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CONTAMINATION OF ARSENIC IN RICE PLANTS AND MITIGATION STRATEGIES: A REVIEW

Anjani Kumar[1]*, Manas Denre[2], R. K. Singh[3], A. N. Dubey[4] and Dinmani[5]
[1]Department of Genetics and Plant Breeding, Agriculture College Garhwa, Bishunpur, Garhwa,
Birsa Agricultural University, Jharkhand (822 114), India
[2] Department of Soil Science and Agricultural Chemistry, Agriculture College Garhwa, Bishunpur,
Garhwa, Birsa Agricultural University, Jharkhand (822 114), India
[3] Department of Horticulture, Agriculture College Garhwa, Bishunpur, Garhwa,
Birsa Agricultural University, Jharkhand (822 114), India
[4] Department of Soil Science and Agricultural Chemistry, Rabindra Nath Tagore Agriculture College,
Deoghar, Jharkhand (814 157), India
[5] Department of Agricultural Engineering, Agriculture College Garhwa, Bishunpur, Garhwa,
Birsa Agricultural University, Jharkhand (822 114), India
*Corresponding author E-mail: anjani0039@gmail.com
ORCID: 0000-0001-9900-2126

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ABSTRACT

In this chapter, we would know about the research advances and practical agronomic strategies on arsenic contamination in rice crops. Millions of people across the world were suffering from arsenic (As) toxicity. In the environment, Arsenic was found in several oxidative states and entered the food chain through soil and water. In the field of agriculture, if arsenic-contaminated water was used in irrigation, that was, having a higher level of arsenic contamination on the topsoil, which might affect the quality of crop production. Among other crops, paddy required a large amount of water to complete its life cycle. Accumulation of arsenic in rice plants was particularly inorganic arsenic (iAs) from the soil. There were many transporters in plant cell arsenic accumulation that have been reported; for example, arsenate (AsV) was absorbed by phosphate transporters, and arsenite (AsIII) through protein (Nodulin 26-like Intrinsic Protein) with the help of silicon transport pathway and plasma membrane intrinsic protein aquaporins**.** To mitigate the problem of Arsenic contamination in rice, many researchers were trying their level best. The concentration of arsenic in rice plants was governed by different factors in the rhizosphere for example, availability and concentration of various mineral nutrients (Fe, S, and Si) in soil solution, inter-conversion between inorganic and organic arsenic compounds. Some agronomical practices such as rainwater harvesting for irrigation, use of natural components that helped in arsenic methylation, and biotechnological approaches might explore how to reduce arsenic uptake by food crops.

***Keywords* :** arsenic, rice, mitigation, transporters, uptake.

Introduction

Arsenic (As) is ubiquitous in the environment and very toxic metalloid. It creates major problems for both environment and human health. The food crops, specifically rice, serve as a major source of arsenic is the dietary staple of half of the world's population (Banerjee *et al.*, 2013). Paddy is the main food source of South as well as Southeast Asian countries and used up by fifty percent of the world population (Srivastava *et al.*, 2022). Arsenic (As) is classified as a metal and chemically it often behaves as non-metal properties (Hu *et al.*, 2020). There are variety of mineral nutrient found in soil and some amount is beneficial to agricultural crops however others are non-crucial or even poisonous (Zhao and Wang, 2020). Human being is also very sensitive to this heavy metal like arsenic by food, air, and drinking water (Hu *et al.*, 2020; Khan *et al.*, 2022). The dangerous diseases such as cancer, lung infection and skin related problem in human are mainly caused by arsenic (As), chromium (Cr), lead (Pd), cadmium (Cd) contain in the food crops (Chakraborty *et al*., 2022). There are several mineral nutrients such as sulphur (S), phosphorus (P), zinc (Zn), selenium (Se) and silica (Si) reduce the arsenic toxicity and also beneficial to the plant growth, yield, and productivity (Sahay *et al*., 2020; Moulick *et al*., 2023). There are two main forms of arsenic found in the soil which is inorganic and organic forms. Arsenite or As(III) and arsenate or As(V) are the main dominant kinds of inorganic arsenic contain in anaerobic as well as aerobic situations, respectively (Srivastava *et al*., 2017; Yan *et al*., 2019). In rice field, there are two important organic forms of arsenic occur namely monomethylarsonic acid and dimethylarsinic acid (Xiao *et al*., 2021). Arsenic accumulates as higher concentration in roots but low level in grain, however rice culm contains intermediate level (Cao *et al*., 2020). Stunted growth, brown spots, and scorching on leaves are the toxicity symptoms of rice plants grown in soils containing greater than 60 mg/ kg of total arsenic present in the soil. (Bakhat *et al.,* 2017). Due to the high concentration of arsenic, it adversely affects the plant metabolism and also a reason for death. The intensity of plant transpiration was decreased after arsenic exposure. In the comparison to other crops like wheat, maize, and barley, rice is the most affected staple food crop to arsenic contamination due to its cultivation in flooded conditions. Accumulation of arsenic affects the root elongation and proliferation. Generally, the accumulation of arsenic decreases from root to above-ground parts due to translocation in plants. In various species of rice, about 40% of the total translocated arsenic is found in form of arsenate or As(V) (Rascio *et al.,* 2011). In aerobic rice cultivation, alternate wetting and drying and raised bed cultivation have very effective for the reduction of arsenic accumulation in rice and also these are water saving methods. The groundwater is also contaminated through arsenic chemicals in several countries like India, China, Bangladesh as well as Argentina (Praveen *et al*., 2020; Shaji *et al*., 2021). In our country India, several states like Uttar Pradesh, Bihar, Assam, West Bengal, Jharkhand, Manipur and Chhattisgarh have arsenic prone region (Shamim *et al*., 2017). In this chapter, we would know about arsenic bioavailability to rice from soil, its uptake, accumulation, and oxidative stress in rice and possible cost-effective productive strategies to reduce arsenic contamination in rice.

