

Review

Arsenic Uptake and Accumulation Mechanisms in Rice Species

Tayebeh Abedi ^{1,*} and Amin Mojiri ²

¹ Umea Plant Science Centre, Department of Forest Genetics and Plant Physiology, Swedish University of Agricultural Sciences, 90183 Umea, Sweden

² Department of Civil and Environmental Engineering, Graduate School of Civil Engineering, Hiroshima University, 1-4-1 Kagamiyama, Higashihiroshima 739-8527, Japan; amojiri@hiroshima-u.ac.jp

* Correspondence: tayebeh.abedi@slu.se; Tel.: +46-702205522

Received: 27 December 2019; Accepted: 20 January 2020; Published: 21 January 2020



Abstract: Rice consumption is a source of arsenic (As) exposure, which poses serious health risks. In this study, the accumulation of As in rice was studied. Research shows that As accumulation in rice in Taiwan and Bangladesh is higher than that in other countries. In addition, the critical factors influencing the uptake of As into rice crops are defined. Furthermore, determining the feasibility of using effective ways to reduce the accumulation of As in rice was studied. AsV and AsIII are transported to the root through phosphate transporters and nodulin 26-like intrinsic channels. The silicic acid transporter may have a vital role in the entry of methylated As, dimethylarsinic acid (DMA) and monomethylarsonic acid (MMA), into the root. Amongst As species, DMA(V) is particularly mobile in plants and can easily transfer from root to shoot. The *OsPTR7* gene has a key role in moving DMA in the xylem or phloem. Soil properties can affect the uptake of As by plants. An increase in organic matter and in the concentrations of sulphur, iron, and manganese reduces the uptake of As by plants. Amongst the agronomic strategies in diminishing the uptake and accumulation of As in rice, using microalgae and bacteria is the most efficient.

Keywords: arsenic; detoxification; rice; toxicology

1. Introduction

Rice (*Oryza sativa* L.) provides food for more than three billion people [1]. Approximately 90% of rice production and consumption is reported in Asia [2]. By 2050, the production of rice should rise by 60%–70% to meet the requirements of the predicted population growth in Asia [3]. Rice can be cultivated in many regions of the world because of its resourcefulness and diversity. Two species, *Oryza glaberrima* Steud. (in Africa) and *Oryza sativa* L. (in Asia), are commonly cultivated [4]. However, rice consumption can pose problems because of the arsenic (As) accumulation in rice and thus serves a vital source of As exposure in humans [5].

As is the 20th abundant component on the Earth's crust. However, As is a toxic metalloid and is remarked as a considerable global groundwater contaminant, affecting certain rivers and deltas in East and South Asia and in South American countries [6]. Based on the Agency for Toxic Substances and Disease Registry list 2017, As is amongst the most hazardous materials that could be poisonous to humans. Approximately 200 million people in around 70 countries have been exposed to this metalloid [7].

As enters agricultural lands and the environment via natural sources, such as rocks, As-enriched minerals, forest fires, volcanoes and anthropogenic sources (e.g., mining, herbicides, phosphate fertilisers, smelting, industrial processes, coal combustion and timber preservatives) [8]. The average amount of As in agricultural fields that receive As-comprising pesticides and defoliants ranges from

5 mg/kg to 2553 mg/kg [9]. The management of paddy soils for the wet cultivation of rice involves different cycles of submerged and dry days, which cause alternating oxidising and reducing processes in soil. Under this condition in paddy soil, As is reduced to arsenite (AsIII) with high toxicity and mobility in flooded soil, AsIII may then be taken up by rice [10]. Evidence shows considerable As toxicity from the utilisation of rice and rice-based products, especially those consumed as a staple dietary source [11]. Accumulation of As in rice may be decreased by amending cultural practices. Hence, the current work focused on the mechanisms of uptake and accumulation of As in rice and the effective factors which reduce As uptake by rice crops. The results are expected to enrich our understanding of the uptake, transport and distribution of As in rice.

