followed by stalk vegetables, root vegetables, solanaceous vegetables, legume vegetables, and finally melon vegetables, which had lowest accumulation³⁶.

Another study analyzed vegetables grown in soils with a 50-year history of treated wastewater irrigation. The researchers looked at 20 common vegetable species and found significant variations in HM uptake, with some vegetables showing up to 100 times difference in cadmium accumulation. Their health risk assessment indicated that spinach, Chinese lettuce, and Chinese chives posed potentially severe health risks with Health risk index >5, while vegetables like tomatoes, kidney beans, potatoes, and cabbage showed minimal risk (Health risk index <1)¹²¹. A comprehensive study in

northern China, specifically the Xi River sewage irrigation area of Shenyang City, highlighted cadmium as a major pollutant. The metal exceeded standard levels by 1.82 times and accumulated significantly in the soil. The researchers also noted that different vegetables had varying BCFs, with leafy vegetables showing the highest tendency, followed by rhizome and solanaceae vegetables. Moreover, the carcinogenic risk for cadmium in some vegetable consumption was higher and warranted attention ¹²⁰. A recent study examined agricultural soils near Hongfeng Lake in Guizhou Province. The researchers identified mercury as the main pollutant, with arsenic and lead as secondary concerns. Interestingly, while arsenic posed the primary non-carcinogenic risk, chromium was found to be the main carcinogenic threat ¹³¹.

These studies collectively highlight the complex nature of HM contamination in vegetables irrigated with wastewater across China. They emphasize the importance of considering factors such as soil characteristics, crop selection, and regional differences when developing strategies to reduce health risks associated with HM accumulation in vegetables. The research underscores the need for continuous monitoring and targeted interventions to ensure food safety in areas where wastewater irrigation is practiced.

7. Comparative analysis of Heavy metal contamination in developing countries.

The examination of metal concentrations across India, China, Bangladesh, and Pakistan reveals significant variations and critical contamination issues as shown in table 2, emphasizing the urgent need for targeted interventions and enhanced regulatory measures. The severity of contamination varies by metal and location, but certain areas emerge as hotspots for multiple contaminants. In India, the Yamuna Floodplain in New Delhi and peri-urban areas of Lucknow show alarmingly high levels of several metals. Studies evaluating the HM contamination in urban and peri-urban areas of India consistently showed high levels of HMs in the vegetable samples, signifying the extent of this contamination in the food of urban population. In Pakistan, regions like Vehari and Bhakkar are similarly affected. Bangladesh faces severe contamination near Dhaka Export Processing Zone and in Tangail district. The limited data from China also indicates significant contamination in Suxian District and Baiyin city, Gansu Province. In India, Lucknow's peri-urban regions report alarmingly high levels of As, Cd, Cr, Cu, Mn and Ni which far exceed the permissible limits and had the highest concentrations

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among all the other locations studied. Highest levels of Co (Kirri Shamoza), Fe (Dera Ghazi Khan) and Pb (Bhakkar) were found in Pakistan and highest mercury levels were in Dhaka, Bangladesh as shown in table 2.

Lead pollution was particularly severe, with numerous locations exceeding the 0.3 mg/kg limit. India's Dehradun (49.54-86.69 mg/kg) and Patna (9.42-30.08 mg/kg) showed high levels, while Pakistan's Bhakkar region reported an extreme range of 0.42-500 mg/kg. In all the studies across India and Pakistan, Lead levels exceeded the permissible limits. These levels reflect severe environmental pollution, with potential long-term health effects on the population. Similarly, Baiyin city in China reports concerning levels of Pb concentrations (0.32-7.8 mg/kg), surpassing the safety threshold of 0.3 mg/kg. In Bangladesh, Lead contamination is notable in Tangail district exceeding safety thresholds at even the lower value of 0.84 mg/kg.