Mechanisms of arsenic uptake in Rice Plants

Uptake and transport of organic As species

The predominant species (Arsenite) was present in the submerged soil, and microbial change of inorganic species to an organic form produces significant amounts of methylated arsenic species dimethyl arsenic acid (DMA) and less amounts of monomethyl arsenic acid (MMA) in the field of paddy soil (Meharg *et al.,* 2009). This transformation is very beneficial to organic form because MMA species are low toxic as compare to pentavalent As species. The uptake mechanisms of methylated species are less extensively studied than inorganic arsenic species. Nodulin 26-like intrinsic protein is the main source for uptake of MMA and DMA. AsIII and As V are inorganic As species which are more productively taken up by roots in comparison of DMA and MMA, whereas the translocation rate in shoot of inorganic As species is lesser than DMA and MMA (Raab *et al.,* 2007). The reason for better translocation of methylated As species may be diminished complex formation of DMA and MMA with glutathione/ phytochelatin (Raab *et al.,* 2007). In rice grain, AsIII is the most abundant species, whereas DMA with low concentrations of AsV, MMA and two unknowns As species, as found by analysis of 121 samples of 12 rice types (Huang *et al.,* 2012).

Uptake and transport of inorganic As species

Inorganic As species is up taken by rice roots that occurs by two mechanisms. The phosphate (PO_4) transport pathway is the first one using high-affinity PO_4 transporters (Catarecha *et al*., 2007), which uptake As(V) from the soil solution and subsequently to the aerial parts of the plants and the second mechanism by which As is uptake by roots is through aquaporin channels, which uptake As(III) and methylated As species (Li *et al*., 2009). As(III) uses this Si transporter owing to its similarities with silicic acid, both have a high pKa (9.3 and 9.2 for silicic acid and arsenous acid, respectively) and the same size (tetrahedral structure) of the molecules in rice root cells. Those plants which are deficient in Si supply expression of Lsi1 are promoted (Ma and Yamaji, 2006). Lsi1 and Lsi2 are the transporters that controls the accumulation of Si in rice. The family of Lsi1 is aquaporin, whereas Lsi2 is putative anion transporter. Both Lsi1 and Lsi2 are confined to the epidermis and endodermis of rice roots (Ma and Yamaji, 2006). The location of these two transporters (Lsi1 and Lsi2) are distal side and proximal side, respectively of these two cell layers. The localization and distribution of both transporters are heterogeneous, which facilitates the As transport across the cells and tissues. Those methylated As species having low concentrations, uncharged can be present in the soil are also uptake by rice roots through Lsi1 (Li *et al.,* 2009). As(III) uptaken by root cells, after that, some of it is instantly released into the rhizosphere, and this process is partially mediated by Lsi1serving as a bidirectional channel, while the remaining As is sequestered into the root vacuoles or it is translocated to the shoots where it is distributed to various organs (Zhao *et al.,* 2010).