2. Arsenic Uptake and Transport by Rice Plants

Rice is more seriously affected by As pollution than other crop plants. Its cultivation is carried out in flooded conditions, which lead to the reduction conditions [12]. As may be found in the environment, organic and inorganic AsIII and arsenate (AsV) are the dominant As species that reduce paddy soil conditions, followed by methylated As species. Moreover, plant roots selectively may uptake specific As forms [13]. Table 1 shows the reported concentrations of As in rice around the world. All As species can be transferred through the plant cell via specific transporter proteins [14]. The genes involved in transporting As in rice are shown in Table 2.

Table 1. Arsenic found in rice plants around the world.

Plant's Parts	As ($\mu\text{g}/\text{Kg}$); Average or Range	Remarks	Area	Reference
Grains	230	* Boro rice	Sadar Upazila (subdistrict), Faridpur, Bangladesh	[15]
Straw	2890			
Husk	750			
Grains	235	White rice	Comilla district, Bangladesh	[16]
Straw	1149			
Grains	600	BRRI dhan28	Satkhira district, Bangladesh	[17]
Straw	1700			
Root	46,300			
Grains	700	BRRI hybrid dhan1		
Straw	1900			
Root	51,900			
Grains	78 \pm 26	White rice	Barisal, Bangladesh	[18]
	185 \pm 82		Chandpur, Bangladesh	
	189 \pm 72		Comilla, Bangladesh	
	180 \pm 65		Dhaka, Bangladesh	
	177 \pm 52		Munshiganj, Bangladesh	
	210 \pm 95		Narayanganj, Bangladesh	
Grains	170 to 260	Boro	Bhanga and Faridpur in Bangladesh	[19]

Table 1. Cont.

Plant's Parts	As ($\mu\text{g}/\text{Kg}$); Average or Range	Remarks	Area	Reference
Straw	390 to 3430			
Whole grains	20 to 130	<i>Oryza sativa</i> var. kalijira	MATLAB, Bangladesh	
Grains	129.4	White rice	Huang, China	[20]
Grains	250 \pm 51	White rice	Renhua, China	[21]
Straw	3300 \pm 1300			
Root	25,600 \pm 12,500			
Grains	280 \pm 67	White rice	Lechang, China	[21]
Straw	5800 \pm 2800			
Root	35,000 \pm 9400			
Grains	147	Indica	Fujian, China	[22]
	202	Indica	Guangdong, China	
	302	Indica	Guangxi, China	
	200	Indica	Yunnan, China	
	184	Indica	Chongqing, China	
	218	Indica	Sichuan, China	
	187	Japonica	Jiangsu, China	
	277	Indica	Zhejiang, China	
	309	Indica	Jiangxi, China	
	216	Japonica	Henan, China	
	308	Indica	Hunan, China	
	246	Indica	Hubei, China	
	263	Indica	Anhui, China	
	196	Japonica	Liaoning, China	
	426	Japonica (Unpolished samples)	Jilin, China	
Grains	0.127 to 0.275	Indica	Huahang-Simiao, China	[23]
Husk	0.314 to 0.985			
Shoot	0.93 to 6.19			
Root	35.4 to 327.3			
Grains	230 \pm 240	Taikeng No. 8	Gaudan Plan, Taiwan	[24]
Straw	4700 \pm 1400			
Root	266,000 \pm 98,000			
Grain	150 \pm 50	Tain Nan No. 11		
Straw	3200 \pm 400			
Root	157,000 \pm 27,000			
		* Rice Types	Ambagarh Chouki, India	[25]
Husk	432	IR-64		
	147	Culture		
	411	Shyamla		
	415	G. Gurmatia		
	235	Masuri		
	167	Purnima		
	144	Mahamaya		
	446	Kalinga		
	324	Luchai		
	18	Safari		
Grains	3.30 to 4.91	** NR the rice species	Punjab, India	[26]
Straw	7.30 to 9.89			
Grains	451	Boro rice	West Bengal, India	[27]
Grains	334	Aman rice		
Grains	8.78	<i>Oryza sativa</i> L.	Central and sub-mountainous Punjab, India	[28]

Table 1. Cont.