Arsenic contamination is widespread, with levels surpassing the 0.5 mg/kg limit in multiple locations. In Bangladesh, Savar Upazila (0.84-1.45 mg/kg) and Tangail (1.31-3.89 mg/kg) showed elevated concentrations. China's Suxian District (0.014-1.780 mg/kg) and Baiyin city (0.12-2.87 mg/kg) also exceeded safe levels. India presented severe contamination, particularly in peri-urban Lucknow (13.73-2392.05 mg/kg), while Pakistan's Vehari (BDL-3.7 mg/kg) and Lahore (0.477-3.50 mg/kg) also reported concerning levels. Cadmium pollution is equally troubling, with the 0.2 mg/kg threshold frequently surpassed. Bangladesh's Dhaka Export Processing Zone reported levels of 0.82-4.85 mg/kg, while China's Baiyin city showed concentrations of 0.06-6.47 mg/kg. India's peri-urban Lucknow again emerged as a hotspot with 5.90-503.86 mg/kg, and Pakistan's Kirri Shamoza registered 0.70-11.0 mg/kg. Chromium contamination exceeds the 2.3 mg/kg limit in several areas. Bangladesh's Tangail (2.1-33.16 mg/kg) and Dhaka Export Processing Zone (1.19-11.84 mg/kg) showed high levels. In India, the Yamuna floodplain in New Delhi (BDL-173.1 mg/kg) and Lucknow's peri-urban regions (7.14-215.02 mg/kg) displayed severe contamination. Pakistan's Punjab region reported levels up to 75.89 mg/kg. Copper levels above the 73.3 mg/kg threshold were observed in Lucknow (65.58-868.53 mg/kg) and parts of Pakistan, including Gujranwala (31.1-78.2 mg/kg) and Vehari (5-81 mg/kg). Iron contamination surpassed the 425.5 mg/kg limit in several locations, with Lucknow again showing extreme levels (1460.28-27363.74 mg/kg) and Pakistan's Vehari reporting 228-1125 mg/kg. Mercury pollution exceeded the 0.03 mg/kg limit in parts

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of India and Pakistan. While most areas in Bangladesh and China showed levels within safe limits, India's Patna, Bihar (0.145-0.705 mg/kg) and Pakistan's Dera Ghazi Khan, Punjab (2.3-18.8 mg/kg) reported significantly elevated concentrations. Manganese levels in most locations remained below the 500 mg/kg threshold, except for Lucknow's peri-urban regions, which reported an astounding range of 298.17-11667.87 mg/kg. Nickel contamination surpassed the 10 mg/kg limit in several areas, including Bangladesh's Savar Upazila (17.66-30.33 mg/kg) and Tangail (1.41-37.52 mg/kg), India's Lucknow (19.96-82.62 mg/kg), and Pakistan's Kirri Shamozai (5.28-66.0 mg/kg) and Bhakkar (4.29-67.90 mg/kg). Zinc concentrations also surpassed the 99.4 mg/kg threshold in several areas, with Lucknow again showing the highest levels (119.33-988.248 mg/kg).

The data presented paints a deeply concerning picture of widespread HM contamination across various regions in South Asian countries. The levels of contamination for multiple metals far exceed permissible limits in many locations, posing significant risks to human health and the environment. The data highlights the urgent need for comprehensive environmental monitoring and stringent regulatory measures to address contamination. There is a pressing need for comprehensive action plans to address contamination, safeguard public health, and ensure environmental safety.

Table 2: Range of various HMs (mg/kg) at different locations in developing Asian countries. BDL-Below Detection limits.

Coun try	Sampling site	A s	Cd	Co	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Zn	Refer ences
India	Nashik (Maharash ra)	0. 50 - 2. 30	BD L- 3.30			2.20 - 30.8 0					BDL- 9.70		78
	Dehradun, Uttarakhan d		17.5 1- 23.1 9		15.3 0- 57.1 8	23.6 5- 33.4 9				65.69 - 80.72	49.54 - 86.69	48.1 2- 161. 86	79
	Patna, Bihar					2.17 - 36.3		0.14 5- 0.70 5	13.0 9- 143. 36		9.42- 30.08	24.6 6- 183. 72	80

