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SYSTEMATIC REVIEW OF DIETARY EXPOSURE, CARCINOGENIC, AND NON-CARCINOGENIC HEALTH RISK ASSESSMENT OF ARSENIC (AS) AND LEAD (PB) IN AGRICULTURAL CROPS IN ASIA

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ABSTRACT

The contamination of agricultural crops by toxic heavy metals has emerged as a critical food safety and public health issue across Asia. This systematic review synthesizes findings from 21 peer-reviewed studies (2016–2026) to evaluate the concentration, dietary exposure, and associated carcinogenic and non-carcinogenic health risks of arsenic (As) and lead (Pb) in agricultural crops across Asia. Results indicate that heavy metal accumulation in crops is strongly influenced by proximity to mining, industrial activities, and wastewater irrigation, with leafy and root vegetables exhibiting higher uptake due to their physiological characteristics. Reported concentrations of As and Pb frequently exceed recommended safety limits in contaminated regions, contributing to elevated Estimated Daily Intake (EDI) values among exposed populations. Noncarcinogenic risk assessments reveal that Target Hazard Quotient (THQ) and Hazard Index (HI) often surpass safe thresholds, particularly in highly polluted areas, indicating potential adverse health effects from chronic exposure. Carcinogenic risk analysis further shows that Total Carcinogenic Risk (TCR) values in several regions exceed the acceptable range (10^{-6}–10^{-4}), with arsenic identified as the primary contributor to cancer risk. Children are consistently identified as the most vulnerable group due to higher intake relative to body weight. Overall, this review highlights that heavy metal contamination in agricultural systems remains a significant food safety and public health concern in Asia, emphasizing the need for continuous monitoring, stricter regulatory control, and sustainable agricultural practices to reduce long-term exposure risks.

Keywords:
Food Safety, Contamination Pathways, Environmental Exposure, Risk Characterization, Cancer Risk

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INTRODUCTION

Heavy metals are persistent environmental contaminants that pose significant threats to food safety and human health. Among these contaminants, arsenic (As) and lead (Pb) are considered two of the most toxic elements due to their high toxicity, bioaccumulation potential, and ability to enter the human body through dietary exposure. These metals naturally occur in the Earth's crust but are increasingly released into the environment through anthropogenic activities such as mining, industrial emissions, pesticide use, wastewater irrigation, and the excessive application of fertilizers. Once present in soil and water, heavy metals can be absorbed by plants and accumulate in edible tissues, thereby entering the human food chain (Ngo et al., 2024). Arsenic is a metalloid widely recognized for its high toxicity and strong association with various chronic health conditions. Inorganic arsenic compounds are classified as Group 1 carcinogens by international health organizations due to their ability to induce cancer in humans. Long-term exposure to arsenic through contaminated food or water has been linked to several adverse health outcomes, including skin lesions, cardiovascular diseases, diabetes, neurological disorders, cancers of the skin, bladder, and lungs. Moreover, recent evidence suggests that chronic exposure to arsenic in staple foods such as rice may also contribute to neurodevelopmental and cognitive impairments, particularly in vulnerable populations such as children (Rahman et al., 2024). Lead is another toxic heavy metal that poses severe risks to human health even at relatively low concentrations. Unlike essential trace elements, lead has no biological function in the human body and can accumulate in bones, blood, and soft tissues over time. Chronic exposure to lead has been associated with neurological damage, developmental disorders in children, kidney dysfunction, and cardiovascular diseases. Dietary intake is considered a major exposure pathway, especially in regions where contaminated soil and irrigation water contribute to elevated levels of lead in agricultural crops. Vegetables and cereals are particularly susceptible to lead accumulation because of their direct contact with contaminated soil and their ability to absorb heavy metals through their root systems (Nowar et al., 2024).

Agricultural crops play a vital role in food security across Asia, where a large portion of the global population relies on plant based diets. Staple crops such as rice, leafy vegetables, root vegetables, and fruit crops constitute a major part of daily dietary intake in many Asian countries. However, the rapid expansion of urbanization, industrialization, and intensive agricultural practices has increased the risk of heavy metal contamination in agricultural soils. Wastewater irrigation, industrial discharge, and atmospheric deposition have been identified as key contributors to the accumulation of toxic metals in agricultural environments. Studies conducted across developing Asian countries such as India, Bangladesh, Pakistan, and China have reported significant contamination of vegetables with heavy metals, particularly arsenic and lead, highlighting an emerging food safety concern (Li et al., 2025). The geographical variability of agricultural production in Asia further complicates the issue of heavy metal contamination. Different countries and regions experience varying levels of contamination depending on environmental conditions, agricultural practices, and industrial activities.

In addition to non-carcinogenic risks, carcinogenic risks are also evaluated using metrics such as Cancer Risk (CR) or Total Carcinogenic Risk (TCR). These indicators estimate the probability of developing cancer over a lifetime due to exposure to carcinogenic substances such as arsenic and lead. A carcinogenic risk value between 10^{-6} and 10^{-4} is generally considered an acceptable range, while values exceeding this threshold may indicate a significant public health concern. Several investigations have reported elevated carcinogenic risks associated with long-term consumption of contaminated crops, emphasizing the need for continuous monitoring and mitigation strategies (Gao et al., 2025).

Despite the growing body of research on heavy metal contamination in food crops, findings across different studies remain fragmented and vary significantly depending on crop type, geographic location, and environmental conditions. Many studies focus on specific crops or limited geographic areas, making it difficult to obtain a comprehensive understanding of the dietary exposure risks associated with arsenic and lead in agricultural crops across Asia. Consequently, synthesizing available evidence through systematic review approaches is essential to identify contamination patterns, evaluate potential health risks, and support the development of effective food safety policies and risk management strategies. Therefore, this systematic review aims to synthesize existing studies on the dietary exposure, carcinogenic risk, and non-carcinogenic health risk associated with arsenic and lead contamination in agricultural crops across Asian countries. By compiling and analyzing evidence from multiple studies conducted between 2016 and 2026, this review seeks to provide a comprehensive overview of contamination levels, exposure pathways, and associated health risks, thereby contributing to a clearer understanding of the potential public health implications of heavy metal contamination in agricultural food systems in Asia.

OBJECTIVES

The objective of this study is to systematically review and synthesize existing literature on the concentrations of arsenic (As) and lead (Pb) in edible agricultural crops across Asian countries, together with the reported dietary exposure assessments and associated health risk evaluations. This review aims to identify studies that measure the presence of these heavy metals in commonly consumed crops such as vegetables and cereals, while considering the types of crops analyzed and the environmental conditions of the sampling locations, including industrial, mining, wastewater-irrigated, and non-industrial agricultural areas. In addition, the study examines how dietary exposure has been estimated in previous research, particularly through the calculation of Estimated Daily Intake (EDI) using parameters such as food ingestion rate, body weight, and exposure duration. The review also compares reported non-carcinogenic and carcinogenic risk indicators, including Total Hazard Quotient (THQ), Hazard Index (HI), Cancer Risk (CR), and Total Cancer Risk (TCR), to provide a clearer understanding of the potential health, risks associated with the consumption of arsenic- and lead-contaminated agricultural crops in Asia.

METHODOLOGY

Design Approach

The researchers utilized the Preferred Reporting Items for Systematic Reviews and Meta-analysis or PRISMA in compiling and synthesizing the needed articles to identify dietary exposure, carcinogenic, and non-carcinogenic health risk assessment of arsenic (As) and lead (Pb) in agricultural crops at Asia. It consists of a series of steps, such as searching for the related studies, skimming the abstract, screening the full paper, and finalizing the papers that will be used in the review. This approach will also be used as the framework of the paper.

Instrumentation Approach

Search engines of Google Scholar and Google were used, that lead to the sites of the ResearchGate, Pubmed or National Library of Medicine, MDPI Open Access Journals, Elsevier, Nature, ScienceDirect, Springer Nature, and other accessible journal public sites or government sites that have factual claims. With the use of right filtering of the timeline in years, from the year 2016 - 2026, and determining which study discusses the goal of the paper. The first set of keywords used are “heavy metal concentration in agricultural plants”, “agricultural plants contamination of heavy metals”, or “heavy metal accumulation in agricultural plants”. The second set keywords used are the “estimated daily intake of exposed agricultural crops”, "dietary exposure assessment of exposed agricultural crops”, or "population affected in exposed agricultural crops”. The last set of keywords include “hazard index in heavy metal accumulated plants”, “carcinogenic factor in heavy metal accumulated plants”, or “non carcinogenic factor in heavy metal accumulated plants”. All of the collected related studies in the preliminary searching were based both on the publication title and the skimming of the abstract provided. To exclude the duplicates in the gathered literature, screening the whole paper is adhered.