Arsenic Accumulation in grains of Rice

Among all crop plants, rice is one of the most efficient transporters of Si and inadvertently passes arsenite through silicic acid transporter (Norton *et al.,* 2010). Due to this factor, higher concentrations of arsenic are found in rice grain, greater than the recommended safe limit (Zhao *et al.,* 2010). AsIII uploading more than 90% into the grain is contributed from phloem transport. The first step of arsenic detoxification in rice plants is the reduction of arsenate. Many researchers have found different arsenate reductases in rice, like, OsHAC1;1, OsHAC1;2 and OsHAC4 (Shi *et al.,* 2016), which help in the conversion of arsenate to arsenite. These genes catalyze the reaction in the outer cell layer of the root, thereby facilitating arsenite efflux from the root to soil. OsHAC1;1 is mainly found in the epidermis, root hair, and pericycle, whereas OsHAC1;2 being abundant in the epidermis, outer cortex layer, and endodermis (Shi *et al.,* 2016). The location of OsHAC4 is mainly in the root elongation and mutation zone of the epidermis and exodermis. Overexpression of OsHAC1;1 and OsHAC1;2 altogether expanded arsenite efflux into external medium and diminished arsenic accumulation in rice. Then again, mutation of OsHAC1;1, OsHAC1;2, and OsHAC4 prompted decline arsenate decrease in the root, diminish arsenite efflux, and increment arsenic accumulation in root and grain (Shi *et al.,* 2016). In phloem companion cells, if the tonoplast transporter is present, increase the arsenic sequestration in vacuoles, which help in reduced arsenic translocation into rice grains. Whereas, especially DMA (methylated As species) is transported at a higher rate than inorganic species (Carey *et al.,* 2011) and its redemption in aleurone, endosperm, and the embryo may reduce the seed setting rate and also induce sterility of spikelet and a reduced yield (Zheng *et al.,* 2013). In the rice grain accumulation of rice varies according to the genotype of the plant (Norton *et al.,* 2010). The genotypes IAPAR9 and Nanyangzhan contain more inorganic As in their grains than TD71 and Yinjingruanzhan genotypes (Bastías *et al.,* 2016). In the whole world, more than 1700 varieties of rice are found for their differences in arsenic accumulation, and about 20 fold variations were found among various strains of rice (Pinson *et al.,* 2015). Types of rice varieties, plant physiology, a place where the plant was cultivated, and the method of processing of rice are the major factors that influence the accumulation of arsenic in rice grain. In brown rice, the concentration of arsenic was higher than the white rice (Bakhat *et al.,* 2017).

Factors affecting the uptake and translocation of arsenic in Rice plant

The microclimate presents in the root rhizosphere, i.e., the association of microbes with root and root exudates, also contributes to the concentration of metal ions from soil (Wenzel *et al.,* 2009). The different factors affect arsenic uptake and translocation in rice plant and its detoxification process from root and shoot of the plants are clearly seen in figure 1 (Bakhat *et al.,* 2017). The factors influencing the translocation as well as uptake of arsenic are below:

Arsenic Speciation

Inorganic and organic forms of As are present in the soil. Arsenate (AsV) and arsenite (AsIII) are the most common inorganic species, whereas MMA and DMA are the most common organic species. The order of toxicity of arsenic species is AsIII > AsV > MMA (Baig *et al.,* 2010). Generally, AsIII predominates in anaerobic soil i.e. submerged paddy soil. However, AsIII can be transformed into organic forms by methylation promoted by microbial actions in paddy soil (Islam *et al.,* 2004). Marin *et al.* (1992) observed that the order of bioavailability of arsenic to rice plants are AsIII > MMA >AsV > DMA; all of the species are uptake by rice roots, but the rate of organic species uptake is lower than that of inorganic arsenic (Abedin *et al.,* 2002).

