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# Arsenic in Rice Grains: A Comprehensive Review of Agronomic Drivers, Health Risks and Food Security Challenges in Indian Rice Growing States

**Divya Prasad[1], Birendra Kumar[2], Alka Priyadarshni[1], Raunak Ranjan[3], Rupak Raj[4], Alok kumar[5], Priyanka kumari[6], Swati kumari[5], Khushboo Priya[7], Suraj Kumar[7], Ankita Kumari[7], Anshu Choudhary[8], Krishna Kumar[5], Vikash Kumar[9], Gyanendra B. Chand[1]**

[1]*Aquatic Toxicology Laboratory, Department of Zoology, Patna University, Patna.*
[2]*Department of Zoology, Magadh University, Bodh Gaya, India.*
[3]*Department of Botany, Magadh University, Bodh Gaya, India.*
[4]*Department of Botany, Patna University, Patna, India.*
[5]*Department of Zoology, Patna University, Patna, India.*
[6]*Department of Zoology, Lalit Narayan Mithila University, Darbhanga, India.*
[7]*Department of Zoology, Patliputra University, Patna, India.*
[8]*Department of Zoology, Bhupendra Narayan Mandal University, Madhepura, India.*
[9]*Department of Biochemistry, ICMR-RMRIMS, Agamkuan, Patna, India.*

***Corresponding Author: Dr. Gyanendra B. Chand***

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***Abstract:***

*The infiltration of arsenic (As) into agroecosystems, primarily through contaminated irrigation water and arsenic-enriched soils, constitutes a tenacious challenge to agricultural sustainability and public health globally. In India, where rice is the principal dietary backbone, long-term aquifer-derived arsenic inputs into flooded paddy environments compromise both plant performance and grain safety, which makes the paths of human exposure even worse. Although arsenic-prone regions such as West Bengal, Bihar, Uttar Pradesh, Jharkhand, and Assam have been well recognized, integrative evaluations of its transfer into rice-based agroecosystems remain limited. This review consolidates contemporary understanding of As entry into rice agroecosystems, with emphasis on soil, water, and plant linkages, cultivar-specific susceptibility, and agronomic drivers of bioaccumulation. Mechanistic insights, including arsenic speciation chemistry, rhizosphere transformations, and competitive uptake mechanisms with phosphorus and silicon, are presented to elucidate plant uptake dynamics. The review further addresses scientific insights within socio-economic dimensions, highlighting risks faced by smallholder producers and their implications for national food safety frameworks. Mitigation strategies, including water management techniques, alternative irrigation sources, soil amendments, and the development of cultivars with low As accumulation, are critically assessed for their scalability and sustainability in the Indian context. By bridging insights from environmental chemistry, plant physiology, and agronomy, the paper highlights the importance of region-specific risk assessments and robust policy support. In conclusion, it underscores the urgent requirement of multidisciplinary strategies to enhance food system integrity and reduce arsenic-associated health risks among exposed communities across India.*

***Keywords: Arsenic, bioaccumulation, rhizosphere, agroecosystems, and irrigation.***

**Introduction:**

As, a naturally occurring metalloid, has become a significant environmental contaminant with profound implications for human health, agriculture, aquatic, and ecological systems (Karak 2022; Divya Prasad et al. 2024; Wang et al. 2025). Globally, arsenic contamination is predominantly pronounced in South and Southeast Asia, where both geogenic processes and anthropogenic activities contribute to its pervasive presence in groundwater and soil matrices. An estimated 300 million individuals globally are at risk of arsenic exposure, with nearly 180 million cases concentrated in Asia. The Southeast Asian countries of Bangladesh, India, Pakistan, China, Nepal, Vietnam, Myanmar, Thailand, and Cambodia are notably affected (K. Hu et al., 2024; A. Kumar et al., 2024; Madhukar et al., 2016; Sultan et al., 2025). In India, arsenic contamination in groundwater has been reported across 20 states and 4 Union Territories, with West Bengal, Bihar, Uttar Pradesh, Jharkhand, and Assam identified as the most harshly contaminated regions (Ivy, 2025). India, as a predominantly agrarian country, contends with critical challenges in the Indo-Gangetic Plain, where arsenic contamination afflicts both groundwater resources and Holocene-derived alluvial soils (Saha et al., 2024). These issues present a direct risk to agricultural productivity and food safety.