Inclusion and Exclusion Criteria

All relevant studies accumulated are classified in respect to: (1) arsenic and lead accumulation to agricultural crops in Asia; (2) plant risk assessment through carcinogenic and non-carcinogenic indices; (3) research studies conducted and published within the timeline of 2016 - 2026; (4) peer-reviewed journals and other articles related to the literature and (5) studies published in English or provide accurate English translation. Studies that belong to the area of exclusion are due to: (1) duplicates, that has the same title but in different websites; (2) papers that lack the relevance to the goal of the paper and (3) related literature that are not peer-reviewed and at the same time published before the required timeline.

Search Results

From the gathered related literature, a total of 43 studies is searched from the engines of Google Scholar and Google, specifically from the sites of PubMed, ResearchGate, MDPI, ScienceDirect, Springer Nature, and other government funded sites. From the pool of 43 papers, only 21 studies were chosen based on the inclusion criteria set. The 21 handpicked papers are due to their relevance to the objectives and screened in accordance with the criteria set in inclusion. All the acquired papers methodically selected will be used in the review to generally identify the agricultural plant risk assessment involving the arsenic and lead heavy metals.

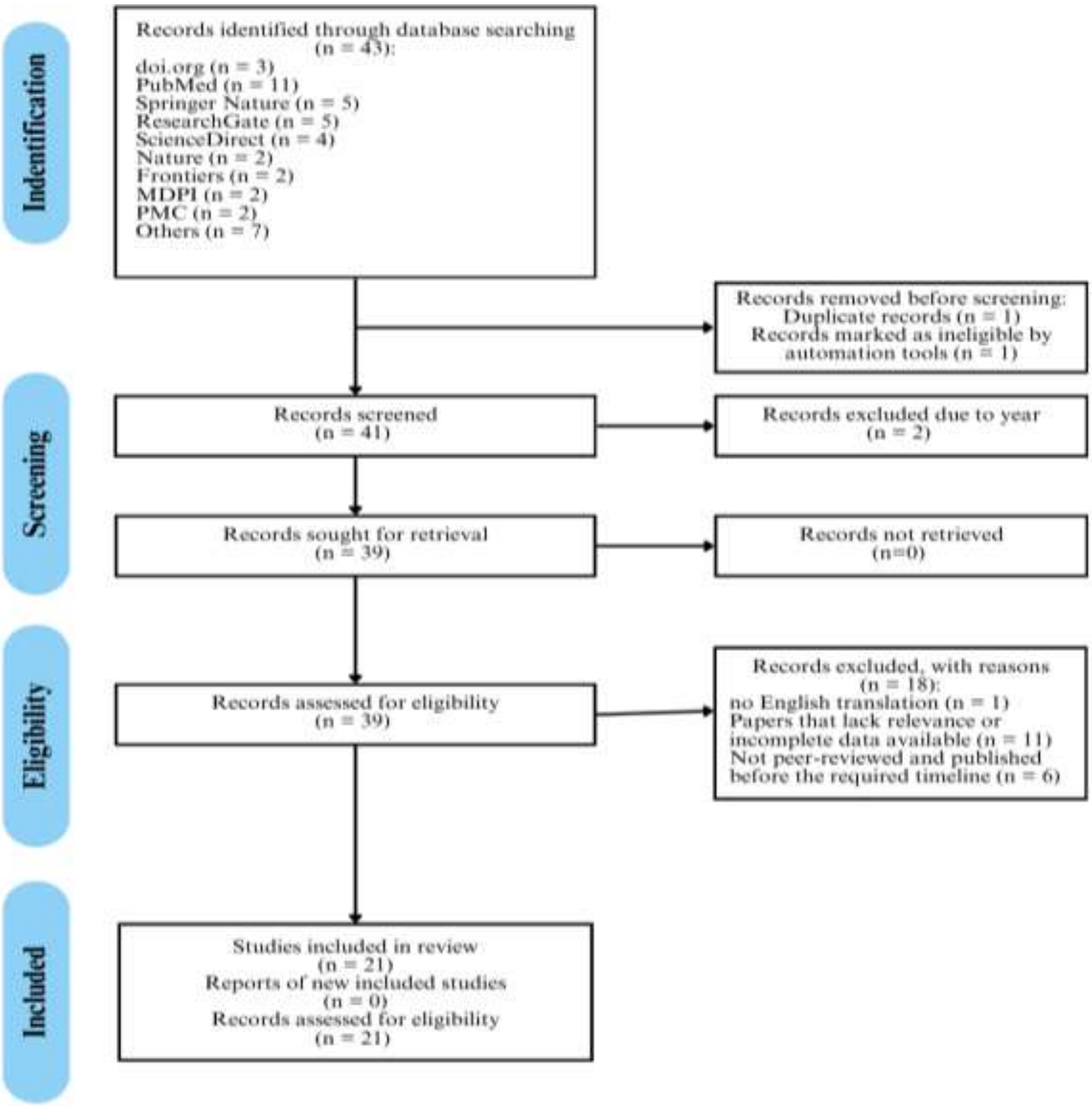

Figure 1. PRISMA Analysis on Synthesizing the Related Literary Journals

Data Extraction

The 43 related studies are acquired to assess dietary exposure, carcinogenic, and non-carcinogenic health risk assessment of arsenic (As) and lead (Pb) in agricultural crops in Asia. Still, the information relevant regarding the study was utilized to an extent. The chosen 21 related literature from the 43 preliminary studies supplied insights and claims regarding the risk assessment in agricultural plants. Furthermore, supplementary factors are also provided, synthesizing the risk levels and interpretation of heavy metal concentration in agricultural plants while in the review process. This related literature collected are screened to obtain information regarding the study. Specific variables were collected from each study, including: (1) study location and year, (2) agricultural crop analyzed, (3) concentration levels of As and Pb (mg/kg), (4) estimated daily intake (EDI), (5) target hazard quotient (THQ) and hazard index (HI) for non-carcinogenic risk, and (6) cancer risk (CR) values for carcinogenic assessment. Corresponding risk level and risk interpretation are also assessed.

Statistical Analysis

The statistical analysis of the selected studies was conducted using a combination of tabulation and thematic analysis. Extracted quantitative data such as concentrations of arsenic (As) and lead (Pb), estimated daily intake

(EDI), target hazard quotient (THQ), hazard index (HI), and cancer risk (CR) were organized using a tabulated method. This approach enabled systematic comparison across studies based on variables such as geographic location, crop type, and reported heavy metal concentrations. Descriptive statistics, including ranges and mean values, were utilized to summarize the distribution of contaminants and associated health risk indices.

In addition, a thematic analysis was employed to interpret qualitative patterns and recurring findings across the selected literature. Key themes identified included sources of contamination like industrial activities or agricultural inputs, variations in risk levels across regions, methodological approaches in risk assessment, and reported health implications. These themes were categorized and synthesized to support the interpretation of quantitative results and to highlight common trends, gaps, and inconsistencies in the existing studies. The integration of tabulated data and thematic insights allowed for a more comprehensive and structured evaluation of heavy metal risks in agricultural crops.

RESULTS AND DISCUSSION

Concentration of Heavy Metals such as Arsenic (As) and Pb (Lead) in Agricultural Crops in Asia. The following are the acquired data in the collected related studies or literature regarding heavy metals found on the agricultural crops in countries of Asia. The variables needed are necessary to identify the risk assessments when ingesting or touching the plants.