Effect of Soil pH

Soil pH is the major factor for arsenic speciation and leaching, and therefore, the solubility and bioavailability of As is directly affected by soil pH (Quazi *et al.,* 2011). Uptake and accumulation of arsenic by rice plants are influenced at both lower and higher pH. Due to very low pH (pH < 5) arsenic-binding species, i.e Fe-oxyhydroxide compounds, becoming more soluble (Signes *et al.,* 2007) and increasing uptake of arsenic by plants. It was found that the relationship between arsenic concentration in rice and soil pH was negative (Bhattacharya *et al.,* 2010). Whereas, a relationship between arsenic accumulation and soil pH is positive, also supported by many authors (Ahmed *et al.,* 2011). Generally, soil pH 8.5 (high soil pH) increases the negative surface charges, such as hydroxyl ions, facilitating desorption of arsenic from Fe-oxides leading to arsenic mobilization in root vicinity, which, in turn, increases the accumulation of arsenic in the plant (Ahmed *et al.*, 2011).

Effect of Organic Matter

The translocation of arsenic is regulated by the soil organic matter (OM), and its chemical nature and complexes (Williams *et al.*, 2011). Pikaray *et al.* (2005) observed that solubility of arsenic becomes reduced in soils that have a high amount of organic matter, which in turn affects its availability to plants due to the formation of an organo-arsenic complex, OM has more affinity for As sorption. The same findings of reduced arsenic content in the grains were reported from other studies, where rice plants were grown in soil having higher OM content (Rahaman *et al.*, 2011). Many researchers were reported that the soil pH and arsenic accumulation in rice grain is positively correlated. The OM in the soil is directly proportional to the mobility of arsenic and indirectly proportional to the soil redox potential (Turpeinen *et al.*, 1999).

Genotypic Variation in Rice

The arsenic accumulation in rice grains differs with the rice cultivars. In BR11 variety (1.77 mg kg^{-1}) highest accumulation of As was found then the others (Meharg *et al.*, 2003). Among the different rice varieties, IR 50, White Minikit, and Red Minikit were efficient accumulators of arsenic (0.24–0.31 mg kg^{-1}) than the Nayanmani, Jaya, Ratna, Ganga-Kaveri, and Lal Sanna (0.14–0.20 mg kg^{-1}); The arsenic accumulation was found maximum in White Minikit (0.31 mg kg^{-1}), whereas the accumulation was minimum in Jaya (0.14 mg kg^{-1}) (Bhattacharya *et al.*, 2010). The root and vegetative parts of cultivar 'TN1' and 'ZYQ8'were the largest arsenic concentrations, whereas the lowest arsenic concentration was found in cultivar 'JX-17'. The concentration of As in shoot or root of 'JX-17' was about 50% of that in cultivar 'ZYQ8' (Zhang *et al.*, 2008). The environmental conditions, genetic differences, and the presence of a different level of arsenic in the irrigation water and soils might be affected by this type of variation (Norton *et al.*, 2009). A field-based experiment was conducted in Bangladesh by Norton *et al.* (2009) with 76 rice cultivars, and in multiple environments at two field sites each in Bangladesh, India, and China, 4–5 fold variations were observed in the grain arsenic concentration among cultivars. Due to differences in root anatomy, porosity, Fe-plaque formation on the root surfaces, Phytochelatins (PCs), rhizosphere interactions, and differences in the arsenic tolerance gene, the differences in accumulation of As in grain occurs.

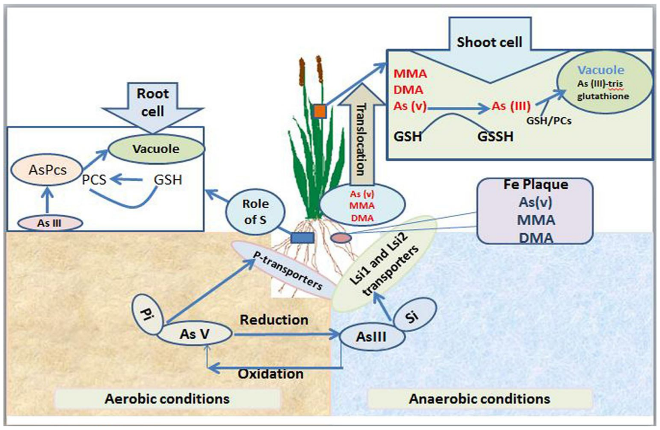

Fig. 1 : Factor affecting As uptake and translocation in rice plant and its detoxification in root and shoot of the plants (Source: - Adapted from Bakhat *et al.*, 2017)

