REVIEW ARTICLE

Bibliometric Analysis and Hidden Risks of Arsenic Contamination in Vegetables and Edible Crops: A Review

Namrata Pandey[1], Abhishek Saxena[1*], Pragya Singh[1], Shivam Saw[2], Geetgovind Sinam[3], Biswajeet Thakur[4]

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Abstract

Among elemental toxins, arsenic (As) is one of the most notorious and extensively studied. It is a naturally occurring metalloid in the earth's crust, and arsenic poisoning, recognized as a serious health hazard, primarily occurs through the ingestion of contaminated food, water, or agricultural products. The Indo-Gangetic Plain in India is particularly known for arsenic pollution due to the region's natural geological composition. Within this area, the mid-Gangetic plain, especially districts in Uttar Pradesh such as Bahraich, Gorakhpur, Ghazipur, Chandauli, and Bareilly, are severely affected by arsenic contamination in both soil and groundwater.

This review aims to investigate the health risks and the urgency of addressing arsenic contamination in vegetables and edible crops in Uttar Pradesh, India. Employing a systematic review methodology, it compiles data from previous studies to assess arsenic concentrations across various crops. Additionally, a bibliometric analysis reveals that arsenic-related research is a global concern and ranks among the most highly cited topics in the biological sciences. This review explores the origin, mobilization, and contamination of arsenic in groundwater and its subsequent accumulation in vegetables.

Highlights

- Global status of arsenic contamination.
- Arsenic contamination in vegetables and crops.
- Sources and pathways of arsenic entry into vegetables and crops.
- Bibliometric analysis of global research on arsenic contamination.
- Impact of arsenic research on scientific development and R&D Initiatives.

Keywords: Arsenic, Crops, Mitigation, Vegetables, Uttar Pradesh.

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Introduction

Arsenic (As), a toxic metalloid with significant environmental and health implications, is widely distributed in the environment. The use of arsenic-contaminated groundwater for irrigation exacerbates its accumulation in surface soils and crops (Bhattacharya *et al*., 2010). This contamination presents a major global public health and environmental challenge. Groundwater arsenic concentrations exceeding the World Health Organization (WHO) guideline of 10 parts per billion (ppb) have been reported in 108 countries, placing over 230 million people at risk, 180 million of whom reside in Asia (Mukherjee *et al*., 2024; Rahaman *et al*., 2021). South Asia and South America are among the most affected regions (Saw et al., 2023). Countries severely impacted include Bangladesh, India, China, Nepal, Cambodia, Vietnam, Myanmar, Laos, Indonesia, and the United States. Other nations facing substantial challenges include Argentina, Chile, Hungary, Canada, Pakistan, Mexico, and South Africa.

Even developed countries such as the United States and Canada are affected by groundwater arsenic contamination, although the levels are generally lower than those observed in many Asian nations. Asia and Europe report the highest number of documented arsenic pollution cases, followed by Africa, North America, South America, and Australia (Shaji *et al*., 2021). In Asia, groundwater arsenic contamination significantly affects 33 countries, with China, Bangladesh, India, and Pakistan among the most severely impacted. Southeast Asian nations, including Nepal, Vietnam, Myanmar, Thailand, and Cambodia—also face serious challenges. In India alone, arsenic contamination has been reported in 20 states and four union territories (Shaji *et al*., 2021). The Ganga Delta, encompassing Bangladesh and the Indian state of West Bengal, is one of the most severely affected regions globally. Inhabitants of this area are exposed to elevated levels of arsenic in drinking water, which is also used for irrigation, compounding health risks (Ali *et al*., 2019; Prasad *et al*., 2022).

Several Indian states, including West Bengal, Jharkhand, Bihar, Uttar Pradesh, Assam, Manipur, and Chhattisgarh,

[1]Faculty of Civil Engineering, Shri Ramswaroop Memorial University, Barabanki (UP), India.

[2]National Institute of Technology, Durgapur, West Bengal- 713209

[3]Plant Ecology and Climate Change Science, CSIR-National Botanical Research Institute, Lucknow, India.

[4]Birbal Sahni Institute of Paleoscience, Lucknow.