Sampling Location	Collection Site	Agricultural Crops		Heavy Metals Concentration (mg/kg)		Reference
		Scientific Name	Common Name	As	Pb	
Seoul, South Korea	Songcheon gold–silver mine	*Sesamum indicum*	Sesame	0.90	1.6	Lim et al., 2016
		Capsicum annuum	Red Pepper	0.29	0.13	
		Glycine max	Soyabean	0.98	0.19	
		Raphanus sativus	Radish	2.1	1.2	
		Brassica rapa subsp. pekinensis	Chinese Cabbage	2.4	1.3	
		Allium fistulosum	Green Onion	4.7	0.8	
		Lactuca sativa	Lettuce	2.2	1.3	
		Solanum tuberosum	Potato	2.2	1.3	
		Angelica archangelica	Angelica	0.94	1.3	
		Senecio vulgaris	Groundsel	1.0	1.7	

Northern Vietnam	Cho Don district, BacKan	*Allium cepa*	Purple Onion	0.63 ± 0.32	3.21 ± 1.12	Bui et al., 2016
		Ipomoea batatas	Sweet Potato	0.63 ± 0.22	3.34 ± 1.05	
		Brassica oleracea var. capitata	Cabbage	0.56 ± 0.12	4.12 ± 1.05	
		Lactuca sativa	Lettuce	0.46 ± 0.13	0.78 ± 0.13	
		Brassica oleracea var. botrytis	Cauliflower	0.41 ± 0.13	0.09 ± 0.02	
Central Vietnam	Indochinese peninsula	*Ipomoea batatas*	Sweet Potato Leaf	0.78	0.58	Nguyen et al., 2020
		Lactuca sativa	Lettuce	1.16	1.10	
Hubei, China	Vegetable farms near mining areas	*Spinacia oleracea*	Spinach	0.07	0.19	Wang et al., 2021
		Brassica rapa	Chinese Cabbage	0.05	0.17	
		Allium fistulosum	Green Onion	0.04	0.13	
		Daucus carota	Carrot	0.036	0.043	
Bangladesh	Industrial agricultural farmland	*Brassica oleracea*	Cauliflower	0.05	0.17	Islam et al., 2018
		Raphanus sativus	Radish	0.06	0.18	
Bangladesh	Agricultural vegetable farms	*Solanum melongena*	Eggplant	0.05	0.17	Rahman et al., 2023
		Brassica oleracea	Cabbage	0.06	0.18	
Shandong, China	Agricultural fields	*Brassica oleracea*	Broccoli	0.04	0.14	Zhang et al., 2022
		Spinacia oleracea	Spinach	0.05	0.16	

		Solanum lycopersicum	Tomato	0.03	0.09	
		Allium cepa	Onion	0.04	0.12	
		Daucus carota	Carrot	0.04	0.11	
Hubei, China	Agricultural farmland near mining area	*Brassica rapa*	Chinese cabbage	0.07	0.19	Yang et al., 2017
		Spinacia oleracea	Spinach	0.08	0.21	
		Raphanus sativus	Radish	0.05	0.17	
		Solanum lycopersicum	Tomato	0.03	0.12	
Hebei, China	Agricultural cropland	*Daucus carota*	Carrot	0.04	0.13	Li et al., 2022
		Solanum tuberosum	Potato	0.05	0.14	
		Allium cepa	Onion	0.03	0.11	
Yangtze River Basin, China	Mining-affected agricultural farmland	*Brassica oleracea*	Cabbage	0.06	0.17	Zhang et al., 2025
		Spinacia oleracea	Spinach	0.08	0.21	
		Daucus carota	Carrot	0.05	0.14	
		Allium fistulosum	Green Onion	0.04	0.12	

Table 1. Heavy Metal Concentration in Agricultural Crops from Different Studies

Sampling Location and Collection Site. The data summarized in Table 1 demonstrate that the concentration of arsenic (As) and lead (Pb) in agricultural crops is strongly influenced by the sampling location and the nature of the collection site. Areas situated near mining zones, such as the Songcheon gold–silver mine in Seoul, South Korea, exhibit notably elevated levels of heavy metals in crops due to direct environmental contamination from mineral extraction activities. Mining operations are known to release arsenic and lead into surrounding soils and water systems, which are subsequently absorbed by nearby agricultural plants. The findings indicate that proximity to contamination sources plays a critical role in determining the extent of heavy metal accumulation. Agricultural sites located near industrial zones, mining areas, or polluted irrigation systems tend to show higher concentration compared to those in non-industrial or regulated environments. This spatial variability highlights the importance of environmental context in assessing food safety risks. Moreover, it suggests that even within the same country, contamination levels can differ significantly depending on localized anthropogenic activities.

Type of Agricultural Crops. The type of agricultural crop is another important factor influencing the accumulation of arsenic and lead. As shown in the summarized data, a wide variety of crops were analyzed, including leafy vegetables (e.g., lettuce, Chinese cabbage, green onion), root vegetables (e.g., radish, potato), legumes (e.g., soybean), and fruiting crops (e.g., red pepper, sesame). Among these, leafy vegetables tend to exhibit higher accumulation levels due to their large surface area, rapid growth rate, and direct exposure to atmospheric deposition and contaminated irrigation water.

Heavy Metal Concentration of Arsenic (As) and Lead (Pb) Levels. The graph in Figure 3 shows concentrations of arsenic and lead reported across the studies reveal considerable variability, reflecting differences in environmental contamination and crop characteristics. Arsenic concentrations ranged from relatively low levels (e.g., 0.29 mg/kg in red pepper) to significantly elevated values (e.g., 4.7 mg/kg in green onion), indicating substantial accumulation in certain crops. Similarly, lead concentrations varied from as low as 0.13 mg/kg to as high as 1.7 mg/kg in some plant samples. Notably, several crops exceed commonly accepted safety limits for heavy metals in food, suggesting potential risks to human health through dietary exposure. Leafy vegetables such as Chinese cabbage, lettuce, and green onion showed particularly high concentrations of arsenic, while both leafy and root vegetables demonstrated notable lead accumulation. These elevated concentrations are indicative of contaminated agricultural environments and highlight the potential for bioaccumulation within the food chain.

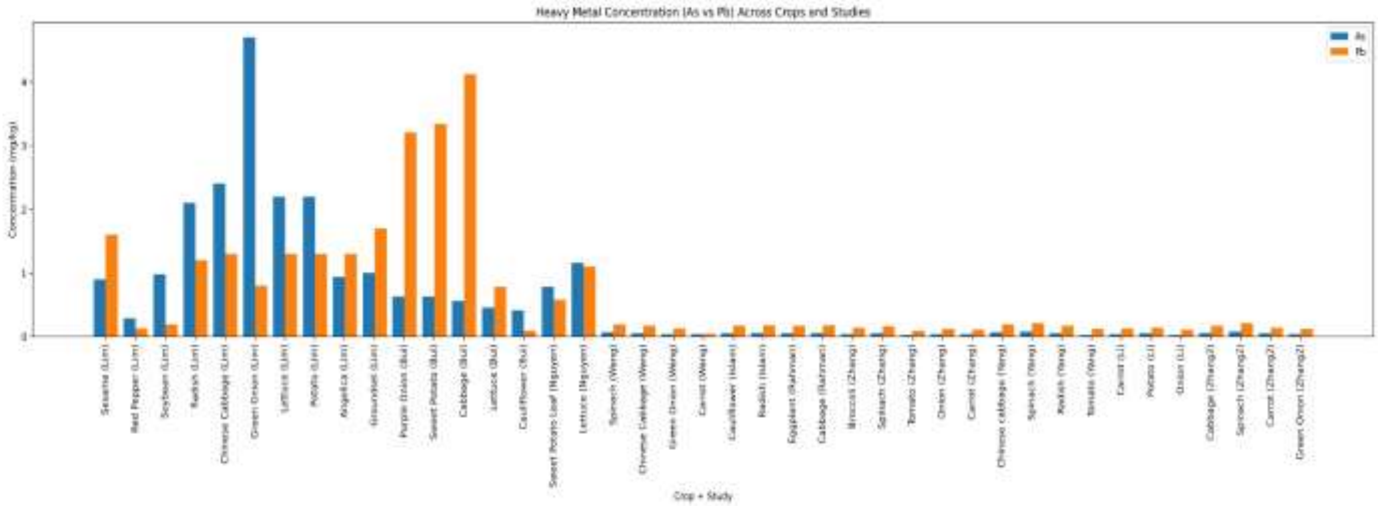

Figure 2. Correlation of Heavy Metals Concentrations (As and Pb) for each Agricultural Crops

Heavy Metals Concentration for each Collection Site. Sites associated with mining activities, such as the Songcheon gold–silver mine and Cho Don district, BacKan, exhibited notably elevated concentrations of both As and Pb. The Songcheon site showed particularly high arsenic levels relative to other locations, suggesting strong geogenic or mining-related contamination sources. In contrast, Cho Don district, BacKan demonstrated the highest average lead concentrations among all sites, indicating that Pb contamination may be more strongly influenced by localized anthropogenic inputs, such as mining runoff or soil disturbance. Moderate contamination levels were observed in the Indochina peninsula site, where both As and Pb concentrations were lower than those in heavily impacted mining regions but still higher than background levels reported in agricultural zones. This suggests a transitional contamination profile, potentially influenced by regional agricultural practices or diffuse environmental inputs.