Concentration of Arsenic Species in Rice Grain

There is a big difference in toxicity between inorganic and organic As species, the toxicity of arsenic depends not only on total concentrations but also on its chemical forms. Rice from various parts of the globe differs incredibly in arsenic concentration and speciation. The elaborative and comparative study was firstly made by Williams *et al.* (2005) in market rice. Measurement and capability of low level of arsenic required to survey arsenic speciation in rice grain became possible due to the development of inductively-coupled plasma mass spectrometry (ICP-MS) as an ultra-sensitive arsenic detector combined with High-Performance Liquid Chromatography (Williams *et al.*, 2005). The findings of Williams *et al.* (2005) observed that rice produced in the US and European Union (EU) having a high percentage of DMA when compare d to Bangladeshi and Indian rice. Inorganic arsenic was dominant than DMA in Chinese rice. Meharg *et al.* (2009) reported that the rice of Ghana had the lowest median arsenic concentration (20 ng g^{-1}), followed by India (50 ng g^{-1}), whereas the USA, Italy, and Thailand had maximum arsenic concentration, with China and Bangladesh being intermediate. Other reports were also related to the color of the rice showed that concentration of arsenic in brown rice is 0.196 ± 0.111 mg kg^{-1}, in white rice is 0.127 ± 0.087 mg kg^{-1}, and 0.07 ± 0.05 mg kg^{-1} for other colors (Zavala and Duxbury, 2008). The maximum amount of arsenic is in brown rice because its outer layers have a higher content of the metalloid.

Risk of Arsenic to Human Health from Rice

Rice (*Oryza sativa* L.) is a miracle crop that can be grown in a varied ecosystem of the world (Kumar *et* *al.*, 2025). It is being cultivated under the diverse environmental condition in the world ranging from irrigated to rainfed and upland to lowland to the deep-water system (Kumar *et al.*, 2020). Rice requires more water per unit grain production as comparison to other cereal crops like wheat, maize, sorghum, pearl millet and finger millet (Kumar *et al.*, 2020). It is the staple food and primary route of arsenic exposure in many countries and has adverse health results (Rahman *et al.*, 2014). A significant relationship between intake of rice with both urinary arsenic and prevalent skin lesions has been reported from a study on 18,470 persons of Bangladesh (Melkonian *et al.*, 2013). A positive correlation between rice consumption and the concentration of urinary arsenic was showed from the USA. Rahman *et al.* (2014) revealed that specific cultivars of protein-rich rice promote arsenic bio-accessibility, as thiol groups are strongly bound to AsIII. Then again, utilization of vegetable-rich diets decreases the chance of developing arsenic-induced skin lesions due to differences in arsenic metabolism rate (Koch *et al.*, 2013). The population of gut microbial also plays an important role in the arsenic speciation and absorption into the blood. Arsenic undergoes a series of biotransformation in the gastrointestinal tract, including oxidation, reduction, methylation, and thiolation (Alava *et al.*, 2015). Arsenic bio-accessibility is increasing due to acidic pH in the stomach as compared to the intestine. AsV is released more easily than DMA from the rice matrix during gastrointestinal digestion. The thiol-containing amino acid in the endosperm cells of rice seed is bound by inorganic arsenic species (Alava *et al.*, 2015). Various studies report the view that real exposure to arsenic through foods depends on food processing methods, temperature, duration, and cooking medium. The concentration of arsenic in rice is reduced by well-cooked rice with profuse water (Rahman *et al.*, 2014). The methods of root uptake, rhizosphere, bioavailability, transport, accumulation, and grain unloading of arsenic are imperative aspects of research to alleviate arsenic in rice (Wang *et al.*, 2015).

Strategies for Mitigating Arsenic Accumulation in Rice

There are several agronomic methods that may be adopted as strategies to reduce the effects of accumulation of arsenic in rice, including aeration of soil by water management practices and preventing reduction of arsenic, creating the condition that favours the formation and precipitation of insoluble arsenic in the soil; and, reducing arsenic uptake and translocation in rice plants by augmenting mineral nutrients in soil that competes with arsenic uptake. The cost-effective remedies which can help to decrease the risk associated with As in plants are as (Bakhat *et al.*, 2017)

Soil Fertilization with Minerals

Some specific mineral nutrients like Fe, S, P, and Si can play an important role in decreasing the arsenic accumulation in edible plant parts by minimizing its uptake and translocation in food crops (Bakhat *et al.*, 2017).