Jhansi (North India)		0.00 - 2.23	0.08 - 1.63		3.45 - 15.3 3			3.56 - 59.4 7	0.06- 4.09	0.00- 8.03	5.89 - 57.1 4	⁸² View Article Online DOI: 10.1039/D4EM00565A
New Delhi (Urban and Peri-urban areas)	0. 05 6- 0. 96 4	0.00 9- 0.33 2		0.00 8- 0.73 1			BD L- 0.91 1			0.040 - 2.215		⁶³
Lucknow (Peri-urban regions)	13 .7 3- 23 92 .0 5	5.90 - 503. 86		7.14 - 215. 02					19.96 - 82.62	1.66- 18.99		⁸³
Prakasam, Andhra Pradesh	0. 26 9 ± 0. 26 5	0.37 1 ± 0.38 3		18.1 11 ± 24.5 42			0.01 9 ± 0.02 6			1.409 ± 1.761		⁸⁸
Ladakh	0. 02 - 0. 25	0.03 - 0.06 9	0.00 - 0.00		0.07 - 0.66	1.07 - 14.9 9				0.05- 0.56	0.02 - 2.33	⁸⁷
Faridabad (Agra Canal)	0. 11 - 0. 68			3.41 - 28.6 7	4.92 - 21.6 2			107. 67- 368. 12	7.25- 58.00	4.00- 12.33	24.1 2- 126. 13	⁸⁴
Solapur, Maharashtr a	0. 00 1- 0. 01 3	0.00 1- 0.37					0.00 1- 0.35 6			0.001 - 1.741		⁸⁵
Lucknow (Peri-urban regions)			0.94 7- 249.		65.5 8- 868. 53	146 0.28 - 273		298. 17- 116			119. 33- 988. 248	⁹⁰

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				278 6			63.7 4		67.8 7					
	Delhi & Dehradun (Urban and peri-urban areas)	0. 00 3- 0. 75 7	0.01 4- 1.07 0	0.02 2- 0.83 0	0.07 0- 9.36 0	2.40 0- 24.8 00		0.00 0- 0.13 5	8.55 0- 101. 000	0.090 - 3.330	0.020 - 8.580	15.0 00- 59.0 00		
	Bokaro, Jharkhand	0. 01 - 0. 04	0.79 - 2.18		0.80 - 2.90			0.00 6- 0.05			0.50- 2.07			⁹¹
	Yamuna floodplain, New Delhi			BD L- 2.2	BD L- 173. 1			1.4- 206. 2	0.2- 19.0	BDL- 27.9	15.7 - 78.3			⁹²
	Kolkata, West Bengal		0.07 5- 0.28 5							0.12- 0.34	0.112 -1.33			⁹³
Bangl adesh	Dhaka Export Processing Zone		0.82 - 4.85		1.19 - 11.8 4	7.16 - 37.7 3	108. 57- 560. 44			2.41- 26.63	2.17- 26.34	11.4 3- 67.0 6		⁹⁵
	Chittagong				0.05 0- 4.25	BD L- 25.0 4					BDL- 2.99			⁹⁶
	Savar Upazila, Dhaka	0. 00 2- 0. 07 6								0.072 - 1.069	0.026 - 0.188			⁹⁸
	Pakshi, Pabna	< 0. 1	<0.1 	<0.1 	<0.1 - 0.75	BD L	6.44 4- 136. 3	<0.0 3 	0.99 - 5.72 0	<0.1- 0.840	0.119 - 1.596	1.20 6- 11.3 05		⁹⁷
	Dhaka metropolita n city area		0.01 6- 0.14		0.02 2- 0.09 4						0.011 - 0.066			⁹⁹