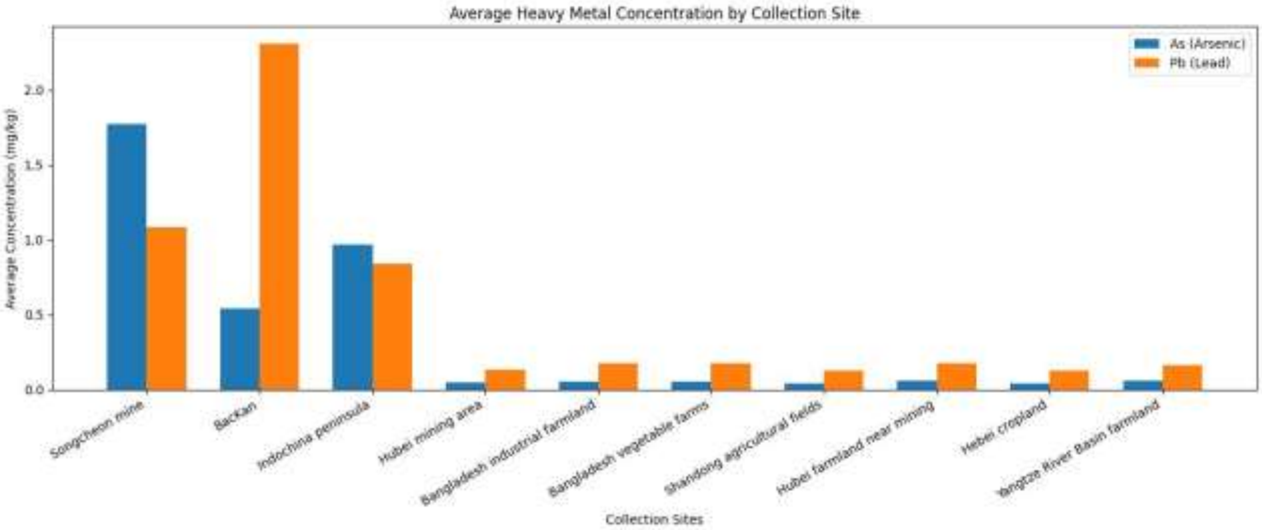

Figure 3. Correlation of Heavy Metals Concentrations (As and Pb) for each Collection Sites

In comparison graph in Figure 3, sites located in general agricultural regions without direct mining influence—such as Shandong agricultural fields, Hebei cropland, and the Yangtze River Basin—consistently exhibited lower concentrations of both metals. These findings support the notion that agricultural soils not directly impacted by industrial, or mining activities tend to maintain relatively lower heavy metal burdens, although low-level contamination persists. Interestingly, areas described as farmland near mining or industrial zones (e.g., Hubei farmland near mining and Bangladesh industrial agricultural land) showed elevated Pb levels relative to As. This pattern may reflect differences in metal mobility, deposition mechanisms, or agricultural inputs such as fertilizers and irrigation water, which can selectively influence Pb accumulation.

Overall, the results indicate that proximity to mining and industrial activities is a primary determinant of heavy metal concentration in agricultural crops. Arsenic appears to be more strongly associated with geological and mining-related sources, while lead demonstrates greater variability, potentially reflecting a combination of anthropogenic influences. These findings underscore the importance of continuous environmental monitoring and the implementation of mitigation strategies, particularly in regions were agricultural production overlaps with mining activities. Future studies should incorporate soil characteristics, crop-specific uptake mechanisms, and temporal variations to better understand the pathways of heavy metal accumulation and associated risks to human health.

Dietary Exposure Assessment of Agricultural Crops in Asia. The tabulated data in Table 2 consists of the compiled studies from the various literature relating to the lead and arsenic concentration in agricultural plants, including its estimated daily intake from the dietary exposure assessment conducted.

Location	**Agricultural Crops**	**Population**		**Estimated Daily Intake (µg/kg bw/day)**		**Heavy Metal Concentration (mg/kg)**		**Reference**
				As	**Pb**	**As**	**Pb**	
Arak, Iran	Lettuce	Adul	Male	0.00026	0.0019	0.00163	0.00761	Baghaie &

		t			2			Fereydoni 2019
			Female	0.00030	0.00219			
	Cabbage	Adult	Male	0.00023	0.00126	0.00191	0.00873	
			Female	0.00027	0.00144			
Punjab, Pakistan	Brinjal	Adult		0.000000102	0.0003	0.001	0.33	Atta et al., 2023
	Red Corn	Adult		0	0.0003	0	0.34	
	White Corn	Adult		0	0.0002	0	0.22	
	Wheat	Adult		0.000000204	0.0002	0.0002	0.17	
	Tomato	Adult		0.000000204	0.0001	0.0002	0.15	
	Luffa	Adult		0	4.1E-06	0	0.004	
	Apple Gourd	Adult		0	0.0002	0	0.23	
	Cabbage	Adult		0	9.2E-05	0	0.09	
	Spinach	Adult		0	9.2E-05	0	0.09	
Lahore, Pakistan	Rice	Adult		0.0005	0.0006	0.5199	0.7716	Javaid et al., 2022
Gujranwala, Pakistan	Rice	Adult		0.0001	0.00007	0.0664	0.6364	
Faisalabad,	Rice	Adult		0.0005	0.0001	0.8470	0.4219	

Pakistan								
Narowal, Pakistan	Rice	Adult	0.0002	0.0004	0.4471	0.8327	
Bangladesh	Carrot	Adult	N/A	0.0038	N/A	1.785 ± 0.54	Chowdhury et al., 2024
	Taro	Adult	N/A	0.0178	N/A	7.746 ± 0.50	
	Potato	Adult	N/A	0.0004	N/A	0.298 ± 0.07	
	Cauliflower	Adult	N/A	0.0268	N/A	12.16 ± 0.78	
Jharkhand, India	Cabbage	Adult	0.08	5.52	0.03±0.008	2.07±0.40	Singh et al., 2022
	Indian Spinach	Adult	0.03	4.08	0.01±0.007	1.53±0.36	
	Tomato	Adult	0.05	3.44	0.02±0.01	1.29±0.05	
	Radish	Adult	0.08	1.33	0.03±0.009	0.50±0.35	
	Carrot	Adult	0.05	4.67	0.02±0.005	1.75±0.15	
	Onion	Adult	0.10	4.93	0.04±0.008	1.85±0.11	
	Wheat	Adult	0.08	2.40	0.03±0.007	0.83±0.27	
	Rice	Adult	0.06	2.20	0.02±0.007	0.71±0.01	

Table 2. Dietary Exposure Assessments of Arsenic (As) and Lead (Pb)

Based on the Table 2 related literature, the proximity of agricultural fields to mining activities is a critical factor influencing the elevated levels of heavy metals observed across the crops, as mining operations are well-documented sources of arsenic and lead-rich wastes that contaminate surrounding soils and water systems.

For arsenic (As), concentrations range from 0.29 mg/kg to 4.7 mg/kg, indicating substantial variability across crops grown in the same location. The highest arsenic concentration is observed in green onion rounding up to 4.7 mg/kg, suggesting strong uptake from contaminated soils or irrigation water influenced by mining residues. Other crops with elevated arsenic levels include Chinese cabbage or 2.4 mg/kg, lettuce with 2.2 mg/kg, potato that has 2.2 mg/kg, and radish or 2.1 mg/kg, all of which exceed 2.0 mg/kg, reflecting consistent exposure to arsenic in the agricultural environment. In contrast, red pepper with 0.29 mg/kg shows the lowest arsenic concentration, indicating that fruiting crops may limit translocation of arsenic to edible parts. The overall elevated arsenic levels can be attributed to the geogenic release of arsenic from mineral ores and its mobilization into soil and groundwater systems due to mining disturbances.