***Corresponding author:** Abhishek Saxena, Shri Ramswaroop Memorial University, Barabanki, India, Email: dr.abhisheksaxena2020@gmail.com

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report groundwater arsenic concentrations exceeding the WHO guideline of 10 µg/L (Marghade *et al*., 2023; WHO, 2018). Among these, the majority of research has been conducted in West Bengal, followed by Bihar (Signes-Pastor *et al*., 2024; Mondal *et al*., 2021; Kumar *et al*., 2016; Bhattacharya et al., 2010). A review by Namrata et al. (2015) focused specifically on the eastern districts of Uttar Pradesh. The consumption of arsenic-contaminated drinking water poses a serious health risk to affected communities. India and Bangladesh are among the most severely impacted countries, with over 100 million people at risk of arsenic poisoning. Between 2005 and 2013, hundreds of arsenic-related deaths were reported, according to the International Science Congress Association. Despite the scale of the crisis, many affected regions still lack effective treatment and mitigation strategies (Podgorski & Berg, 2020).

The issue of arsenic contamination in Indian groundwater was first identified in Chandigarh in the late 20th century. Subsequent investigations revealed that drinking water in several states contained arsenic concentrations exceeding both the WHO guideline of 10 µg L^{-1} and the Bureau of Indian Standards (BIS) limit of 50 µg L^{-1} (BIS, 2012). One of the most severely affected regions in South Asia is the Gangetic Plain, which extends along the border between Bangladesh and Nepal. Within this region, Bihar and West Bengal, both part of the Middle-Gangetic Plain, are particularly impacted. Chakraborti et al., (2018) reported arsenic concentrations as high as 1654 µg L^{-1} in drinking water samples from Semaria Ojha Patti village in Bihar's Bhojpur district (Chakraborty & Mukherjee, 2018). Nationwide, arsenic levels exceeding 10 µg L^{-1} have been detected in shallow aquifers across 10 Indian states, while deeper aquifers typically below 100 meters generally remain uncontaminated. Although Chandigarh was the first location where arsenic contamination was reported, more widespread and severe contamination was later found in the lower Gangetic Plain of West Bengal. Additional cases have since been documented in numerous other states, including Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, Tripura, Punjab, Himachal Pradesh, Chhattisgarh, and Andhra Pradesh. To date, arsenic contamination has been confirmed in 20 Indian states and four Union Territories (Chakraborty & Mukherjee, 2018). In Uttar Pradesh, arsenic pollution is prevalent along the linear tract following the Ganga River. Bihar, due to its geographic proximity to this region, also faces significant exposure and risk (Shah, 2015).

Arsenic contamination in food crops has emerged as a significant global concern due to its detrimental effects on human health and the integrity of food systems. This naturally occurring element enters agricultural ecosystems through various pathways, compromising both food safety and quality. Arsenic, the 20th most abundant element in the earth's crust, is classified as a Group I carcinogen by the International Agency for Research on Cancer (IARC) and identified as a major environmental pollutant by the U.S. Environmental Protection Agency (USEPA). Its propensity for uptake by crops, particularly rice, leafy vegetables, and seafood, is especially alarming (Jomova *et al*., 2011; Britannica, 2003; WHO, 2018).

When arsenic enters the soil, it is absorbed by plant roots and subsequently translocated to the edible parts of the plant, leading to significant health risks for consumers. Prolonged exposure to arsenic-contaminated food has been linked to severe health issues, including cancer, cardiovascular diseases, and neurological impairments. Vulnerable populations such as children and pregnant women are particularly at risk, underscoring the urgent need for targeted interventions (Rahman *et al*., 2013). This review examines arsenic contamination in vegetables and food crops, focusing on its sources and mechanisms of plant uptake. A bibliometric analysis of related research was conducted using the Web of Science database and VOSviewer. The review also explores the origin, mobilization, and accumulation of arsenic in groundwater and its transfer into agricultural produce. Furthermore, it provides a global overview of arsenic contamination, with particular emphasis on the situation in Uttar Pradesh, India, and aims to highlight the potential health risks associated with consuming arsenic-laden vegetables.