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	Tangail	1.31-3.89	0.093-4.09		2.1-33.16	2.97-25.45				1.41-37.52	0.84-28.14		100
	Savar Upazila, Dhaka	0.84-1.45	1.00-3.05			11.20-18.25	125.58-510.31		21.06-374.23	17.66-30.33	5.83-8.75		102
	Dhaka-Mymensingh highway		0.001		7.98-9.02	9.86-17.6	183.4-281.2		16.9-387.6	2.02-2.92	0.001	28-80.7	103
Pakistan	Gujranwala		0.15-3.06		0.86-4.32	31.1-78.2	148-261		79.2-107	3.81-9.61	1.05-6.29	51.8-68.3	104
	Vehari	B-D-L-3.7	0.0-3.7		19-55	5-81	228-1125		14-119	0.0-7.8	25-38	57-148	109
	Lahore	0.47-3.50	0.149-0.944								1.065-7.83		108
	Khyber Pakhtunkhwa Region		1.8-7.5		6-38	11.7-27	7.2-39.3		12.4-60.4	15.6-61.2	7-41	7.9-34.9	107
	Mingora Swat			0.07-0.14	0.43-2.30		1.70-24.90		0.08-0.97	0.20-0.39	0.67-3.58		106
	Kirri Shamoza		0.70-11.0		6.0-41.0	9.70-31.1	7.0-59.0		2.90-63.1	5.28-66.0	5.0-44.0	4.90-23.0	112
	Bhakkar		0.67-8.0	1.01-14.89			3.0-150		6.89-85.0	4.29-67.90	0.42-500		111
	Punjab		BD-L-3.43		BD-L-					BDL-32.39	BDL-59.40		110

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					75.89							View DOI: 10.1039/D1	
	Dera Ghazi Khan, Punjab	0-0.001	0-0.18		1.22- 4.61	10.6- 33.5	12.7- 329.8	2.3-18.8		0-2.0	0.004- -0.34	11.3- 29.3	¹¹³
	Sargodha district		1.153-1.389	0.037-0.095	0.61- 0.892	0.625- 0.921	1.165- 2.399		1.268- 1.816	0.561- 0.652	0.565-0.585	0.159- 0.218	¹¹⁵
	Faisalabad and Multan		0.19- 5.36								0.21- 15.34		¹¹⁶
	Sargodha										1.289-9.071		¹¹⁷
	Bahawalpur	0.0009- 0.07	0.14- 0.25		<0.01					0.01- 0.08	0.15- 0.35		¹¹⁸
	Pearl River Delta, South China	0.033- 0.063	0.027- 0.060		0.095- 0.23			0.0014- 0.0026			0.055- -0.26		¹¹⁹
China	Suxian District	0.014- 1.780	0.002- 2.918			0.155- 3.125					0.004- 2.361	1.151- 54.65	³⁶
	Xi River, Northern China		0.0056- 0.0365			0.1529- 0.3287					0.0017- 0.06	0.5931- 2.488	¹²⁰
	Baiyin city, Gansu Province	0.12- 2.87	0.06- 6.47		0.82- 16.8	2.54- 14.3					0.32-7.8	16- 172	¹²¹

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	Permissible limits	0.5 ^c	0.2 ^a	50 ^a	2.3 ^a	73.3 ^a	425.5 ^a	0.03 ^d	500 ^a	10 ^b	0.3 ^a	99.4 ^a	59,60,85 ^a
	Oral Reference dose	0.0003	0.001	0.003	1.5 ^b	0.04	0.7		0.14 ^b	0.02 ^b	0.004	0.3	84,87

8. Heavy metal Accumulation Patterns in Vegetable Crops: A Comparative Analysis of Plant Types and Tissues

Research on HM contamination in vegetable crops reveals a consistent trend of higher metal accumulation in leafy vegetables compared to fruit vegetables such as Brinjal or chili ^{36,82,132}, suggesting higher HM accumulation capacity by leaves than fruits ^{133–135}. This phenomenon can be attributed to several physiological and morphological factors. Leafy vegetables, in particular, demonstrate significantly higher metal uptake as shown in figure 4 for various heavy metals ^{84,85,121}, hypothesized to be due to their elevated transpiration and translocation rates ¹³⁶, facilitating enhanced HM absorption via roots and subsequent translocation to foliar tissues. Secondly, a significant amount of absorbed HMs in fruit plants are deposited in organs other than the edible parts, particularly in the leaves. Moreover, the larger surface area of leaves renders vegetables more susceptible to physical contamination from atmospheric deposition and soil particles ^{137,138}. Notably, members of the Brassicaceae family exhibit hyperaccumulator properties, consistently showing the highest total metal concentrations among studied crops ^{101,139}. Leafy vegetables such as spinach (*Spinacia oleracea*), fenugreek (*Trigonella foenum-graecum*), and coriander (*Coriandrum sativum*) consistently display higher metal content compared to non-leafy varieties.