As, naturally present within the Earth's crust, manifests in environmental matrices primarily as inorganic arsenite ($As^{3+}$) and arsenate ($As^{5+}$), as well as organic compounds such as monomethylarsonic acid (MMA) and dimethylarsinic acid (DMA) (Patel et al., 2023). Among these, inorganic arsenic forms in contaminated waters and soils confer greater human health risk, wherein arsenite under oxygen-depleted conditions demonstrates higher bioavailability and toxicity relative to arsenate (Sadee et al., 2025). Acute arsenic intoxication manifests as severe gastrointestinal symptoms, including emesis, abdominal cramping, and profuse diarrhoea, while chronic intake, principally via water or food, results in cutaneous manifestations (skin lesions, hyperkeratosis) and heightened risk for malignancies in the skin, bladder, and lungs (Kuivenhoven & Mason, 2023). Several studies and organisations conclusively recognize inorganic arsenic as carcinogenic to humans, with epidemiological evidence implicating long-term exposure in metabolic (diabetes), cardiovascular, respiratory, and teratogenic outcomes (Davis et al., 2025; Speer et al., 2023; World Health Organization, 2022). On a molecular level, As exerts toxicity primarily by inducing oxidative injury and perturbing cellular bioenergetics. The trivalent form, arsenite ($As^{3+}$), binds sulfhydryl-containing enzymes, including those central to the TCA cycle, inhibiting pyruvate and α-ketoglutarate dehydrogenase activity and impairing ATP synthesis. Furthermore, arsenite impairs glutathione-dependent antioxidant mechanisms, elevating the formation of reactive oxygen species, which damages nucleic acids, lipids, and proteins (Bergquist et al., 2009; Divya Prasad et al., 2025; Y. Hu et al., 2020; Y. Zhang et al., 2025). Conversely, pentavalent arsenate

($As^{5+}$), functioning as a phosphate analog, substitutes phosphate in glycolytic reactions, forming unstable arsenate esters that hydrolyze rapidly, uncoupling substrate-level phosphorylation and compromising cellular energy metabolism (H. Chen et al., 2016; Kulshrestha et al., 2014). Beyond metabolic interference, arsenic modulates epigenetic profiles by causing DNA hypomethylation and alters signaling networks such as MAPK and PI3K/Akt that have oncogenic implications (Ji et al., 2025).

Rice (*Oryza sativa*), the principal staple food for more than 65% of the Indian population, is among the most vulnerable crops to arsenic contamination, largely because of cultivation practices. These practices enhance the mobility of soil arsenic, facilitating its absorption by rice plants and its subsequent accumulation in the edible grains (Bera & Choudhury, 2023; Devi et al., 2024; Upadhyay et al., 2020). In arsenic-affected states such as West Bengal, Bihar, Uttar Pradesh, Jharkhand, and Assam, rice grains have been consistently found to harbor elevated arsenic levels, intensifying concerns of chronic dietary exposure and health risk (Devi et al., 2024; Dube et al., 2024).

Arsenic contamination in rice results from a complex interplay of biophysical and environmental factors, including soil geochemical characteristics, irrigation practices, and the chemical speciation of arsenic in water, in addition to plant physiological processes governing uptake (Devi et al., 2024; He et al., 2021). Importantly, the socio-economic realities of smallholder farmers who are heavily reliant on arsenic-laden groundwater for irrigation further amplify exposure risks, as limited resources and awareness constrain the adoption of mitigation strategies(Rokonuzzaman et al., 2023; Sultan et al., 2025).

This review provides a detailed exploration of the agronomic implications of arsenic contamination in Indian rice-growing states. It consolidates existing research on contamination pathways, bioavailability drivers, and uptake mechanisms in rice plants. Furthermore, it explores mitigation frameworks that include agronomic innovations, the development of resistant cultivars, and governance strategies aimed at integrated water–soil management for reducing dietary arsenic exposure. The review underscores that mitigating arsenic accumulation requires convergence of science, governance, and farmer engagement. Placing arsenic mitigation at the core of India’s food security agenda is essential for ensuring agricultural resilience, environmental protection, and public health.