Sources of arsenic contamination of soil and plants

Arsenic contamination arises from both natural and human activities. Naturally, geological processes such as weathering and erosion release arsenic from minerals in sandy aquifers into groundwater (Mukherjee *et al*., 2024; Shrivastava *et al*., 2015; Smedley & Kinniburgh, 2002). Minerals like arsenopyrite and realgar, found in geological formations, serve as arsenic reservoirs, leading to soil and water contamination (Marghade *et al*., 2023; Bissen & Frimmel, 2003). Additionally, volcanic activity and hydrothermal processes can introduce arsenic into surface and groundwater systems. Fig. 1 illustrates the potential sources of arsenic contamination in plants.

Human activities have significantly worsened arsenic pollution, often surpassing natural sources in many areas. Mining operations for metals like gold and copper releases arsenic into the environment through waste and tailings. Industrial activities, such as metal refining and semiconductor production, significantly contribute to arsenic contamination by releasing arsenic-rich effluents into water systems. Agricultural practices, particularly the application of arsenic-based pesticides and fertilizers, further exacerbate soil and water pollution (Meharg & Whitaker, 2002). Domestic actions, including the burning of arsenic-treated wood and the use of arsenic-containing household products, also play a role in environmental

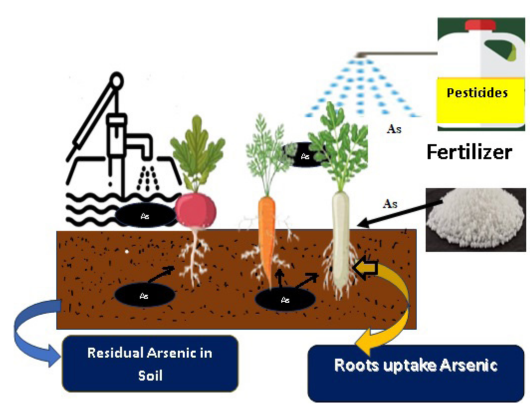

Fig. 1: The possible source of arsenic contamination in plants

contamination (Brammer & Ravenscroft, 2009). Additional sources of arsenic pollution include atmospheric deposition from industrial emissions, the application of sewage sludge as fertilizer, and arsenic-contaminated drinking water (Bissen & Frimmel, 2003; Smedley & Kinniburgh, 2002). Although natural processes are responsible for the mobilization of arsenic in certain contexts, human activities have significantly amplified its impact on the environment (Barcelos *et al*., 2020). The presence of arsenic in drinking water, especially in regions with arsenic-rich bedrock, underscores the need to address both natural and human-induced sources of contamination.

Sources and routes of arsenic contamination in crops

All plants, including vegetables and crops, grow traditionally on the soil. The plants, through their root system, get their water and nutrients from the soil. In the process of up-taking nutrients from the soil, the plants also accumulate when their root system is exposed or comes in contact with them. The crops growing in the As-affected regions are facing the problem of As-contaminated vegetables and crops (Kumar *et al*., 2024; Dwivedi *et al*., 2023; Chakraborty *et al*., 2014). The alternate route of As into the plant is by foliar or surface absorption. In the pursuit to meet the demand-supply chain to feed the ever-increasing human population, the humongous application of fertilizers and pesticides is also contributing to the contamination of crops. The levels of arsenic accumulation vary among different species and varieties of crops when irrigated with arsenic-contaminated water. Human consumption of vegetables and crops contaminated with As is causing serious health issues. Furthermore, consuming food products derived from marine life and livestock, such as meat and milk, in areas with high arsenic levels can further contribute to arsenic contamination in the food chain. Generally, organic forms of arsenic are less hazardous than their inorganic counterparts (Singh *et al*., 2023).