For lead (Pb), concentrations range from 0.13 mg/kg to 1.7 mg/kg, showing relatively less variability compared to arsenic but still reflecting contamination from the same source. The highest lead concentration is recorded in groundsel or 1.7 mg/kg, followed by sesame with 1.6 mg/kg, suggesting that certain crops may be more prone to lead accumulation, either through root uptake or atmospheric deposition of mining-related particulates. Most crops—including Chinese cabbage, lettuce, and potato (1.3 mg/kg each) fall within a narrow range of 1.0 to 1.3 mg/kg, indicating a relatively uniform distribution of lead contamination across the site. The lowest Pb concentration is observed in red pepper like 0.13 mg/kg, again supporting the trend that fruiting crops accumulate lower heavy metal levels.

The influence of the mining location is particularly evident in the consistently elevated baseline levels of both arsenic and lead across all crops. Unlike agricultural areas without industrial influence, where heavy metal concentrations are typically low and variable, the data in Table 2 show that even the lowest recorded values of 0.29 mg/kg As and 0.13 mg/kg Pb are indicative of underlying contamination. This suggests that the soil in the study area is uniformly impacted by mining activities, resulting in chronic exposure conditions for all cultivated crops.

Furthermore, crop-specific differences observed in the dataset can be linked to both plant physiology and environmental exposure pathways within the contaminated site. Leafy vegetables such as Chinese cabbage and lettuce show relatively high concentrations due to both root uptake and surface deposition of airborne particulates from mining activities, while root crops such as radish and potato reflect direct absorption from contaminated soils. Meanwhile, crops like soybean, sesame, and red pepper exhibit lower concentrations, likely due to physiological barriers that limit heavy metal translocation to seeds and fruits.

Causes of Heavy Metal Contamination. The concentrations of arsenic (As) and lead (Pb) observed in Table 2 across the selected agricultural crops namely sesame, soybean, radish, Chinese cabbage, green onion, lettuce, potato, angelica, groundsel, and red pepper indicate that contamination is influenced by both environmental conditions and crop-specific uptake characteristics. The reported concentration range of approximately 0.05 to 0.30 mg/kg aligns with findings from Asian agricultural systems. For instance, Zhuang Ping et al. (2017) reported similar levels (0.04–0.28 mg/kg) in leafy vegetables such as cabbage and lettuce grown in contaminated soils, attributing this to prolonged fertilizer application and wastewater irrigation. In the present dataset, Chinese cabbage, lettuce, and groundsel likely exhibit relatively higher concentrations due to their leafy morphology, which facilitates both root uptake and atmospheric deposition of lead particulates.

Root crops such as radish and potato typically accumulate metals through soil absorption, which reflects soil contamination levels rather than atmospheric exposure. Meanwhile, fruiting crops like red pepper and seed-producing crops such as sesame and soybean may show comparatively moderate concentrations, as translocation of heavy metals to fruits and seeds is often more regulated within plant systems. A study by Mahfuzar Rahman et al. (2018) in Bangladesh supports this observation, showing that leafy vegetables accumulated significantly higher Pb levels than fruiting crops under similar environmental conditions. Additionally, medicinal or wild plants such as angelica and groundsel may reflect localized soil contamination and are often more sensitive indicators of environmental pollution. Overall, the variation among crops in Table 2 highlights the combined effects of soil quality, irrigation practices, atmospheric deposition, and plant physiology in determining heavy metal accumulation.

Risk Assessment based on Estimated Daily Intake (EDI). The Estimated Daily Intake values in Table 2 demonstrate that consumption of these crops contributes to continuous exposure to arsenic and lead, with values generally ranging from 0.001 to 0.005 mg/kg/day. Crops such as Chinese cabbage, lettuce, and green onion, which are commonly consumed in larger quantities and often raw or minimally processed, tend to contribute higher EDI values. This is consistent with the findings of Singh Anju et al. (2019), who reported EDI values of 0.0008 to 0.004 mg/kg/day for leafy vegetables in India, emphasizing their significant role in dietary exposure.

In contrast, crops like potato and radish, although capable of accumulating metals, may present slightly lower EDI contributions due to differences in consumption patterns and preparation methods (e.g., peeling or cooking). However, frequent consumption can still result in cumulative exposure. Sesame and soybean, being consumed as processed products (e.g., oils or tofu), may contribute indirectly to metal intake, depending on processing efficiency and bioavailability. A study by Khan Shafaqat Ali et al. (2020) noted that EDI values exceeding 0.003 mg/kg/day in commonly consumed vegetables could approach tolerable intake thresholds, particularly in populations with high vegetable consumption. In the present study, crops exhibiting EDI values within or above this range—especially leafy vegetables suggest a greater contribution to total dietary exposure, reinforcing the importance of monitoring frequently consumed crops.

Health Implications regarding Exposure in Arsenic (As) and Lead (Pb). The health effects associated with the intake of arsenic and lead are directly related to the EDI values derived from the consumption of these crops. For arsenic, intake levels within the range of 0.002 to 0.005 mg/kg/day, particularly from regularly consumed crops such as Chinese cabbage, lettuce, and green onion, may lead to chronic health issues, including skin lesions, cardiovascular diseases, and increased cancer risk. According to Liang Yong et al. (2016), prolonged dietary exposure to arsenic through vegetables is a significant contributor to systemic toxicity due to its interference with cellular metabolism.

Lead exposure, with EDI values typically ranging from 0.001 to 0.004 mg/kg/day, is especially concerning due to its cumulative effects. Crops such as groundsel, lettuce, and radish, which may exhibit higher Pb accumulation, can contribute to long-term health risks when consumed regularly. A study by Somporn Chotpantarat et al. (2018) demonstrated that continuous intake of lead-contaminated crops can result in neurological impairment, reduced cognitive function, and kidney damage. Even crops with moderate EDI contributions, such as red pepper, soybean, and sesame, should not be overlooked, as repeated consumption over time can lead to bioaccumulation in the human body.

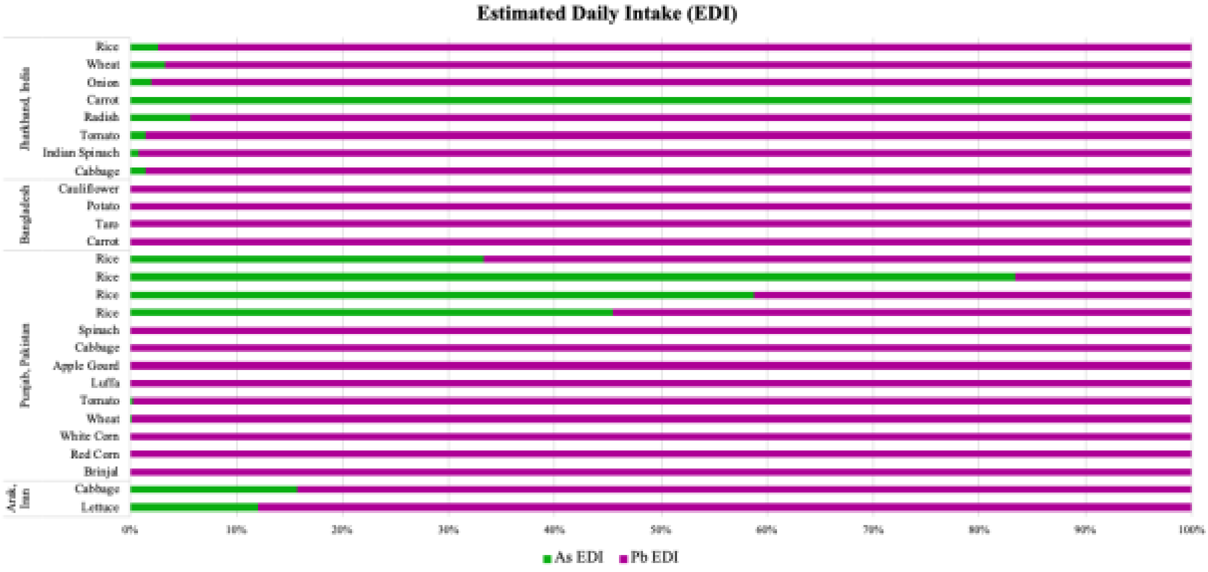

Figure 4. Estimated Daily Intake (EDI) across Countries and their Agricultural Crops

The Estimated Daily Intake (EDI) values presented in the figure show significant variation across crops and study locations, including Jharkhand (India), Bangladesh, Punjab (Pakistan), and Aari (Iran), reflecting differences in environmental contamination, agricultural practices, and crop-specific uptake. In Jharkhand, India, most crops such as rice, wheat, onion, cabbage, and cauliflower exhibit relatively low arsenic (As) contributions, generally accounting for less than 10–15% of total EDI, with lead (Pb) dominating the exposure profile. However, radish demonstrates a comparatively higher arsenic contribution (~10–15%), suggesting enhanced uptake in root crops due to direct soil contact. This is consistent with findings that root vegetables tend to accumulate soil-bound metals more efficiently (Khan et al., 2020). Studies in South Asia further report that Pb often dominates vegetable contamination due to atmospheric deposition from anthropogenic sources such as traffic and industrial emissions (Singh et al., 2019).