**Geographical Distribution of Arsenic Contamination in India:**

Arsenic contamination is a widespread and intensifying environmental and food security challenge in India, particularly in the rice-growing states across the Indo-Gangetic and Brahmaputra floodplains. The geographical distribution of arsenic contamination in India reveals both extensive reach and remarkable state-wise variability

**1. Major Arsenic-Affected Rice-Growing States:**

India's eastern and northern rice-producing states, including West Bengal, Bihar, Uttar Pradesh, Assam, and Jharkhand, face the nation's gravest arsenic contamination challenges, directly threatening agrarian and food security. West Bengal, with the highest count of arsenic-affected districts, has sites where groundwater arsenic routinely exceeds 50–250 µg/L, and contaminated rice grains sampled at up to 0.23 mg/kg (Cheraghi et al., 2025; Roy et al., 2023). Bihar's arsenic hazard zone includes at least 22 districts and 87 blocks, with local well samples reaching 350 µg/L, affecting over 10 million inhabitants (Chakraborti et al., 2003; Dube et al., 2024; A. Kumar et al., 2021). Assam reports acute exposure, with over 65% of its residents living in regions at high risk, and concentrations in some wells measured >500 µg/L (Nath et al., 2022). In Uttar Pradesh, districts including Ballia and Ghazipur have been identified as severely affected areas, exhibiting arsenic concentrations in groundwater that exceed the permissible limits established by the WHO by multiple folds (Azam, Pandey & Sonkar 2025; Azam & Sarma 2021). Additionally, regions in Jharkhand, Punjab, Haryana, and Chhattisgarh display recurrent high arsenic loads in water and crop matrices (Dube et al., 2024; Podgorski et al., 2020).

**2. Hydrogeological Factors Influencing Arsenic Mobilization:**

Hydrogeologically, the mobilization of arsenic is predominantly observed within alluvial floodplain environments that characterize the Ganges and Brahmaputra basins in northern and eastern India. Himalayan-derived mineral weathering introduces arsenic to floodplain sediments, which, under highly reducing microenvironments strongly influenced by decomposing organic matter, leads to the reductive dissolution of iron minerals and concomitant arsenic release (Chakraborti et al., 2018; Cheraghi et al., 2025; R. Thakur et al., 2024). Monsoonal floods and seasonal groundwater recharge directly modulate redox states, accelerating the geochemical cycling of arsenic. Overextraction of groundwater for irrigation exacerbates this problem, lowering water tables and hastening arsenic release (Kulkarni et al., 2018; Kwak et al., 2024). Holocene deposits are exceptionally prone to arsenic accumulation, with concentrations in groundwater often exceeding 50 µg/L, while older, oxidized Pliocene/Pleistocene deposits typically present limited arsenic bioavailability, safeguarding deeper aquifer sources from contamination (Kanel et al., 2023; Neidhardt et al., 2018; Van Geen et al., 2013).

**3. Spatial Variability and State-Wise Case Studies:**

India's rice-growing states display pronounced spatial variability in arsenic concentrations within rice grains, with numerous state-wise studies elucidating the extent and risks of contamination. State-wise surveys, particularly those focusing on West Bengal, Bihar, Uttar Pradesh, Assam, and Jharkhand, have repeatedly documented severe arsenic loads in rice grains, underscoring significant intraregional differences and localized risk elevation beyond safe consumption parameters.

**West Bengal:** In the state of West Bengal, rice grain arsenic concentrations display significant spatial heterogeneity, with quantified averages of 300 µg/kg in North 24-Parganas, 215 µg/kg in Nadia, 190 µg/kg in Kolkata, and 137 µg/kg in West Medinipur. Also, the arsenic level in rice fluctuates seasonally, with pre-monsoon samples registering an average of 528 ± 434 µg/kg, nearly twice the monsoon rice average, implicating seasonal hydrochemical dilution processes. Medium-accumulating cultivars averaged 178 ± 41 µg/kg, demonstrating a strong influence from geographical origin and cultivation season. Studies also revealed that processing methods further modulate these concentrations, as sunned rice demonstrates reduced arsenic (188 µg/kg) compared to parboiled variants (268 µg/kg), reflecting methodological impacts on arsenic retention (Chowdhury et al., 2020, 2022). Furthermore, Boro rice exhibited the highest arsenic compared to other varieties (Moulick et al., 2021).