Arsenic Uptake by Plants

Arsenic uptake is predominantly a passive process driven by the concentration gradient of arsenic in the soil solution. It is present in the soil in different chemical forms, primarily as arsenate [As(V)] and arsenite [As (III)]. Arsenate (As(V)), being a chemical analog of phosphate, can be absorbed by plant roots using phosphate transporters (Suriyagoda *et al*., 2018). Plants take up arsenate through these transporters, as the arsenate ion mimics the phosphate ion structurally. Arsenite [(As (III)] is taken up by plants through specific membrane transporters known as aquaporins. These proteins help transfer water and tiny chemicals across the cell membrane, including arsenite (Abbas *et al*., 2018). Arsenate absorption may occur via ligand-exchange processes, in which arsenate competes with phosphate for binding sites on root cell membranes. This competition can be influenced by the concentration of arsenate and phosphate in the soil. Active transport systems within plant roots may play a role in arsenic uptake. These systems involve the energy-driven movement of arsenic ions across the cell membrane, contributing to the accumulation of arsenic within the plant. Root hairs, which are extensions of root epidermal cells, increase the surface area for arsenic absorption (Abedi & Mojiri, 2020). The presence of root hairs enhances the contact between the root system and the surrounding soil, facilitating arsenic uptake. The availability of arsenic in the soil is influenced by its chemical speciation. Arsenic transforms different oxidation states (e.g., As(III) to As(V)) based on soil redox conditions, impacting its uptake by plant roots. Soil pH plays a critical role in arsenic uptake. Arsenate is more prevalent and soluble in alkaline

Table 1: The report of As in the vegetables from different countries across the world

Continent	*Country*	*References*
Asia	Bangladesh	Rahman *et al*., 2013; Alam *et al*., 2003
	Cambodia	Uy *et al*., 2010
	China	Meng *et al*., 2022; Li *et al*., 2017
	India	Kumar *et al*., 2016
	Indonesia	Laela *et al*., 2023; Ginting *et al*., 2018
	Japan	Sawada *et al*., 2023
	Malaysia	Sulaiman *et al*., 2020; She & Kheng, 1992
	Nepal	Dahal *et al*., 2008
	Pakistan	Shandana *et al*., 2024; Abbas *et al*., 2010
	Russia	Panov *et al*., 2023; Tumanyan *et al*., 2019
	South Korea	Lee *et al.,* 2023; Go *et al*., 2012
	Sri Lanka	Jinadasa & Fowler, 2019
	Thailand	Monboonpitak *et al*., 2018; Ruangwises *et al*., 2012
	Vietnam	Ngoc *et al*., 2020
Africa	Burkina Faso	Clair-Caliot *et al*., 2021
	Ethiopia	Gebeyehu & Bayissa, 2020
	Ghana	Lente *et al*., 2012
Australia	Australia	Fransisca *et al*., 2015; NSW, 2010
	New Zealand	Fransisca *et al*., 2015
Europe	Croatia	Stančić *et al*., 2016
	Italy	Spognardi *et al*., 2019; Beccaloni *et al*., 2013
	Hungary	Szalay *et al*., 2014
	Portugal	Pacheco *et al*., 2006
	Romania	Harmanescu *et al*., 2011
	Spain	Matos-Reyes *et al*., 2010
	UK	Norton *et al*., 2013
	Turkey	Varol *et al*., 2022
North America	USA	Seyfferth *et al*., 2016; McBride, 2013
South America	Bolivia	Bundschuh *et al*., 2012
	Chile	Bundschuh *et al*., 2012; Sancha & O'Ryan, 2015
	Mexico	Bundschuh *et al*., 2012
	Brazil	Ciminelli *et al*., 2017

conditions, while arsenite is favored in acidic conditions. The pH of the soil thus affects the speciation and availability of arsenic for root absorption (Zhao *et al*., 2009).

Arsenic in Crops and Vegetables

Arsenic contamination in vegetables and edible crops is caused mostly by the absorption of arsenic from polluted soil and water. When arsenic is prevalent in the environment, plant roots absorb it, causing it to accumulate in numerous tissues, including leaves, stems, and edible sections (Alam *et al*., 2003). Arsenic is mostly geogenic, originating from natural geological processes that result in changing soil amounts depending on local conditions. However, human activities such as the use of arsenic-based insecticides, herbicides, and fertilizers, as well as poor industrial waste disposal and mining operations, all contribute considerably to arsenic pollution in agricultural soils (Kanel et al., 2024). As the quandary of arsenic contamination is worldwide, it has affected all the human-populated continents of the earth. The vegetables and crops grown therein are contaminated with As and pose a serious health risk factor. There are numerous reports of As presence in the vegetables and crops from across the globe (Table 1).