Role of Iron

Iron (Fe) is an important plant mineral nutrient and has a strong affinity towards As and can decrease the arsenic absorption in rice (Liu *et al.*, 2004). In this possible exogenous application of Fe includes (i) deposition of Fe-oxide around (Fe-plaque formation) plants roots of rice and reduces As uptake, (ii) increase co-precipitation of Fe and arsenic (iii) decreased availability of soluble AsV to rice plant due to an adsorption of AsV on Fe surface. Fe-plaque formation around the rice roots, which consists of ferrihydrite (63%), goethite (32%), and siderite (5%) are promoted by the anaerobic cultivation of rice (Liu *et al.*, 2004). It also plays an important role in decreasing As uptake in rice because of high affinity towards AsV and is able to sequester the As, which ultimately helps to reduce arsenic translocation from roots to shoots (Liu *et al.*, 2004); Fe oxides concentration also increases in the rhizosphere that consequently reduce the As uptake in rice (Lee *et al.*, 2013). The application of steel slag (rich in Fe and silicate) in rice production systems is very common in Southeast Asia.

Role of Phosphorus

Phosphorous (P) plays an important role in the solubility of arsenic in the soil of the paddy field and its uptake by plants as it competes with arsenate (AsV) at the same sorption area in soils or Fe-plaque through ligand exchange mechanisms (Peryea *et al.*, 1997). Many different studies supported that the application of phosphate in soil reduces arsenic content in Fe-plaques, leading to an upsurge in arsenic solubility and bioavailability in the soil and rhizosphere (Smith *et al.*, 2002). In any case, phosphate has an inhibitory impact, at critical concentration, at which it competes with arsenate for the similar transporter during take-up by the plasma membrane (Abedin *et al.*, 2002) and increasing the phosphate concentration in the solution leads to reduces in arsenate uptake by the plant (Rahaman *et al.*, 2011). Three main factors controlling the effect of P on arsenic mobility in soil and its uptake in rice were suggested by Lee *et al.* (2016) (1) competition between arsenic and P for adsorption sites on soil particles, (2) the antagonistic impact between arsenic and inorganic phosphate (Pi) during uptake in rice roots, and (3) the role of Pi in translocation of arsenic from root to shoot. In plants, the toxicity of As depends on As/P ratio in the soil rather than the absolute arsenic concentration. China reported that by altering phosphorous status in shoots, the accumulation of arsenic could be reduced in rice grains (Lu *et al.*, 2010). Moreover, in arsenic enriched soils, the application of Ca in addition to P forms Ca-P-As complex, and it causes a decrease in arsenic mobility.

Role of Silica

Silicic acid (H_4SiO_4) is the major form of silicon primarily absorbed by plant roots. Solubility of silicon in the soil depends on soil pH, the most important determinants in soil solution (Korndörfer *et al.,* 2005). Supplement of silicon improves crop yield by increasing both the number of spikelets per panicle and especially the percentage of filled spikelets (Tamai *et al.,* 2008). Si nutrition results in alteration of primary metabolism and stimulating amino acid remobilization in rice was reported by Detmann *et al.* (2012). Arsenite uptake occurs through nodulin-26, such as intrinsic proteins (NIPs), similar transporter for uptake and translocation of silicon (Si). The presence of high silica available in the soil decreases the uptake of arsenite by rice (Bogdan *et al.,* 2008). This was also revealed that the ortho silicic acids decreased the arsenic toxicity in rice grain as well as help in improve the plant growth (Dwivedi *et al*., 2020) Application of silicon in soil decreased the total arsenic accumulation in rice straw and grain by 78% and 16%, correspondingly; strongly reduces the arsenic concentration in leaves and limits the negative effects on the photosynthetic apparatus (Sanglard *et al.,* 2014). This is reported that the combined treatment of arsenic+selenium+silicon to rice plant showed maximum reduction of arsenic in root and shoot was 57% and 64%, respectively (Kumar *et al*., 2024). Marmiroli *et al.* (2014) was observed that the growth of shoot was adversely affected by the AsIII and AsV exposure in the absence of Si supplementation. Application of silicate and Fe containing materials like furnace slag and calcium silicate slag is a very common practice in Southeast Asia. So that the application of silica gel (10 g kg^{-1} of soil) was much more effective to reduce the concentration of arsenic in flag leaf, straw, husk, and grains of rice as reported by some researchers (Fleck *et al.,* 2013). Roughly 33% decrease of AsIII concentration in polished rice was found as a result of ~50% decreased vascular transportation of arsenic after application of silicon under flooded condition of paddy field (Fleck *et al.,* 2013). The accumulation of As(III) by plant roots is decreased when there is bulk amount of silicon found in the soil as also depicted in figure 1.