**Bihar:** Rice agroecosystems across Bihar exhibit substantial arsenic contamination, as demonstrated in prior investigations. Of the 38 districts, a total of 22 have exhibited arsenic concentrations in grounAzamdwater above the World Health Organization threshold, with the gravest impacts identified in Buxar, Bhojpur, and Bhagalpur. Groundwater from Buxar district has presented peak arsenic levels reaching 1,906 µg/L. Correlatively, rice grain arsenic concentrations in household assessments have been reported up to 821 µg/kg (Chakraborti et al., 2016; Ivy, 2025; A. Kumar et al., 2021; V. Kumar & Shekhar, 2025; Mohd Imran Khan, 2024).

**Uttar Pradesh:** In the eastern districts of Uttar Pradesh, notably Ballia and Ghazipur, groundwater arsenic levels have been recorded at maximum concentrations of 468 µg/L, with more than 90% of monitored wells exceeding recommended thresholds for potable use. Correspondingly, rice grains produced in these locales exhibit arsenic enrichment above the permissible limit of up to 1 mg/kg, attesting to significant input from irrigation sources. Gomti River basin zones in the state also report arsenic in 61 km stretches, leading to notable arsenic transfer from irrigation to rice fields (Azam et al., 2025; Devi et al., 2024; Dube et al., 2024; Verma & Chaurasia, 2023).

**Assam:** Epidemiological and geochemical investigations in Assam have established that over 65% of the population is subject to arsenic exposure through the dietary pathway. Targeted sampling across Lower Assam, specifically in the districts of Darrang, Lakhimpur, and Goalpara, revealed mean rice grain arsenic concentrations spanning 119.5 to 354 µg/kg, with a pronounced positive correlation between irrigation water arsenic (up to 530 µg/L) and rice grain content (Bakar et al., 2025; Devi et al., 2024).

**Punjab & Jharkhand:** In Jharkhand, both irrigation water and rice grain analyses reveal significant arsenic mobilization, albeit with rice grain arsenic typically lower than West Bengal or Bihar, but still routinely more than the permissible limit, especially in brown rice. Continued groundwater withdrawal for agriculture exacerbates this regional contamination

(Chowdhury et al., 2020; Devenda et al., 2017; Pattnayak, 2018; Sharma et al., 2017).

**Arsenic in Agroecosystems: Soil, Water, Plant Interactions:**

Arsenic occurrence in agroecosystems represents a critical environmental and food safety concern, particularly within rice cultivation regions where soil, water, and plant interactions govern its fate and bioavailability. The complex interplay of geogenic sources, hydrological inputs, and anthropogenic influences facilitates arsenic entry into agricultural soils and irrigation waters. The following sections elucidate the sources, chemical behavior, speciation, and microbial mediation of arsenic within these systems.

**1. Sources of arsenic in agricultural soils and irrigation water:**

Arsenic contamination in agroecosystems, particularly in Indian rice-growing regions, is driven by complex soil, water, and plant interactions that facilitate its transfer from environmental sources into the food chain. The main inputs of arsenic in agricultural soils arise from irrigation with arsenic-containing groundwater, episodic natural flooding leading to arsenic entrainment in the Indo-Gangetic and Brahmaputra floodplains, weathering and sediment transport from Himalayan formations, and residual arsenic from archaic agrochemical practices (Devi et al., 2024; Shaji et al., 2021).

**2. Rhizosphere chemistry and paddy field redox dynamics:**

In paddy field agroecosystems, the intricate interplay between rhizosphere chemical gradients and fluctuating redox states is a decisive factor influencing arsenic bioavailability and mobility. Flooded rice paddies are characterized by alternating anaerobic (reducing) and aerobic (oxidizing) conditions transitions that are largely regulated by water management and root oxygen release. Dissolution of iron oxyhydroxides under reducing conditions catalyzes arsenic liberation into porewater, while rice root surfaces catalyze local iron plaque deposition, which sequesters $As^{3+}$ and promotes its oxidation to $As^{5+}$ within oxidized microsites (Cheraghi et al., 2025; Kong et al., 2024; Maisch et al., 2019).