In paddy fields, water management and quality are critical in determining arsenic dynamics and accumulation in rice grains. Arsenic uptake by rice plants is reduced in aerobic or non-flooded circumstances, whereas it is increased in flooded or anaerobic conditions (Harine *et al*., 2021). The prolonged usage of irrigation water during the rice-growing season increases arsenic levels in paddy soils (Biswas & Naher, 2019). Considering the nutritional importance of vegetables, numerous studies have focused on arsenic levels in these crops (Mondal *et al*., 2021; Kumar *et al*., 2016; Chakraborty *et al*., 2014; Bhattacharya *et al*., 2010). Potato (Solanum tuberosum), a globally significant crop alongside maize, rice, and wheat (Leff *et al*., 2004), has been extensively studied. Williams *et al*. (2006) analyzed arsenic speciation in potato tubers from Bangladesh and detected only inorganic arsenic (iAs) with no traces of organic arsenic (oAs) species. Similarly, Signes-Pastor *et al*. (2008) reported the presence of monomethyl arsenic acid (MMA) in potato tubers from a village in West Bengal.

Research reveals that certain vegetables can contain arsenic concentrations similar to those found in rice when measured on a dry-weight basis (Bhattacharya *et al*., 2010). Potatoes, in fact, may accumulate more arsenic than rice. For example, a study by Rahman *et al*. (2013) in Malda, West Bengal, reported total arsenic levels in food crops ranging from 0.000 to 1.464 mg kg^{-1} dry weight (dw), with potatoes showing the highest concentration (0.456 mg kg^{-1}), followed by rice grains (0.429 mg kg^{-1}). Arsenic levels in irrigation water in the region exceeded the WHO recommended limit for drinking water (0.01 mg kg^{-1}) (Bhattacharya *et al*., 2010). Upadhyay *et al*., (2019), reviewed the As presence in different dietary sources. In the review study by Bundschuh *et al*., (2012), the work compiled the As in the food chain of Latin America.

In Bangladesh, arsenic levels in vegetables vary significantly across regions. For instance, in Chandpur and Jamalpur, concentrations ranged from 0.070 to 3.990 mg kg^{-1}, whereas in Sathkhira, Rajshahi, and Comilla, they ranged from <0.040 to 1.930 mg kg^{-1} (Williams *et al*., 2006). Similarly, in West Bengal, India, Gupta *et al*., (2022) found mean arsenic levels in vegetables from the Jalangi and Domkal blocks to be 0.0209 mg kg^{-1} (<0.00004–0.138 mg kg^{-1}) and 0.0212 mg kg^{-1} (0.00004–0.212 mg kg^{-1}), respectively. Leafy vegetables tend to accumulate higher arsenic levels (0.041–0.464 mg kg^{-1}) compared to non-leafy ones (0.011–0.145 mg kg^{-1}). In Bangladesh, cooked vegetables from Munshiganj and Monohordi were reported to have arsenic levels ranging from 0.019 to 2.334 mg kg^{-1} (Smith *et al*., 2006).

The concentration of arsenic in a plant's edible parts depends on its bioavailability in soil and the plant's uptake and translocation capabilities (Huang *et al*., 2013). Certain species, such as the Chinese bracken fern (*Pteris vittata*), are known hyperaccumulators of arsenic and can effectively extract it from the soil (Ma *et al*., 2001). Other plants, including Indian mustard (Brassica juncea) and Arabidopsis thaliana, can reduce arsenic (V), although their accumulation capacity is lower than that of *P. vittata* (Tripathi *et al*., 2007). Additionally, vegetables like arum (Colocasiaantiquorum) and kalmi (Ipomoea aquatica) have shown high arsenic uptake, while plants like maize, barley, ryegrass, and *Spartina alterniflora* also demonstrate arsenic accumulation capabilities. Although plants seldom collect arsenic at levels that are directly dangerous to humans, phytotoxicity typically occurs at lower levels (Bhattacharya *et al*., 2010). In Murshidabad, West Bengal, arsenic concentrations in food composites such as potato peel, vegetable leaves, rice, wheat, cumin, turmeric powder, and cereals ranged from 7 to 373 mg kg^{-1} in arsenic-affected areas (Harine *et al*., 2021).