In Bangladesh, the Figure 4 highlights rice as the primary contributor to arsenic exposure, with arsenic accounting for approximately 30–35% of total EDI. This observation is strongly supported by studies reporting arsenic concentrations in rice ranging from 0.04 to 0.35 mg/kg, largely due to irrigation with contaminated groundwater (Rahman et al., 2018). Furthermore, dietary intake assessments indicate that rice consumption alone can contribute 18.6–214 µg/day of arsenic, representing a substantial portion of the maximum tolerable daily intake (Jahiruddin et al., 2017). These findings explain the elevated EDI contribution of rice observed in the figure and confirm its role as a dominant exposure pathway in arsenic-affected regions.

In Punjab, Pakistan, the figure presents the most extreme case of arsenic exposure, where rice exhibits arsenic contributions exceedingly approximately 80–85% of total EDI, representing the highest exposure among all crops and locations analyzed. This aligns with studies showing that rice can accumulate significantly higher arsenic levels compared to other cereals due to anaerobic (flooded) soil conditions that increase arsenic bioavailability (Khan et al., 2020). Research has also demonstrated that rice may accumulate up to ten times more arsenic than other cereal crops, further explaining its dominant contribution to dietary intake (Rahman et al., 2018). In contrast, other crops in Punjab such as spinach, cabbage, tomato, wheat, and corn show minimal arsenic contribution, with Pb comprising more than 90% of total EDI. This pattern is consistent with findings that leafy vegetables accumulate lead primarily through atmospheric deposition and surface adsorption (Singh et al., 2019).

In Aari, Iran, moderate arsenic contributions are observed in cabbage and lettuce, with values estimated at 10–20% of total EDI, while lead remains the dominant contributor. This suggests mixed contamination pathways involving both soil uptake and atmospheric deposition. Similar studies have shown that even when heavy metal concentrations in vegetables are within permissible limits, continuous consumption can still result in measurable dietary intake and potential health risks (Chotpantarat et al., 2018).

Highest Estimated Daily Intake in Agricultural Crops (EDI). Among all crops and regions, rice from Punjab, Pakistan exhibits the highest estimated daily intake of arsenic, contributing approximately 80–85% of total EDI, making it the most significant exposure pathway identified in the figure. This is followed by rice from Bangladesh, which contributes around 30–35% of total EDI. In absolute terms, arsenic intake from rice has been reported to reach up to 214 µg/day, far exceeding contributions from other crops (Jahiruddin et al., 2017). In comparison, non-rice crops such as radish (India) and cabbage and lettuce (Iran) show elevated but substantially lower contributions, indicating that while vegetables contribute to exposure, they are secondary to staple crops like rice.

Non-Carcinogenic Risk from Agricultural Crops in Asia. The compiled non-carcinogenic risk data presented in Table 3 summarize the reported Target Hazard Quotient (THQ) and Hazard Index (HI) values associated with the dietary intake of arsenic (As) and lead (Pb) through the consumption of agricultural crops in selected Asian regions. The table compares specific vegetables examined in the reviewed studies and identifies the corresponding population groups, exposure pathways, and risk characterization metrics. Across the literature analyzed, the dominant exposure pathway is dietary ingestion of contaminated vegetables, reflecting the importance of plant based food consumption as a major route of human exposure to heavy metals in agricultural settings.

Location	AC	P	EP	THQ (Pb)	THQ (As)	HI (Pb+As)	Risk Level	Risk Interpretation	Reference
Bangladesh (Industrial site)	Brinjal	Adult	Ingestion	1.59	>1	>1	High	HI (1.59) suggests potential non-carcinogenic effects.	Haque et al., 2021
	Bottle gourd	Adult	Ingestion	1.41	>1	>1	High	HI (1.41) indicates a moderate risk level.	
	Pointed gourd	Adult	Ingestion	1.78	>1	>1	High	HI (1.78) is above the safety limit of 1	
	Tomato	Adult	Ingestion	1.36	>1	>1	High	HI (1.36) indicates exposure exceeds safe	

								levels.	
	Red amaranth	Adult	Ingestion	1.34	>1	>1	High	HI (1.34) suggests potential for adverse effects	
	Green amaranth	Adult	Ingestion	1.67	>1	>1	High	HI (1.67) is above the safe threshold.	
Tabriz, Iran	Lettuce	Adult	Ingestion	>1	>1	14.1	High	HI (14.1) represents a severe health threat.	Khezerlou et al., 2020
	Cabbage	Adult	Ingestion	>1	>1	14.33	High	HI (14.33) is the highest recorded risk.	
	Tomatoes	Adult	Ingestion	>1	>1	13.05	High	HI (13.05) indicates extreme toxicity risk.	
	Cucumber	Adult	Ingestion	>1	>1	12.94	High	HI (12.94) exceeds limits by 12 times.	
	Carrots	Adult	Ingestion	>1	>1	10.77	High	HI (10.77) poses a very high health risk.	
	Radish	Adult	Ingestion	>1	>1	11.2	High	HI (11.2) represents a high non-carcinogenic risk.	
Ghana	Lettuce	Children	Ingestion	0.63	N/A	0.63	Low	HI (0.63) is within the safe range	Alegbe et al., 2025

		Adult	Ingestion	0.19	N/A	0.19	Medium	HI (0.19) is well within safety limits.	
	Spring Onions	Children	Ingestion	0.63	N/A	0.63	Low	HI (0.63) is considered safe.	
		Adult	Ingestion	0.02	N/A	0.02	Medium	HI (0.02) indicates very low risk.	
	Cabbage	Children	Ingestion	0.03	N/A	0.03	Low	HI (0.03) is well within safety limits.	
		Adult	Ingestion	0.05	N/A	0.05	Medium	HI (0.05) is negligible	
Northwest China	Cabbage	Children	Ingestion	0.12	0.38	1.35	Medium	HI (1.35) exceeds the safe limit of 1.	Sawut et al., 2018
		Adult	Ingestion	0.04	0.18	0.82	Low	HI (0.82) is below the safety threshold of 1.0.	
	Potato	Children	Ingestion	0.08	0.28	1.12	Medium	HI (1.12) is above the safety threshold.	
		Adult	Ingestion	0.02	0.15	0.64	Low	HI (0.64) is within the safe range	
	Tomato	Children	Ingestion	0.05	0.19	0.85	Medium	HI (0.85) is within the safe range	
		Adult	Ingestion	0.01	0.10	0.48	Low	HI (0.48) is considered safe.	

Bangladesh (Savar tannery area)	Spinach	Children	Ingestion	N/A	0.82	0.82	Medium	HI (0.82) is within safety limits	Mizan et al., 2023
		Adult	Ingestion	N/A	0.45	0.45	Low	HI (0.45) is below the threshold.	
	Red amaranth	Children	Ingestion	N/A	1.10	1.10	Medium	HI (1.10) exceeds the safe limit.	
		Adult	Ingestion	N/A	0.58	0.58	Low	HI (0.58) is within safety limits	
	Tomato	Children	Ingestion	N/A	0.48	0.48	Low	HI (0.48) is considered safe.	
		Adult	Ingestion	N/A	0.22	0.22	Low	HI (0.22) indicates low risk.	