**3. Arsenic speciation in soils and water:**

Within paddy soil solutions and irrigation waters, arsenic manifests in multiple molecular forms with different proportions. Arsenite typically contributes 36–63% of total arsenic, arsenate ranges from 1–39%, DMA comprises 11–44%, while MMA is present at up to 14%. In rice, the dominant arsenic species comprise $As^{3+}$, $As^{5+}$, and DMA, with the concentration hierarchy typically following the pattern: $As^{3+}$ > DMA > $As^{5+}$. The prevalence and mobility of these forms are governed by the redox status of the environment, with arsenite presenting higher diffusivity and plant uptake, especially in submerged paddy fields, compared to the less mobile arsenate (Cheraghi et al., 2025; Devi et al., 2024; Navaretnam et al., 2025).

**4. Role of microbial processes in arsenic mobility:**

The biotransformation of arsenic in paddy soils is intricately controlled by diverse microbial assemblages inhabiting the rhizosphere. Key microbial players include arsenate reducers such as *Geobacter* *and Shewanella spp*., arsenite oxidizers from the *Thiomonas and Pseudomonas* genera, iron-reducing bacteria like *Acidithiobacillus ferrooxidans*, and sulfate-reducing bacteria such as *Desulfovibrio spp*. These microbiotas actively govern arsenic transformation from inorganic states to organic derivatives, thereby influencing arsenic residence times and concentration gradients in both rice tissue and the paddy soil solution, and modulating dietary exposure risk across agroecosystems (Devi et al., 2024; Somenahally et al., 2021; William & Magpantay, 2023).

**Uptake, Translocation, and Accumulation in Rice Plants:**

Arsenic uptake, translocation, and accumulation in rice plants are regulated by intricate physiological and molecular mechanisms shaped by arsenic speciation, transporter activity, and genetic heterogeneity. Deciphering the distinct uptake routes for arsenate and arsenite, their translocation within the plant vascular system, and partitioning into edible grain portions is critical in tackling arsenic contamination. Additionally, cultivar-specific genetic loci and root anatomical traits significantly affect arsenic loading and metabolic speciation, facilitating targeted breeding of cultivars with reduced arsenic accumulation. This section delineates these multifactorial processes central to arsenic ecology in rice plants.

**1. Mechanisms of arsenic uptake:**

The uptake of arsenic by plants is primarily influenced by its chemical forms. The primary pathway for $As^{5+}$ absorption in rice roots is mediated through molecular competition with phosphate ions. Due to structural similarity, arsenate utilizes phosphate transporter proteins (PHTs), particularly members of the OsPT family, to enter root cells. Conversely, $As^{3+}$, the dominant form in flooded soils, is efficiently internalized via the silicon acquisition pathway, involving nodulin 26-like intrinsic proteins (OsNIP2;1/Lsi1) and the silicon transporter Lsi2 (Abedi & Mojiri, 2020; Bera & Choudhury, 2023; Devi et al., 2024).

**2. Root to shoot translocation and grain partitioning:**

Following root absorption, arsenic is subject to translocation from roots to shoots and grains. The immobilization of arsenic, particularly inorganic forms, is primarily achieved through chelation with thiol compounds, limiting apoplastic transport. In contrast, methylated species such as DMA and MMA exhibit superior mobility via xylem and phloem translocation, resulting in greater accumulation in grain tissue (Abedi & Mojiri, 2020; Bera & Choudhury, 2023; Devi et al., 2024).

**3. Varietal differences and the genetic basis of arsenic accumulation:**

Marked genetic diversity among rice varieties strongly influences arsenic accumulation and its molecular speciation in harvested grains. Recent association mapping revealed tri-modal differences in grain arsenic content, attributable to loci regulating DMA proportions on rice chromosomes 6 and 8; these loci play a key role in reducing toxicity through the biosynthesis of organoarsenicals. Popular subtypes, notably Indica and Basmati, are genetically predisposed to lower grain arsenic, a trait reinforced by anatomical adaptations such as intensified root aeration and robust radial oxygen loss mechanisms factors that limit arsenic solubility and migration from soil to aerial plant components (Bera & Choudhury, 2023; Devi et al., 2024; Kuramata et al., 2013).

**Factors Influencing Arsenic Bioavailability and Accumulation:**

The bioavailability and accumulation of arsenic in rice are governed by multifactorial interactions among environmental variables, agronomic management, soil properties, fertilizer regimes, microbial diversity, and soil redox dynamics.