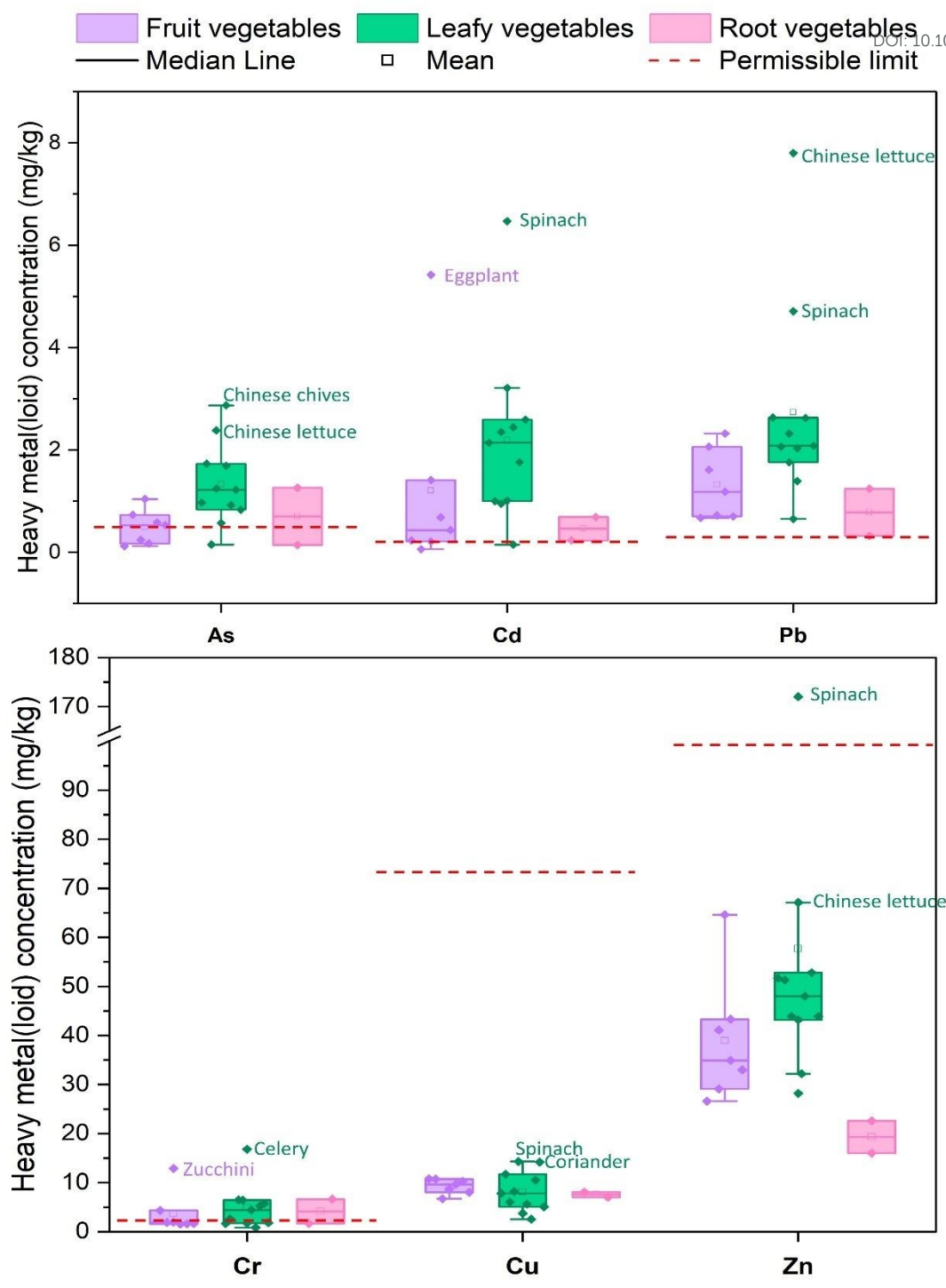


Figure 4: Heavy metal(loid) concentration in the edible parts of different types of vegetables i.e., Fruit (Cucumber, Kidney bean, Pepper, Winged bean, Brinjal, Zucchini, and Tomato), Leafy (Chinese cabbage, Spinach, Shallot, Chinese chives, Cabbage, Celery, Chinese lettuce, Garland chrysanthemum, Coriander, Leafy lettuce, and Rape) and Root vegetables (Carrot and Potato) ¹²¹

Upon examining the distribution of HMs within plant structures, roots generally contain higher concentrations of HMs and metalloids compared to edible parts as shown in figure 5^{102,116,140}. This observation aligns with the well-documented phenomenon of high metal sequestration in root tissues coupled with limited root-to-shoot translocation for most metal(loid)s^{141,142}. Consequently, vegetables where fruit parts constitute the edible portion may present a comparatively lower risk when cultivated in metal(loid)-contaminated soils, as opposed to root vegetables. These results underscore the importance of species-specific and tissue-specific analyses in assessing the potential health risks associated with HM contamination in vegetable crops. Although different vegetable crops have varying capacities for accumulating heavy metal(loid)s from soils to their edible sections, crop selection may be utilised to mitigate the potential health concerns associated with