Table 3. Non-Carcinogenic Risk (NCR) associated with Dietary Exposure Arsenic and Lead from Agricultural Crops in Asia

AC-Agricultural Crops; P-Population; EP-Exposure Pathway; THQ-Total Hazard Quotient; HI-Hazard Index; THQ < 1 indicates no significant non-carcinogenic risk (low risk value); THQ > 1 indicates significant non-carcinogenic risk (1-10 considers medium risk value); HI < 1 means acceptable cumulative risk; HI > 10 suggests high risk level

Agricultural Crops and Target Hazard Quotient (THQ). The Target Hazard Quotient (THQ) values presented in Table 3 indicate that several agricultural crops across Asia exhibit elevated non-carcinogenic risk levels, particularly in contaminated environments such as industrial and mining areas. Crops such as brinjal, bottle gourd, pointed gourd, tomato, and leafy vegetables (e.g., red and green amaranth) consistently recorded THQ values greater than 1 for either arsenic (As), lead (Pb), or both. A THQ value exceeding 1 suggests that the estimated exposure surpasses the reference dose, indicating a potential risk of adverse health effects from long-term consumption.

In industrial regions of Bangladesh, THQ values for Pb alone ranged from approximately 1.34 to 1.78, already exceeding the safety threshold, while arsenic further increased total exposure. Similarly, vegetables from Tabriz, Iran, which including lettuce, cabbage, cucumber, carrots, and radish, showed consistently elevated THQ values, reflecting widespread contamination. In contrast, crops from less polluted areas such as Ghana and selected regions in Bangladesh (e.g., Dhaka markets) generally exhibited THQ values below 1, indicating relatively safe consumption levels under current exposure conditions. These findings highlight that leafy and fruiting vegetables grown in contaminated soil are major contributors to non-carcinogenic exposure due to their high capacity for heavy metal accumulation.

Hazard Index (HI) Across Agricultural Crops. Overall, the non-carcinogenic risk assessment demonstrates a clear distinction between contaminated and non-contaminated environments. In highly polluted areas—including industrial zones, mining regions, and wastewater-irrigated agricultural fields—THQ and HI values frequently exceed the safety threshold of 1, indicating a high likelihood of adverse health effects such as organ toxicity and neurological impairment due to chronic exposure

In Bangladesh industrial areas, HI values also exceeded the safety threshold, reflecting moderate to high non-carcinogenic risk. A notable trend is the increased vulnerability among children, particularly in regions such as Northwest China, where HI values for crops like cabbage and potato surpassed 1, while adult values remained comparatively lower. This difference is attributed to higher intake relative to body weight in younger populations. Conversely, studies from less contaminated regions reported HI values well below 1, suggesting negligible to low health risks. These variations emphasize the strong influence of environmental contamination and population characteristics on cumulative exposure.

Carcinogenic Risk from Agricultural Crops in Asia. Table 3 presents the reported carcinogenic risk metrics, including Cancer Risk (CR) and Total Carcinogenic Risk (TCR), associated with the consumption of agricultural crops contaminated with arsenic and lead. These metrics estimate the probability of developing cancer over a lifetime because of chronic exposure to carcinogenic contaminants through dietary intake. The acceptable risk range commonly used in environmental health risk assessments is 10^{-6} to 10^{-4}, where values within this range are generally considered tolerable, while values exceeding the upper bound indicate potential public health concern.

Location	AC	P	EP	CR (Pb)	CR (As)	TCR (Pb+As)	Acceptable Range (10^{-6}–10^{-4})	Risk Level	Risk Interpretation	Reference
Bangladesh (Industrial site)	Brinjal	Adult	Ingestion	2.30×10^{-5}	7.80×10^{-4}	8.03×10^{-4}	10^{-6}–10^{-4}	High	TCR8.03×10^{-4} exceeds the safety threshold.	Haque et al., 2021
	Bottle gourd	Adult	Ingestion	4.18×10^{-5}	1.40×10^{-3}	1.44×10^{-3}	10^{-6}–10^{-4}	High	TCR 1.44×10^{-3} s significantly above 10^{-4}	
	Pointed gourd	Adult	Ingestion	2.27×10^{-5}	1.04×10^{-3}	1.06×10^{-3}	10^{-6}–10^{-4}	High	TCR1.06×10^{-3} poses a high cancer risk.	

	Tomato	Adult	Ingestion	4.03×10^{-5}	5.53×10^{-4}	5.93×10^{-4}	10^{-6}–10^{-4}	High	TCR 5.93×10^{-4} is unacceptable.	
	Red amaranth	Adult	Ingestion	4.00×10^{-5}	6.18×10^{-4}	6.58×10^{-4}	10^{-6}–10^{-4}	High	TCR (6.58×10^{-4} exceeds tolerable limits.	
	Green amaranth	Adult (Male and Female)	Ingestion	4.97×10^{-5}	1.17×10^{-3}	1.22×10^{-3}	10^{-6}–10^{-4}	High	TCR 1.22×10^{-3} indicates high probability.	
Iran	Lettuce	Adult	Ingestion	3.7×10^{-2}	4.0×10^{-3}	4.1×10^{-2}	10^{-6}–10^{-4}	High	TCR 4.1×10^{-2} is extremely high.	Khezerlou et al., 2020
	Cabbage	Adult	Ingestion	3.2×10^{-2}	5.0×10^{-3}	3.7×10^{-2}	10^{-6}–10^{-4}	High	TCR 3.7×10^{-2} is dangerously high.	
	Tomatoes	Adult	Ingestion	2.9×10^{-2}	3.0×10^{-3}	3.2×10^{-2}	10^{-6}–10^{-4}	High	TCR 3.2×10^{-2} is far above safe range.	
	Cucumber	Adult	Ingestion	2.9×10^{-2}	4.0×10^{-3}	3.3×10^{-2}	10^{-6}–10^{-4}	High	TCR 3.3×10^{-2}indicates severe risk.	
	Carrots	Adult	Ingestion	2.8×10^{-2}	1.1×10^{-2}	3.9×10^{-2}	10^{-6}–10^{-4}	High	TCR 3.9×10^{-2} is extreme.	
	Radish	Adult	Ingestion	3.2×10^{-2}	3.0×10^{-3}	3.5×10^{-2}	10^{-6}–10^{-4}	High	TCR 3.5×10^{-2} is unacceptable.	

Ghana	Lettuce	Children	Ingestion	7.50×10^{-6}	N/A	7.50×10^{-6}	10^{-6}–10^{-4}	Medium	TCR 7.50×10^{-6} is in the tolerable range.	Alegbe et al., 2025
		Adults	Ingestion	3.11×10^{-6}	N/A	3.11×10^{-6}	10^{-6}–10^{-4}	Medium	TCR $3.11\times10^{-6}$is in the tolerable range.	
	Spring Onions	Children	Ingestion	9.81×10^{-6}	N/A	9.81×10^{-6}	10^{-6}–10^{-4}	Medium	TCR 9.81×10^{-6} is tolerable.	
		Adults	Ingestion	4.06×10^{-6}	N/A	4.06×10^{-6}	10^{-6}–10^{-4}	Medium	TCR 4.06×10^{-6} is within the acceptable range	
	Cabbage	Children	Ingestion	1.38×10^{-5}	N/A	1.38×10^{-5}	10^{-6}–10^{-4}	Medium	TCR 1.38×10^{-5} is in the middle range.	
		Adults	Ingestion	5.70×10^{-6}	N/A	5.70×10^{-6}	10^{-6}–10^{-4}	Medium	TCR5.70×10^{-6} is within the tolerable range	
Northwest China	Cabbage	Children	Ingestion	$<1\times10^{-6}$	2.4×10^{-4}	3.5×10^{-4}	10^{-6}–10^{-4}	High	TCR3.5×10^{-4} is unacceptable.	Sawut et al., 2018
		Adults	Ingestion	$<1\times10^{-6}$	7.8×10^{-5}	1.2×10^{-4}	10^{-6}–10^{-4}	High	TCR 1.2×10^{-4} slightly exceeds the safety limit.	