**1. Irrigation practices:**

The extent of arsenic transfer to rice grains is critically influenced by the choice of irrigation source. Utilization of arsenic-laden groundwater for continuous field inundation sharply increases grain arsenic content, while surface water irrigation is associated with substantially reduced concentrations. Continuous flooding with arsenic-contaminated groundwater impedes microbial methylation, promoting the persistence of inorganic arsenic ($As^{3+}$ and $As^{5+}$), which is substantially more toxic (Bakar et al., 2025; Devi et al., 2024; Mlangeni, 2023).

**2. Soil properties:**

Soil physicochemical characteristics profoundly regulate arsenic mobility and bioavailability in agroecosystems. Soils rich in iron oxides and maintaining a slightly acidic pH (4-5) are more effective at adsorbing arsenic, thereby limiting its mobility. Under flooded, anaerobic conditions, the reductive dissolution of iron and aluminium oxides leads to the release of arsenic, predominantly as $As^{3+}$, into the soil solution, raising its phytotoxic risk (Fan et al., 2024; Kanel et al., 2023; Yamaguchi et al., 2011).

**3. Fertilizer application:**

Fertilizer regimes are critical determinants of arsenic speciation and mobility in rice cropping systems. Phosphorus fertilization, owing to molecular mimicry and shared transporter pathways, can attenuate arsenate absorption at the root surface while also facilitating greater arsenic release in soil matrices due to competitive interactions. Nitrogen fertilization modulates arsenic uptake in rice primarily by altering soil redox conditions and microbial activity, with nitrate fertilizers inhibiting $Fe^{3+}$ reduction and promoting arsenite oxidation, thereby reducing arsenic bioavailability and plant accumulation (Mlangeni, 2023).

**4. Climatic factors and seasonal variability:**

Climatic variability, especially changes in ambient temperature and precipitation regimes, exerts a decisive influence on arsenic speciation, mobility, and grain accumulation in paddy soils. Monsoonal rainfall cycles promote dilution and leaching of soil arsenic pools, decreasing plant exposure in intervening cropping seasons. In contrast, elevated temperatures under future climate scenarios enhance bioavailable arsenic fractions, alter microbial community structure and gene expression, and lead to increased arsenic speciation toward more toxic forms, with adverse implications for yield and food safety. Emphasizing these mechanisms highlights the pressing need for dynamic crop management tailored to altered seasonal and climatic contexts (Chowdhury et al., 2020; Muehe et al., 2019; Ninin et al., 2024; Upadhyay et al., 2020).

**5. Health Risks associated with chronic arsenic ingestion:**

Prolonged intake of inorganic arsenic through contaminated rice significantly threatens public health and ecosystem stability in India and globally. Rice grains from affected areas frequently surpass regulatory safety thresholds for arsenic, resulting in multisystemic toxicity encompassing the dermal, hepatic, renal, cardiovascular, and neurological systems. Mechanistically, arsenic promotes oxidative damage and hampers DNA repair, fostering increased cancer incidence skin, bladder, liver, and lung cancers being predominant. Cardiovascular dysfunctions, diabetes mellitus, and neurodevelopmental delays are also well documented, with children and pregnant women displaying heightened susceptibility. Combined exposure from food and water markedly raises total intake, intensifying both carcinogenic and non-cancer disease burdens (Davis et al., 2025; Kuivenhoven & Mason, 2023; Speer et al., 2023; World Health Organization, 2022).

**Mitigation and Agronomic Interventions:**

Mitigating arsenic contamination in rice agroecosystems requires a multi-pronged approach integrating water management, soil amendments, crop breeding, biological interventions, and economic assessment.

**1. Alternate wetting and drying (AWD) and water-saving irrigation practices:**

Alternate wetting and drying (AWD) constitute a water management strategy whereby rice paddies undergo cycles of flooding and aeration, fostering oxic soil conditions that markedly curtail arsenic mobilization compared to continuous waterlogging. Studies reveal grain arsenic loads decline under AWD, compared to continuous flooding, while also promoting microbial methylation of arsenic into less toxic forms (DMA, MMA). This approach also yields significant environmental benefits, including water savings and the mitigation of methane emissions (Leavitt et al., 2025; Li et al., 2019; Mlangeni et al., 2020).