Plant's Parts	As ($\mu\text{g}/\text{Kg}$); Average or Range	Remarks	Area	Reference
Straw	3.94			
Grains	290 \pm 580	<i>Oryza sativa</i>	Alor Setar, Kedah, Malaysia	[29]
Straw	80 \pm 150			
Root	23,100 \pm 12,670			
Grains	189 to 541	<i>Oryza sativa</i>	Besut, Sekinchan, Tanjung Karang and Sabak Bernam; Malaysia	[30]
Grains	124 to 136 186 to 198 832 to 963	Polished rice (White) Brown rice (White) Rice bran (White) (Samples collected from markets (Thailand-grown)	Thailand	[31]
Grains	107 to 166	White rice	Japan; Low-As soils	[32]
Grains				
Grains	160	Brown rice	Japan (average of the country)	[33]
Grains	283 \pm 18	* White rice (organic)	Australia (not specified)	[34]
	241 \pm 07	White rice (long-grain)		
	438 \pm 23	Brown rice (organic)		
	287 \pm 03	Brown rice (whole)		
	198 \pm 41	Brown rice (long-grain) Samples collected from markets (Australian-grown)		
Grains	170 \pm 30	* Mahatma	Australia (not specified)	[35]
	100 \pm 30	Brown		
	120 \pm 30	White		
	90 \pm 20	Medium grain white		
	220 \pm 20	Sushi		
	220 \pm 20	Arborio		
	210 \pm 30	Medium grain Arborio Samples collected from markets (Australian-grown)		
Grains	0.13	<i>Oryza sativa</i>	California, US	[36]
Straw	0.7			
Grains	0.2	<i>Oryza sativa</i>	Arkansas, US	[36]
Straw	1.5			
Grains	230 \pm 10	* Arborio	Lombardia, Piemonte, Emilia Romagna, and Calabria in Italy	[37]
	230 \pm 20	Carnaroli		
	180 \pm 10	Ribe		
	200 \pm 10	Ribe/Roma parboiled		
	190 \pm 10	Roma		
	280 \pm 30	Vialone Nano		
	190 \pm 30	Originario		

Table 1. Cont.

Plant's Parts	As ($\mu\text{g}/\text{Kg}$); Average or Range	Remarks	Area	Reference
Grains	0.32	<i>Oryza sativa</i>	Carmargue, France	[36]
Straw	10.2			
Grains	232 \pm 21	Brown rice	Guayas, Ecuador	[38]
	174 \pm 14	White rice	Guayas, Ecuador	
	186 \pm 17	White rice	Los Rios, Ecuador	
		Samples collected from markets (Ecuadorian-grown)		
Grains	167.94		Around Tumbes river basin in Peru	[39]

* Local name. ** NR: Not Reported.

2.1. Uptake of Inorganic Arsenic

Inorganic As, AsIII and AsV, is more toxic than organic As, dimethylarsinic acid (DMA) and monomethylarsonic acid (MMA) [18]. Inorganic As is the dominant form of As in soil and groundwater. Under aerobic conditions in soil, AsV dominates, whereas, in submerged conditions, AsIII is the dominant species [40].

AsV may generally enter the roots of rice crops through phosphate transporters (PHTs), primarily PHT1 (phosphate transporter1)-type transporters [41] during the regulation of inorganic phosphorous (Pi) [42]. A total of 13 PHTs from the PHT1 family in rice (*Oryza sativa*) have been found to mediate Pi uptake and transport [43] through the highly efficient silicon (Si) uptake pathway.