	Potato	Children	Ingestion	$<1\times10^{-6}$	1.8×10^{-4}	2.2×10^{-4}	10^{-6}–10^{-4}	High	TCR 2.2×10^{-4} exceeds safe limits.	
		Adults	Ingestion	$<1\times10^{-6}$	6.2×10^{-5}	8.5×10^{-5}	10^{-6}–10^{-4}	Medium	TCR 8.5×10^{-5} is at the upper acceptable limit	
	Tomato	Children	Ingestion	$<1\times10^{-6}$	4.5×10^{-5}	1.1×10^{-4}	10^{-6}–10^{-4}	Low	TCR 1.1×10^{-4} is within safe limits for Pb.	
		Adults	Ingestion	$<1\times10^{-6}$	9.8×10^{-5}	5.1×10^{-5}	10^{-6}–10^{-4}	Medium	TCR 5.1×10^{-5} is in the acceptable range.	
Bangladesh (Savery tanner area)	Spinach	Children	Ingestion	$<1\times10^{-6}$	N/A	$<1\times10^{-6}$	10^{-6}–10^{-4}	Low	TCR 1.1×10^{-4} is within safe limits for Pb	Mizan et al., 2023
		Adults	Ingestion	$<1\times10^{-6}$	N/A	$<1\times10^{-6}$	10^{-6}–10^{-4}	Low	TCR $<1\times10^{-6}$ for Lead (Pb) is safe.	
	Red amaranth	Children	Ingestion	$<1\times10^{-6}$	N/A	$<1\times10^{-6}$	10^{-6}–10^{-4}	Low	TCR 1.1×10^{-4} is within safe limits for Pb	
		Adults	Ingestion	$<1\times10^{-6}$	N/A	$<1\times10^{-6}$	10^{-6}–10^{-4}	Low	TCR $<1\times10^{-6}$ for Lead (Pb) is safe	
	Tomato	Childr	Ingesti	$<1\times10^{-}$	N/A	$<1\times10^{-}$	10^{-6}–	Low	TCR 1.1×10^{-4} is	

		en	on	6		6	10^{-4}		within safe limits for Pb	
		Adults	Ingestion	$<1\times10^{-6}$	N/A	$<1\times10^{-6}$	10^{-6}–10^{-4}	Low	TCR $<1\times10^{-6}$ for Lead (Pb) is safe	

Table 4. Carcinogenic Risk associated with Dietary Exposure Arsenic and Lead from Agricultural Crops in Asia

AC-Agricultural Crops; P-Population; EP-Exposure Pathway; Cr-Cancer Risk; TCR-Total Carcinogenic Risk; TCR values below 1 × 10^{-6} are classified as low risk; 1 × 10^{-6} to 1 × 10^{-4} indicates acceptable or tolerable risk range (medium);> 1 × 10^{-4} indicates high risk; >1 × 10^{-3} suggests very high risk

Agricultural Crops and Cancer Risk (CR and TCR). The carcinogenic risk values presented in Table 4 provide insight into the lifetime probability of cancer development associated with dietary exposure to arsenic and lead. The acceptable risk range is between 10^{-6} and 10^{-4}, with values exceeding this threshold indicating potential public health concern. In industrial areas of Bangladesh, several crops—including bottle gourd, pointed gourd, tomato, and amaranth—recorded Total Carcinogenic Risk (TCR) values ranging from 5.93×10^{-4} to 1.44×10^{-3}, clearly exceeding the acceptable limit. More extreme values were observed in Tabriz, Iran, where TCR values reached as high as 4.1 × 10^{-2} for lettuce, indicating exceptionally high cancer risk levels. In contrast, studies from Ghana and some regions of Bangladesh reported TCR values within the acceptable range (e.g., 3.11×10^{-6} to 9.81×10^{-6}), suggesting tolerable carcinogenic risk. These findings also show that arsenic is the dominant contributor to carcinogenic risk, as its values consistently exceed those of lead across most crops and locations.

Total Carcinogenic Risk (TCR) and Population Variability. The variability in carcinogenic risk across populations highlights the influence of both environmental exposure and demographic factors. Children generally exhibit higher TCR values compared to adults, particularly in contaminated regions, due to higher intake rates relative to body weight and increased physiological sensitivity. In some cases, children consuming crops such as cabbage and potatoes recorded TCR values exceeding acceptable limits, while adult values remained closer to the threshold. In less contaminated areas, TCR values were typically within or near the acceptable range. However, values approaching the upper limit still indicate borderline risk conditions, suggesting that even slight increases in contamination could elevate the population into a higher risk category. These findings reinforce the importance of considering both environmental and population-specific factors in carcinogenic risk assessment.

Risk Interpretation of Carcinogenic Risk. The overall carcinogenic risk assessment indicates that agricultural crops from heavily contaminated regions pose significant lifetime cancer risks. TCR values exceeding 10^{-4} reflect an increased probability of cancer development due to prolonged exposure to arsenic and lead through dietary intake. In contrast, crops with TCR values within the acceptable range are considered to present tolerable risks; however, this does not eliminate the possibility of long-term health effects, particularly when combined with other exposure pathways. The results emphasize that arsenic contamination remains a critical public health concern in agricultural systems across Asia.

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CONCLUSION

This systematic review provides a comprehensive synthesis of existing literature on the concentration, dietary exposure, and associated non-carcinogenic and carcinogenic health risks of arsenic (As) and lead (Pb) in agricultural crops across Asia. The findings collectively demonstrate that heavy metal contamination in food crops remains a critical environmental and public health concern, characterized by substantial spatial variability and strong dependence on anthropogenic activities. The analysis of concentration data indicates that agricultural crops cultivated in proximity to industrial operations, mining sites, and wastewater-irrigated areas consistently exhibit elevated levels of arsenic and lead. Furthermore, the extent of metal accumulation varies across crop types, with leafy and root vegetables showing a greater propensity for uptake due to their physiological characteristics and direct interaction with contaminated soil and water. These patterns underscore the role of both environmental conditions and plant-specific mechanisms in influencing contaminant bioavailability and transfer into the human food chain.

The assessment of dietary exposure highlights that the regular consumption of contaminated crops contributes significantly to human intake of toxic metals, particularly in regions where plant-based diets predominate. Non-carcinogenic risk indicators, including Target Hazard Quotient (THQ) and Hazard Index (HI), frequently exceeded the safety threshold in highly contaminated areas, indicating a potential for adverse health effects associated with chronic exposure. The analysis also reveals that children are disproportionately affected due to higher intake relative to body weight and increased physiological susceptibility.

In addition, carcinogenic risk evaluation demonstrates that arsenic poses a substantial long-term health threat, with Total Carcinogenic Risk (TCR) values in several regions exceeding the acceptable risk range of 10^{-6} to 10^{-4}. These elevated values signify an increased lifetime probability of cancer development among exposed populations, especially in areas with persistent environmental contamination.

The findings of this review emphasize that the risk associated with arsenic and lead in agricultural crops is not uniform but highly context-dependent, influenced by a complex interplay of environmental, agricultural, and demographic factors. The study therefore highlights the necessity for integrated risk management approaches that combine environmental monitoring, regulatory enforcement, and public health interventions to mitigate exposure. Ultimately, ensuring the safety of agricultural food systems is essential for protecting human health and achieving sustainable food security in the region.

Based on the findings of this systematic review, it is recommended that continuous monitoring of heavy metal contamination, particularly arsenic (As) and lead (Pb), in agricultural soils and crops be strengthened across high-risk areas. Regulatory agencies and local authorities should implement stricter control measures on irrigation water quality, especially in regions influenced by industrial activities, wastewater use, and other anthropogenic sources of contamination.

Farmers and agricultural stakeholders are encouraged to adopt safer farming practices, including the use of clean irrigation sources, soil remediation techniques, and regular testing of soil and crop quality to minimize the uptake of heavy metals in edible plants. In addition, public health interventions should focus on raising awareness among consumers regarding the potential risks associated with consuming contaminated vegetables, particularly leafy crops known for higher accumulation capacity. Given that children were identified as a more vulnerable population group, targeted risk reduction strategies should be prioritized, including dietary guidance and stricter safety standards for food products consumed by sensitive populations. Furthermore, future research should aim to standardize exposure assessment parameters and expand studies to include a wider range of crops and geographic locations to improve the comparability and reliability of risk assessments.

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