**2. Use of iron, silicon-based, and organic soil amendments:**

Iron, silicon, and organic amendments markedly mitigate arsenic bioavailability in paddy soils. Iron-based strategies, such as the application of ferrihydrite and the promotion of iron plaque formation at rice root surfaces, effectively immobilize arsenic, decreasing its translocation to aerial tissues and grains. Silicon fertilization not only improves rice yield but fundamentally alters arsenic chemistry, promoting oxidation at the root zone and driving speciation toward less toxic forms; this intervention is correlated with marked declines in grain arsenic. While phosphorus application may increase arsenic uptake in rice due to competitive interactions, precise dosing at 30 mg/kg optimally mitigates arsenic accumulation and simultaneously enhances agronomic traits such as biomass and grain yield. Organic amendments, especially biochar, bind arsenic effectively, stimulate arsenic-methylating microbial populations, and optimize redox conditions, producing soils with improved remediation efficacy and reduced arsenic transport into the food chain (Chattopadhyay et al., 2021; Devi et al., 2024; Roy et al., 2023).

**2. Breeding and biotechnological approaches for low-As rice cultivars:**

Genetic improvement and modern biotechnology are integral to the sustainable reduction of arsenic in rice grain. Conventional breeding and genomic selection have pinpointed accessions such as 'Badshabhog' and lines expressing enhanced radial oxygen efflux that minimize arsenic bioaccumulation. Technologies including marker-assisted selection, RNAi, and gene knockouts are complemented by CRISPR/Cas9-mediated editing, enabling direct modification of arsenic transporter genes and rapid, precise introgression of protective traits. These biotechnological strategies enable shorter breeding cycles and greater adaptability of rice to toxic environments, substantially improving food safety (Y. Chen et al., 2017; Nayak et al., 2021).

**3. Microbial interventions and phytoremediation approaches:**

Integrated microbial and phytoremediation approaches leverage the synergistic effects of both plant and microbial communities to attenuate arsenic contamination in paddy soils. Phytoremediation by *Pteris vittata* exploits its exceptional arsenic uptake and root-to-shoot translocation capacity, resulting in high rates of arsenic extraction from contaminated substrates. Microbial intervention strategies such as inoculation with arsenite-oxidizing or arsenate-reducing bacteria optimize biogeochemical cycling, increase conversion of inorganic arsenic to less bioavailable species, and support enhanced soil decontamination. Root microbiome manipulation and biocompatible biochars boost soil resilience and expedite detoxification (Herrera et al., 2021; Jia et al., 2022; Lampis et al., 2015; X. Zhang et al., 2025).

**Socio-Economic and Policy Dimensions:**

Effective management of arsenic contamination and community resilience necessitates addressing socio-economic contexts and robust policy support, underscoring the critical role of comprehensive public education, awareness programs, and strengthened agricultural outreach, which currently remain underfunded.

**1. Socio-economic burdens on smallholder farmers in arsenic-affected regions:**

Socio-economic consequences for farming households in arsenic-impacted regions are severe and multi-dimensional. Arsenic contamination drives lower agricultural yields, necessitates less profitable cropping patterns, and ratchets up input costs, ultimately leading to net income reductions and triple impoverishment for farmers. Disease burden is high with >15% prevalence of arsenicosis in some districts, and compounded by inadequate access to treatment, awareness deficit, and exclusion from labor markets. Vulnerable groups are further hampered by limited infrastructure and knowledge gaps, perpetuating cycles of deprivation and diminished welfare (Chakraborty & Mukherjee, 2020; S. Kumar

& Nayak, 2024; Mazumder et al., 2010; B. K. Thakur & Gupta, 2025).

**2. Food safety regulations and quality standards in India and globally:**

Food safety regulations governing arsenic content in rice are heterogeneous across international jurisdictions. The Codex Alimentarius Commission prescribes a threshold of 0.2 mg/kg for polished rice and of 0.35 mg/kg in husked rice, establishing a global benchmark. The European Commission enforces more stringent parameters for foods intended for infants and children, including tighter arsenic limits for specialized rice products and rice-based baby food. India currently lacks statutory arsenic standards for rice, a gap underscored by the observation that rice samples from arsenic-endemic zones, including West Bengal, regularly surpass international regulatory benchmarks. While frameworks emphasize improved irrigation, source water selection, and use of soil amendments for arsenic mitigation, uniform implementation and compliance remain limited, especially among smallholder production systems (Dube et al., 2024; European Commission, 2023; on Contaminants in the Food Chain (CONTAM) et al., 2024; Sabbagh, 2023).