eating vegetables grown in contaminated soils¹²¹. The data indicate that the accumulation of HMs varies significantly among plant species, attributed to differences in their accumulation capacities, rhizosphere characteristics, and interactions with soil properties affecting metal bioavailability. Thus, establishment of an effective and simpler metal transport model for prediction will help ensure global food safety and assess the effectiveness of various management techniques.

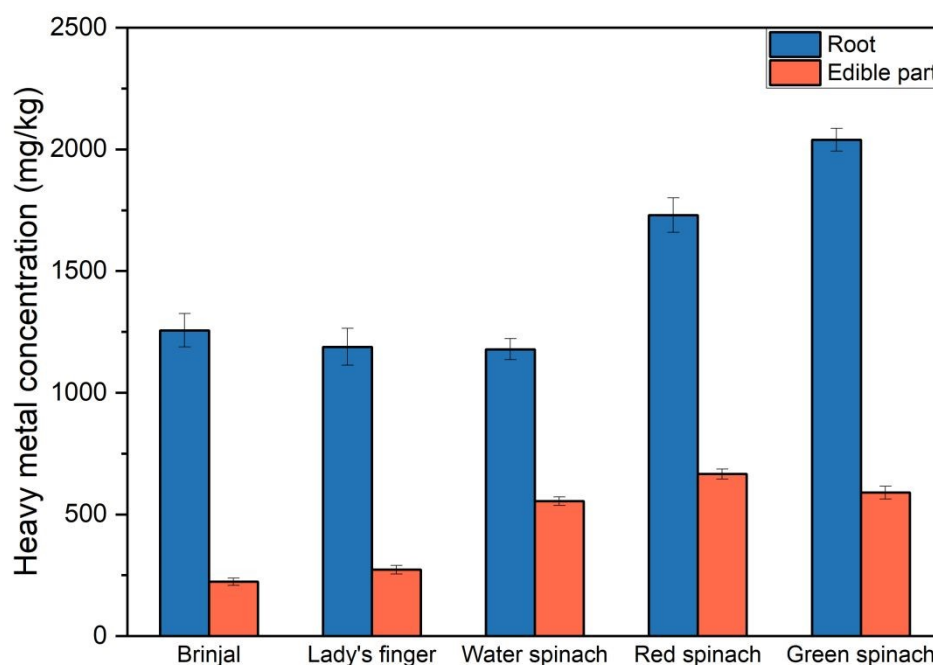


Figure 5: Total heavy metal(loid) concentration (As, Cd, Cr, Pb, Fe, Ni, Mn) in root and edible part of various vegetables¹⁰²

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9. Conclusion:

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The analysis reveals widespread HM contamination in vegetables irrigated with wastewater across developing Asian countries, notably India, Bangladesh, Pakistan, and China highlighting a critical public health and environmental concern. Cadmium, lead, chromium, arsenic, nickel, and mercury are the most commonly reported contaminants, with leafy vegetables such as spinach, amaranth, and cabbage showing consistently higher HM accumulation than fruit and root vegetables. This trend, observed across multiple studies in different countries, suggests a common pattern of bioaccumulation that warrants particular attention.