Management of water and irrigation practices

Management of water in the paddy field is one of the best approaches in controlling arsenic bioavailability of arsenic in the soil-plant system (Somenahally *et al.,* 2011). A system of water-saving has been reported to be an immediate and sustainable solution to reduce arsenic contents in rice. Under flooding conditions, arsenic mobility is largely increased by the reductive dissolution of Fe-oxyhydroxides . The efforts water-saving changes the status of redox in soil and promotes oxidation condition that consequently impedes the reduction of AsV to AsIII and the highly toxic As species, having higher solubility, plant availability, and toxicity (Takahashi *et al.,* 2004). In oxidizing conditions of soil, affinity of arsenic increases for soil minerals and also the oxidation consequences of Fe-to-Fe plaques formation around the root surface (Liu *et al.,* 2004). The overall impact is to reduce arsenic mobility, and accordingly, less arsenic is available for plants (Takahashi *et al.,* 2004). Under aerobic water management practices, rice uptakes less arsenic (0.23–0.26 ppm) than under anaerobic practices (0.60–0.67 ppm) were reported by Talukdar *et al.* (2011). To decrease amount of arsenic in rice grains, sprinkler irrigation practice is also having positive impacts (Spanu *et al.,* 2012). Fe-plaque formation and uptake of arsenic by rice influenced by differential irrigation practices (Somenahally *et al.,* 2011). It was observed in both continuous and intermittent flooding showed that total arsenic concentrations in the rhizospheric soil and grains were significantly reduced in intermittent flooding conditions than the continuous flooding (Somennahally *et al*., 2011)

Bioremediation strategy

Role of Soil Microorganism

The concentration of the mineral in the soil is control by soil microorganisms through different mechanisms, including mineralization, immobilization which directly affects the fate and transport of arsenic in the environment (Huang *et al.,* 2014). These microorganisms help in the detoxification of arsenic species through sorption at their extracellular surface, which has uronic acids, proteins and amino sugars with hydrogen bonding potentials. Adsorptions of different inorganic and organic species of As have been reported by different soil bacteria: *Bacillus* sp. *Rhodococcus* sp., *Halobacterium* sp. (Williams *et al.,* 2013) and the other possible way of arsenic detoxification in soil microorganism is the formation of amorphous Fe hydroxides on the cell surface through the formation of inner-sphere complexes (Yang *et al.,* 2012).

Arbuscular mycorrhizal fungi (AMF) suppresses mRNA expression of OsLsi1 and OsLsi2 and also plays a protective role in arsenic translocation (Chen *et al.*, 2012), so that it helps in biomass and grain yield without accelerating the arsenic accumulation in grain under As stress, which might be an interesting approach to develop a cost-effective mitigation strategy.

Increase AsIII Efflux Rate

S. cerevisiae ACR3 gene encoding arsenite efflux protein increased AsIII efflux and also reduced arsenic accumulation in rice grain of transgenic rice plants. In this rice, plants exhibited 30% less arsenic concentration in root and shoot than wild type plants having similar arsenic translocation factors (Duan *et al.*, 2012).

Volatilization of Arsenic

The process of arsenic volatilization can be done by conversion of inorganic arsenic to methylated organic species like MMA and DMA and finally to the gaseous trimethylarsine (TMA) through the production of transgenic rice plant harbouring the bacterial gene As III-S-adenosyl methioninemethyltransferase ArsM (Qin *et al.*, 2006). Meng *et al.* (2011) suggested that transgenic rice plant expressing ArsM produced tenfold higher volatile arsenical maintaining a low level of arsenic in rice seed along with organic arsenic species in the root and shoot of transgenic rice.

Conclusion

In conclusion, the toxicity of rice from arsenic exposure was a serious threat for mankind as well as food security. Accumulation of arsenic in rice is mainly dependent on its bioavailability, arsenic-rich soil, and was influenced by different factors like soil types, physicochemical parameters, presence of other elements, and mineral composition. Therefore, the requirement of the best technologies and productive actions for the removal of arsenic contamination in rice plants was to make them safe for humankind.

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