Furthermore, AsIII may enter by the nodulin 26-like intrinsic (NIPs) aquaporin channels accompanied by silicic acid and ammonia [42]. NIP proteins are one of the major intrinsic proteins which comprise the family of important membrane channel proteins [44]. NIPs are categorised into three main groups, namely, NIP-I, NIP-II and NIP-III, with regard to the common substrate selectivity and consistency of amino acid composition [45]. The NIP-II group (such as OsNIP3;1, AtNIP5;1, AtNIP6;1 and ZmNIP3;1) has been found to be vital for the uptake and transporting of boron in several plants [44]. NIP-III group members (such as OsNIP2;1, OsNIP2;2, HvNIP2;1, HvNIP2;2 and CmNIP2;1) are revealed to be vital for the effectual uptake and translocation of Si [46]. A family of 10 NIP proteins is found in rice. Bienert et al. [47] reported that NIPs in *Oryza sativa* L., OsNIP2;1 (Lsi1) and OsNIP3;2 (Lsi2) are capable of facilitating an influx of AsIII into rice root cells.

2.2. Uptake of Organic Arsenic

Methylated As species, namely, MMA ($\text{CH}_3\text{AsO}(\text{OH})_2$) and DMA ($(\text{CH}_3)_2\text{AsOOH}$), might be present in soil due to microbial actions or past usage of methylated As compounds, cacodylic acid or sodium salt of MMA and DMA as pesticides [42]. Microorganisms in soil may convert As species from AsV to AsIII and further to MMA and DMA. Suriyagoda et al. [48] stated that DMA and MMA might be taken up by the silicic acid transporter Lsi1. Plant roots are capable of taking up DMA and MMA, but the amounts of uptake are lower than those of inorganic As species and diminish with increasing numbers of methyl groups [49]. MMA(V) is partially reduced to trivalent MMA(III) in rice roots, but only MMA(V) is translocated to shoots [50]. DMA(V) is mobile in plants and may easily transfer from root to shoot. Muehe et al. [51] explained that methylated As is taken up gradually into rice relative to inorganic species but that it is freely translocated to grains.

2.3. Arsenic Species Translocation from Root to Shoot

The average translocation factor for As is around 0.8, which is higher than the other crops, such as barley (0.2) and wheat (0.1) [52].

As mentioned previously, the Si transporter OsNIP2;1 (*Lsi1*) is responsible for AsIII uptake, and *Lsi2* drives AsIII efflux from rice root cells to the xylem [53]. *Lsi1* is located in the distal side of the plasma membranes in exodermal and endodermal cells and is in charge of the influx of AsIII, whilst *Lsi2* is located in the proximal sides of the same root cells and is in charge of the efflux of AsIII [54]. In other words, the synergy of *Lsi1* and *Lsi2* transports Si and AsIII into root cells. Si and AsIII in the xylem vessel are transported to the shoot via transpiration flow by *Lsi1* and *Lsi2* first and then by *Lsi6*, which is localised in the xylem parenchyma cells of leaves [55]. Detmann et al. [56] stated that the *Lsi6* gene plays a vital role in the distribution of Si, or maybe AsIII, in rice shoot.

In rice, 13 Pi transporter genes (*OsPT*) can transport AsV to the root. Amongst these genes, *OsPT1*, *OsPT2*, *OsPT4*, *OsPT6*, *OsPT8*, *OsPT9* and *OsPT10* have a role in P uptake and translocation in rice. Certain Pi transporters also mediate AsV uptake [57]. Amongst these *OsPTs*, *OsPT1* is thoroughly stated in roots and is a main regulator of Pi. *OsPT2* has a vital role in Pi transferring from the root to the shoot [58]. AsV may be reduced to AsIII inside the rice root, and AsIII may then enter the xylem via a silicic acid/AsIII effluxer [59]. Chen et al. [60] explained that AsV may be quickly reduced to AsIII in plant cells by high As content 1 (HAC1) AsV reductases. Chao et al. [61] reported that HAC1 is vital in the reduction of AsV activity in the outer layer of the root (epidermis) and the inner layer adjacent to the xylem (pericycle).