Factors influencing the absorption of arsenic by vegetables

The absorption of arsenic by vegetables is a multifaceted process influenced by soil composition, water quality, plant characteristics, and environmental factors (Zalud *et al*., 2012). Soil pH plays a crucial role in determining arsenic speciation. In acidic soils, arsenic is more soluble, which facilitates the uptake of arsenite [As(III)]. Conversely, in alkaline soils, arsenate [As(V)] becomes more dominant. The availability of these arsenic species for plant absorption is closely linked to the soil's pH. The chemical form of arsenic in the soil, whether as arsenite or arsenate, influences plant uptake, and different plant species exhibit varying affinities for these forms (Ali *et al*., 2019).

The redox potential of the soil, which is determined by oxygen availability, also impacts arsenic speciation. Under low-oxygen (anaerobic) conditions, arsenite is more mobile and prevalent, potentially increasing its uptake by plants. Soil organic matter can interact with arsenic, forming complexes that affect its bioavailability. The type and amount of organic matter in the soil play a significant role in modulating arsenic uptake (Sarwar *et al*., 2021).

Arsenic contamination in irrigation water is another critical factor influencing soil and crop contamination. Regions with high arsenic levels in water are particularly prone to crop contamination. Additionally, fertilizers containing phosphorus can affect arsenic absorption by plants. Since arsenic is chemically similar to phosphorus, it may be absorbed through phosphate transporters, especially when phosphorus levels are elevated (Gan *et al*., 2017). Furthermore, several elements have been reported to interact with arsenic (As) and mitigate its toxic effects on plants (Kumar *et al*., 2024).

Bibliometric survey on the current research status of arsenic contamination

Bibliometric analysis is a crucial tool for examining prior research, evaluating the current knowledge base, identifying studies on arsenic contamination in groundwater, and highlighting research gaps to inform future strategies. Literature on subjects such as coal mine waste management, phytostabilization using native plants, and coal overburden restoration was gathered from established databases, including SCOPUS, Web of Science, PubMed, and Google Scholar. The collected resources comprised journal articles, books, and doctoral dissertations. To refine the search results, keywords were enclosed in quotation marks, and the Boolean operator "OR" was employed in various combinations for title-specific searches. The study was conducted in three distinct phases, ensuring thorough coverage of the literature within the timeframe of 2000–2024. The focus was narrowed to studies on arsenic contamination in groundwater and its impact on vegetables. Bibliometric analysis was conducted to uncover research trends, understand patterns related to coal overburden, and highlight contributions by authors and nations. Data for bibliometric analysis were retrieved from the SCOPUS database, encompassing fields such as Engineering, Environmental Science, Agricultural and Biological Sciences, and Chemical Engineering. A total of 5001 articles in CSV format from 2000 to 2024 were analyzed using the VOS viewer software (version 1.6.20) as described by Cruz *et al*., (2024).

The analysis examined co-authorship patterns among countries to assess global collaboration within this research domain (Fig. 2). Each node represented a country, with its size corresponding to the volume of publications. Node colors indicated clusters of collaborating nations, while line thickness and color depicted the strength and frequency of co-authorship ties. Countries with larger nodes, such as the United States, China, the United Kingdom, and India, emerged as significant contributors to arsenic-related research. Cluster analysis revealed regional collaborations, with countries in the same cluster, such as European nations or those in South Asia, frequently working together. For instance, a robust partnership between China and the United States highlighted a substantial body of shared research output. This visualization offered insights into the global research landscape, key contributors, and collaborative networks in arsenic contamination studies.

Based on the Web of Science data with the keywords "Arsenic" and "Vegetables," a total of 999 records were available for the period from 1956 to 2025. The records type were research articles 493, review articles 32, proceeding paper 25, early access 8 and book chapters 1. The record count and the number of times the articles met the user's information needs were topped by the environmental journals (54%), followed by the food science and technology journals (14%) (Fig. 3). The total citation on this subject was 40061, with an H-index of 95 (Fig. 4). The top five cited journals were Rai *et al*., 2019 (1084), Liu *et al*., 2005 (518), Huang *et al*., 2019 (420), Alam *et al*., 2003 (407) and Huang *et al*., 2018 (397). The records show the problem of the As contamination of vegetables and crops is a global issue and poses a serious health risk factor.