Regional variability in contamination reflects complex interactions among soil properties, irrigation practices, and industrial pollution sources. Many studies report health risk indices above safe limits, highlighting significant non-carcinogenic and carcinogenic risks, especially for vulnerable populations like children. These findings point to significant gaps in regulatory oversight and the enforcement of environmental and food safety standards. Mitigating these risks demands a comprehensive, interdisciplinary approach. Key strategies include upgrading wastewater treatment infrastructure, promoting best agricultural practices tailored to local conditions, and establishing routine monitoring systems for soil, water, and crop contamination. Public awareness and education on the risks of wastewater-irrigated vegetables and safe food handling are also critical. Future research should prioritize cost-effective remediation technologies, alternative irrigation sources, and long-term health impact studies.

While wastewater irrigation offers a practical response to water scarcity in the region, it poses serious, long-term risks to food safety and public health. Addressing this challenge requires coordinated action from policymakers, researchers, agricultural practitioners, and public health authorities. Only through integrated and sustained efforts can we ensure agricultural productivity without compromising human health, thereby advancing both food security and environmental sustainability in rapidly urbanizing, water-stressed regions of Asia.

10. Research gaps and Future directions:

Despite the growing body of research on HM contamination in vegetables, several significant knowledge gaps remain, pointing to critical areas for future research. One

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of the most pressing needs is for comprehensive, longitudinal studies to assess the long-term health impacts of consuming vegetables with elevated HM concentrations. While the acute toxicity of many HMs is well-documented, the effects of chronic, low-level exposure through dietary intake are less understood. Such studies would provide valuable insights into the cumulative health risks associated with long-term consumption of contaminated vegetables and help in developing more accurate risk assessment models. The combined effects of multiple HMs on human health, known as the cocktail effect, are not fully understood and require further investigation.

From a remediation perspective, there is a pressing need for research, required to develop and validate economically viable soil remediation methods that effectively reduce HM contamination and limit vegetable uptake. While various remediation methods have been proposed, many are too expensive or impractical for widespread implementation in developing countries. Research into affordable, scalable solutions that can be readily adopted by farmers in resource-limited settings is crucial.

The search for sustainable alternatives to wastewater irrigation is another important area for future research. Studies on the feasibility and effectiveness of using treated greywater, implementing rainwater harvesting systems, or developing drought-resistant crop varieties could provide valuable alternatives to the use of contaminated water for irrigation. Future investigations should encompass a multifaceted approach, examining not only the technological feasibility but also the socioeconomic determinants that may impact the implementation and widespread acceptance of these proposed alternatives.

Studies examining the effectiveness of existing policies and barriers to their implementation are essential for improving regulatory frameworks. Additionally, research on effective strategies for raising public awareness about the risks of HM contamination and promoting behavioural change is necessary.

Statements and declaration

CRedit Authors Contributions

Navneet Kaur - Data curation, Formal Analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Jagdev Singh** – Conceptualization, Formal Analysis, Investigation, Visualization, Writing – original draft. **Anand Mohan** - Conceptualization, Validation, Writing – review & editing. **Neeta Raj Sharma**-

Writing – review and editing. **Simranpreet Kaur Natt** - Writing – review and editing.
Tabarak Malik – Conceptualization, Supervision, Resources, Writing – review &
editing. **Madhuri Girdhar** - Conceptualization, Supervision, Writing – review &
editing.

Conflict of interest

The authors declare no competing interest.

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Data Availability Statement

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

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Data Availability Statement

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.