Mitra et al. [14] expressed that DMA and MMA enter the NIP protein. However, AsIII is more capably taken up by roots than MMA and DMA. Zhao et al. [49] stated that the transferring from roots to shoots commonly rises with the rising quantity of methyl groups in As. DMA is extremely mobile throughout the xylem and phloem in rice. Tang et al. [62] reported that *OsPTR7* may interact in the transferring of DMA in the phloem or xylem. High mobility of DMA occurs in the moving from roots to shoots and from leaves to grain.

2.4. Phloem and Xylem-Derived Pathways of As Species and As Loading in Grains

As may be transferred from roots to shoots through the xylem [48]. Phloem transportation is probably responsible for 54%, 56%, 100% and 89% of AsIII, AsV, MMA(V) and DMA(V) translocation into rice grains, respectively. In the phloem, organic arsenics are more transportable than inorganic arsenics [63]. Moreover, AsIII is transported to rice grains principally through the phloem pathway, whereas DMA is translocated to rice grains through the xylem and phloem pathways [62]. In arabidopsis, Duan et al. [64] reported that AtINT2 and AtINT4 (inositol transporters) may have a role in AsIII entering into the phloem and in adjusting the accumulation of As(III) in seeds. Hence, similar transporters in rice plants may be responsible for As(III) transport. Furthermore, *OsPTR7* has a role in the long-distance transferring of DMA and in the accumulation of DMA in rice grains [62].

Table 2. Gene families involved in As uptake, transport and metabolism in rice.

Name	Category	As species	Remarks	Reference
<i>OsPT1</i>	P transporter	AsV	AsV transporter to root	[57]
<i>OsPT2</i>	P transporter	AsV	AsV transporter root to shoot	[57]
<i>OsNIP2;1 (Lsi1)</i>	NIPs	AsIII, DMA, MMA	AsIII, DMA and MMA transporter to root	[63]
<i>OsNIP2;2 (Lsi2)</i>				
<i>OsNIP1;1</i>				
<i>OsNIP3;1</i>				
<i>OsNIP3;2</i>				
<i>OsNIP3;3</i>				

Table 2. Cont.

Name	Category	As species	Remarks	Reference
<i>OsPIP1;2</i> <i>OsPIP1;3</i> <i>OsPIP2;4</i> <i>OsPIP2;6</i> <i>OsPIP2;7</i>	PIP (plasma membrane intrinsic protein)	AsIII	AsIII transport root to shoot	[65]
<i>OsNRAMP1</i>	NRAMP (natural resistance-associated macrophage protein)	AsIII	AsIII transport root to shoot	[5]
<i>OsHAC1;1</i> <i>OsHAC1;2</i> <i>OsHAC4</i>	NIPs	DMA, MMA, AsV	DMA and MMA transporter to root AsV reduction to AsIII in root	[63]
<i>OsNPF8;1</i> (<i>OsPTR7</i>)	Putative Peptide Transporter	DMA	Translocation of DMA in plant, including xylem, phloem and grains	[62]
<i>OsABCC1</i>	ATP-binding cassette transporter	As	Detoxifying	[66]

2.5. Phytotoxicity of Arsenic and Arsenic Detoxification Mechanism in Rice Plants

As is extremely phytotoxic to plants as it diminishes plant growth and crop yield [18]. Several rice varieties were subjected to AsIII and AsV by Shakoor et al. [67]. Seed germination was slightly limited at 0.5 and 1 mg·L⁻¹, and a diminishing of around 10% in germination was detected at 2 mg·L⁻¹. The growth of root was limited by 20% at 0.5 mg·L⁻¹ of AsV. In addition, AsV was found to be more toxic than AsIII. The dangerous biochemical impact of As at the subcellular level is the production of reactive oxygen species (ROSs), such as hydroxyl radical (OH), superoxide radical (O₂⁻) and hydrogen peroxide. ROSs are hazardous for plant metabolism and may lead to damage to macromolecules [68].