Human health exposure to arsenic

Arsenic, in all its forms, poses a significant threat to human health. Exposure to arsenic for more than five years can lead to a variety of malignancies, skin lesions, neurological issues, liver damage, respiratory problems, and other carcinogenic and non-carcinogenic effects (USEPA, 2001). The possible human health impact of arsenic is multifaceted. Once it gets into the body, it's spread out in many systems, such as the skin, lungs, liver, and

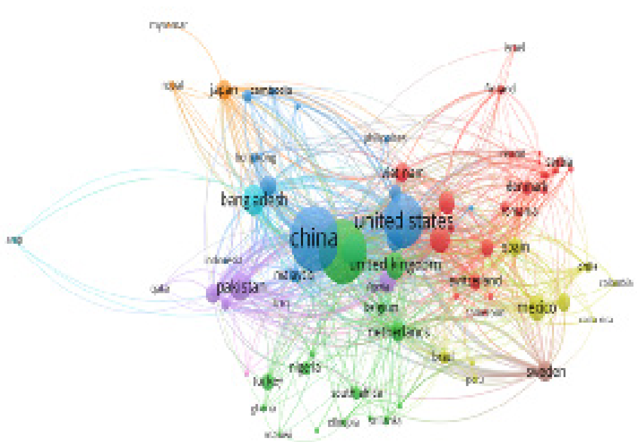

Fig. 2: Network visualization of global research collaboration on arsenic contamination in groundwater, highlighting co-authorship links and country affiliations

Fig. 3: The Treemap chart of count for research article types with the keywords "Arsenic" and "Vegetables." (information from the Web of Science)

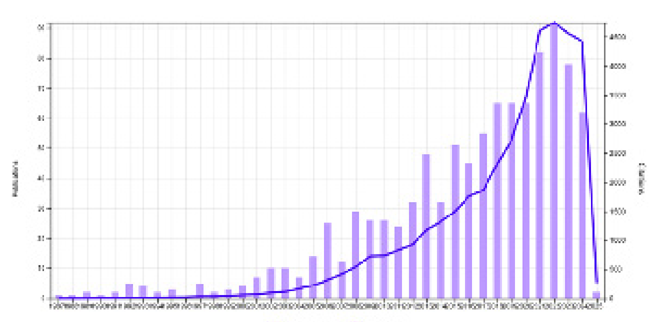

Fig. 4: The citations of research articles with the keywords "Arsenic" and "Vegetables." (Information from the web of science)

kidneys. It is hard to tell if someone has arsenic poisoning from their early symptoms because they could also be signs of other illnesses (Flora, 2020).

According to the WHO (2019), soluble inorganic arsenic is extremely hazardous when ingested in high doses. Long-term exposure to inorganic arsenic can lead to chronic arsenic poisoning, known as arsenicosis. The effects of prolonged exposure may develop over time and include skin lesions, peripheral neuropathy, gastrointestinal issues, diabetes, cardiovascular conditions, developmental harm, and cancers of the skin or internal organs. The primary sources of high inorganic arsenic exposure for humans are consuming groundwater with naturally elevated arsenic levels, food prepared with this water, and crops irrigated with arsenic-contaminated water sources. It is crucial to implement public health measures to reduce human exposure to arsenic, particularly in regions with naturally high levels in groundwater (Flora, 2020).

When contaminated food and water are consumed, only the bioavailable form of arsenic enters the human body, where it disrupts various metabolic pathways. Prolonged exposure to arsenic can result in both carcinogenic and non-carcinogenic health risks, including arsenicosis, various types of cancer, liver damage, kidney failure, and skin disorders. Additionally, arsenic exposure can negatively impact reproductive health and fetal development, with increased risks of miscarriage, stillbirth, and developmental abnormalities in affected populations (Naujokas *et al*., 2013). To maintain a high quality of life, it is essential to have robust ecosystems that provide clean air, water, medicine, and food, all of which help prevent illness and ensure environmental stability. However, the rapid rate of biodiversity loss poses a significant threat to human health and increases the risk of emerging infectious diseases (Thakur *et al*., 2021).