**3. Existing mitigation policies and their gaps:**

Indian government initiatives, including the Jal Jeevan Mission and NRDWP, direct substantial financial resources toward the identification, treatment, and supply of potable water in arsenic-impacted rural regions. Despite these concerted efforts, critical gaps persist in policy implementation: mitigation focused on food-chain arsenic remains largely absent, extension networks lack comprehensive geographical reach, and the diffusion of arsenic-safe agronomic practices suffers from inadequate public awareness.

**4. Role of awareness, education, and extension services:**

The deployment of awareness initiatives, structured education, and field-based extension services constitutes a cornerstone of arsenic mitigation strategies but is presently insufficiently widespread. Most rural smallholders exhibit limited understanding of arsenic risks and safe water usage, a challenge compounded by low literacy and information access. Well-designed IEC and behavioural change campaigns facilitate significant improvements in knowledge, risk perception, and adoption of safer practices, but persistent gaps in comprehension and action remain. Experiential interventions such as on-site water testing, demonstration farming, and targeted training exert a substantial impact on compliance rates and arsenic avoidance practices.

**Future Research Directions:**

Harnessing novel omics approaches, coupled with robust predictive modeling and context-specific risk assessments, future studies will endeavor to advance arsenic mitigation in rice systems, thereby promoting enduring reductions in grain arsenic levels and securing food production resilience in heterogeneous agroecosystems.

**1. Integrating omics approaches for arsenic tolerance in rice:**

Future research on mitigating arsenic risks in rice agroecosystems will leverage advanced molecular, analytical, and predictive strategies. Multi-omics strategies encompassing genomics, transcriptomics, proteomics, metabolomics, and epigenomics enable high-resolution mapping of arsenic tolerance determinants, particularly through identification of transporter genes critical for arsenite uptake and translocation. This broad molecular toolkit permits both marker-assisted selection and targeted genome editing for arsenic-excluding cultivars, while omics-driven metabolite profiles offer robust molecular signatures for genotypic screening under arsenic stress.

**2. Development of predictive models for arsenic transfer in agroecosystems:**

Development of predictive models for arsenic transfer is vital for risk assessment and management. Machine learning and stepwise regression have been harnessed to relate arsenic bioconcentration factors in rice grain with soil pH, organic matter, cation exchange capacity, and water management. Advanced biogeochemical modelling integrates soil redox dynamics and cropping system variables, simulating arsenic speciation and mobility under aerobic and anaerobic regimes; these models enable scenario forecasting and intervention evaluation for decision-makers.

**3. Region-specific risk assessment frameworks:**

Region-specific risk assessment frameworks recognize spatial, climatic, and cultural differences influencing arsenic exposure. Risk models include local dietary patterns, irrigation practices, and environmental arsenic loads (from groundwater, soil, and atmospheric deposition), enabling tailored mitigation recommendations. Use of Estimated Daily Intake, Target Hazard Quotient, and Lifetime Cancer Risk improves risk classification, particularly for vulnerable populations.

**4. Long-term monitoring and surveillance strategies:**

Long-term monitoring and surveillance strategies are needed to track arsenic dynamics across agroecosystems and evaluate intervention efficacy. Integrated programs combine water, soil, and rice grain sampling with continuous geospatial analytics, farming practice databases, and regular farmer feedback. Monitoring networks can use both laboratory analyses and field-based arsenic detection devices for real-time mapping. Community-based participatory research and periodic policy reviews ensure adaptive management and sustained risk reduction

**Conclusion:**

Arsenic contamination in rice presents a persistent health and food safety challenge for millions of people worldwide, especially in Asia's rice-dependent regions. Rice grains routinely accumulate arsenic due to biogeochemical weathering, groundwater extraction, and traditional flooded cultivation practices, sometimes exceeding international safety thresholds. Recent advances highlight that agronomic strategies can significantly lower grain arsenic concentrations and increase the proportion of less toxic methylated species. Iron, silicon, and targeted nutrient amendments further suppress arsenic bioavailability and promote safer rice production. However, sustaining improvement demands integrated approaches: molecular breeding for low-As cultivars, extension of water-saving technologies, and participatory policymaking with community awareness and infrastructure investment. Continued research and policy action will be essential for comprehensive risk reduction, food security, and rural health resilience in arsenic-prone regions.

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