As previously mentioned, AsV is reduced to AsIII in plants. In addition, AsIII efflux to the external medium is a vital way of As detoxification in plants. Inside plant cells, AsIII may be detoxified by complexation with phytochelatins (PCs), followed by the accumulation of AsIII–PC complexes in vacuoles through *OsABCC1* transporters [69]. *OsABCC1* is one of the ATP-binding cassette (ABC) transporters. ABC transporter proteins play roles in the translocation of a broad range of substances within membranes using energy from ATP hydrolysis [70]. Song et al. [66] stated that *OsABCC1* plays a vital role in the detoxification and decreasing As in rice grains.

HAC1 contributes to the defence against As in plants [71] and is essential for the efflux of AsIII from roots for AsV detoxification [72]. In rice, *OsHAC1;1*, *OsHAC1;2* and *OsHAC4* function as AsV reductase. Moreover, glutaredoxin possesses AsV reductase enzyme activity in maintaining the glutathione (GSH) pool and assists in AsIII efflux [73].

Brinke et al. [74] stated that with rising AsIII concentrations, the importance of the term ‘response to stress’ is replaced by the detoxification ways ‘glutathione biosynthesis’, which is related to the term ‘oxidation reduction’. GSH is applied as an electron donor by dehydroascorbate reductase to reconvert dehydroascorbate to ascorbate. GSH disulphide is the oxidised form of GSH, which may be reprocessed to GSH by glutathione reductase via reduced nicotinamide adenine dinucleotide phosphate. Hence, these different components of the ascorbate–GSH cycle may have a vital character in protecting cells against oxidative damage resulted by As toxicity [75].

After the reduction of AsV to AsIII, further mechanisms of detoxification arise in the vacuole via vacuolar sequestration. AsIII chelates with sulfhydryl (–SH)-rich protein and arranges a complex that

is separated by vacuolar transporters (PCs). In rice, two phytochelatin synthase enzymes have been testified, comprising OsPCS1 and OsPCS2 [73].

3. Effects of Different Factors on Reducing Arsenic Uptake by Plants

Certain factors, such as pH, soil texture, organic matter (OM) and sulphide concentrations, may affect As uptake by plants [76]. Soil texture may affect As mobility due to differences in charges on the soil surface, which controls the adsorption and desorption procedures in soil. Soils with high amounts of clay have a higher As retention potential than coarse-textured soils. Reports also indicated that As uptake and concentrations are higher in plants grown in loamy sand than in plants grown in silty clay loam soils [77]. Moreover, As is five times more toxic in sand and loam than in clay soil, and its available form is a vital factor related to phytotoxicity [78].

3.1. Soil pH

pH is an important factor affecting As uptake [79]. An increase in pH commonly results in the mobilisation of As in soil. In general, an increase in soil pH results in a release of anions from within their exchange positions, along with AsV and AsIII [80]. Tu and Ma [79] reported that redox potential and pH influence As species. For example, under oxidising situations at $\text{pH} < 6.9$, H_2AsO_4^- becomes the primary species, and at a high pH, HAsO_4^{2-} is dominant. High soil pH (generally pH 8.5) increases the negative surface charges, such as hydroxyl ions, thereby facilitating the desorption of As from Fe oxides and the resulting mobilisation of As in the root area; these conditions, in turn, increase As accumulation in plants [14].

3.2. Soil Organic Matter

OM in soil may influence the mobility and bioavailability of As over redox reactions, anions (phosphate, DOC and silicate), As-OM complexation and competitive adsorption [81]. OM may also affect plant growth and As accumulation in rice plants. OM, theoretically, insolubilises As over certain mechanisms, such as the binding of As with phenolic OH, carboxylate and sulphhydryl groups with/without ternary complexes [82]. Norton et al. [83] stated that OM is important in the mobilisation of As from paddy fields because microbes utilising OM consume oxygen that results in a reduction in redox potential, which leads to As dissolution from FeOOH. Syu et al. [81] explained that the characteristics of soils and OMs should be considered before using OM amendments to As-polluted soils. The use of OM to As-polluted soils may exert different effects on the As accumulation and growth of rice plants [81]. For example, biochar may improve As reduction and release in flooded paddy soils [84], but augmenting farmyard manure to soils with high amounts of As leads to a reduction of plant growth [83]. Norton et al. [83] stated that OM may also play two other roles in As availability in soils: by desorbing As species from soil surface exchange sites and complexing As species with dissolved organic matter (DOM).