International and National standards for arsenic in vegetables and crops

To safeguard public health and ensure food safety, both international and national standards regulate arsenic levels in food products. The WHO provides health-based guidelines for drinking water quality, which include a guideline value for arsenic in drinking water. While these guidelines are not specific to food, they indirectly influence food safety standards by addressing the overall intake of arsenic from various sources (Meharg & Andrea, 2010).

The U.S. Environmental Protection Agency (EPA) regulates arsenic levels in drinking water, with 10 µg per liter for public water systems (Britannica, 2003). Similarly, the U.S. Food and Drug Administration (FDA) oversees and enforces arsenic limits in specific food products, including established action levels for items like apple juice and rice-based products. In the European Union, the European Commission has set maximum permissible levels for contaminants, including arsenic, in various food categories. For instance, the allowable limit for inorganic arsenic in rice is 0.1 mg per kg (Jinadasa & Fowler, 2019). Besides the International Organization, some of the affected countries have set their own limits for As in vegetables and crops (Table 2).

The monitoring and enforcement of standards for arsenic levels in food are typically the responsibility of regulatory bodies at both international and national levels. Codex standards are influential in global trade, and many countries adopt these standards or use them as a reference. Provides health-based guidelines for contaminants, including arsenic, in drinking water. WHO guidelines influence national standards, and member countries may use them as a basis for setting their regulations. These regulatory agencies play an important role in preserving public health by setting and enforcing arsenic levels in food. They undertake inspections, testing, and surveillance to ensure

Table 2: The recommended As levels in vegetables for different countries

S.No.	*Country*	*As limit in vegetables (mg kg^{-1})*	*Reference guidelines*
1	WHO/FAO	mg Kg^{-1} (Leafy vegetables) 0.3 mg Kg^{-1} (Root vegetables)	FAO/WHO, CAC 39
2	European Union	0.1 mg kg^{-1} (for all vegetables)	EU Regulation (EC) No. 1881/2006
3	United States (FDA)	0.1 mg kg^{-1} (for leafy vegetables)	FDA Guidelines on Arsenic in Food
4	India	0.1 mg kg^{-1} (for all vegetables)	FSSAI Arsenic Standards
5	China	0.2 mg kg^{-1} (for rice and other crops)	Chinese Ministry of Health Arsenic Standards
6	Australia	0.1 mg kg^{-1} (for vegetables)	FSANZ Arsenic Guidelines
7	Japan	0.1 mg kg^{-1} (for vegetables)	Japan Food Safety Standards
8	Canada	0.1 mg kg^{-1} (for vegetables)	Health Canada Arsenic Guidelines
9	Argentina	0.1 mg kg^{-1} (for vegetables)	Argentine Ministry of Health
10	Mexico	0.1 mg kg^{-1} (for vegetables)	Mexican Food Standards
11	Brazil	0.2 mg kg^{-1} (for rice and grains)	Brazilian Health Ministry Standards
12	South Korea	0.1 mg kg^{-1} (for vegetables)	South Korea Arsenic Guidelines
13	Thailand	0.1–0.2 mg kg^{-1} (for rice and vegetables)	Thai National Food Safety
14	Vietnam	0.2 mg kg^{-1} (for rice and some vegetables)	Vietnamese Arsenic Guidelines

that food items fulfill the stipulated safety criteria and take enforcement actions when necessary to resolve noncompliance (Zhao *et al*., 2009).

Conclusion

Addressing arsenic contamination requires a balanced approach that tackles immediate concerns while ensuring long-term environmental health. Techniques like phytoremediation, bioremediation, and cutting-edge water treatment methods show promise, but their effects on ecosystems over time need thorough research. The challenge of detecting arsenic-related diseases early, due to their long latency, underscores the importance of preventive strategies. In addition, ongoing research into the health impacts of chronic arsenic exposure and global monitoring efforts are vital for spotting and managing new contamination hotspots. By encouraging collaboration among scientists, policymakers, and communities, we can craft effective regulations and incentives that promote sustainable practices, protecting both ecosystems and human health for the future.

Data Availability

Data collected and analyzed in this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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