3.3. Concentration of Nitrogen, Phosphorous and Sulphate in Soil

In rice soils, the main form of nitrogen (N) is ammonium, whilst nitrate concentration is less than $10 \mu\text{M}$. Rice roots discharge oxygen into the rhizosphere, thereby causing ammonium nitrification by microbes near the root surface [85]. The procedure of Fe redox cycling may be influenced by N cycling. The coupled NO_3^- reduction and Fe(II) oxidation can diminish As in paddy environments [63].

As previously mentioned, rice crops take up AsV via phosphate transporters [57]. Phosphate and arsenate are analogues and may compete for the same sorption sites on soil particles. The adding of phosphate commonly has two consequences: (i) raised downward move of As resulting in increased leaching from the topsoil and (ii) enhanced accessibility of As in the soil solution. AsV also acts as a phosphate analogue with respect to transport across the root plasma membrane [86]. Pigna et al. [87] reported that As toxicity in crops may be prevalent in situations where As pollution coexists with low available P.

Sulphur (S) is an element that interacts toughly with As, particularly under reducing conditions; the reduced forms of S can make a binding with As(III) [88]. Srivastava et al. [89] stated that S is important for plant growth as it regulates As tolerance over complexation of As by S-containing ligands (glutathione [GSH; γ -Glu-Cys-Gly] and PCs [GSH oligomers]). Zhang et al. [90] reported a reduction in translocating As from roots to shoots in high sulphate-pretreated rice plants.

3.4. Concentration of Iron and Manganese in Soil

Anwar et al. [9] expressed that Fe and Mn-rich compounds, such as goethite, ferruginous smectites, nontronite, pyrolusite and birnessite, absorb large amounts of As(V). Hence, As mobility may be low. A coating of Fe hydroxides/oxides identified as iron plaque, is normally formed on the roots of aquatic plant species. Iron plaque is the result of the oxidation of roots by releasing oxygen and oxidants into the rhizosphere [91,92]. Iron plaque also restrains the uptake of As by plants, possibly due to its adsorption or co-precipitation procedures [93]. Yu et al. [94] reported a negative correlation between As in rice grains and amorphous Fe oxide-bound As in soil and specified that amorphous Fe oxides might play a role as a barrier for As uptake by the plant. Liu et al. [91] expressed that Mn and Fe plaque can reduce the uptake of As in rice seedlings.

4. Agronomic Methods for Reducing Uptake and Accumulation of Arsenic by Plants

Awasthi et al. [12] stated three key plans to decrease As uptake by rice: (1) agronomic practices; (2) transforming the transporters involved in uptake; and (3) influencing the mobility of As in developing the synthesis of chelators.

For the agronomic strategy, researchers have tried to reduce As uptake by rice using different mitigation methods (Table 3). Several strategies are being practiced to mitigate As pollution, and they include overbreeding, bioremediation, transgenics and developed fertilisation; these techniques have their own limitations of time, ethics and applicability [95]. Using Fe oxides/hydroxides is one of the mitigation techniques to diminish As uptake by plants. Anwar et al. [9] reported that a high rate of goethite addition to soils may decrease As uptake by plants because goethite may adsorb As. Farquhar et al. [96] stated that As(V) oxyanions are toughly 'sorbed' to the surfaces of iron oxides such as goethite, hence, As uptake may be reduced by plants. Ultra et al. [92] stated that soil amendments with Am-FeOH can modify the accessibility of As uptake by rice plants irrigated with As-polluted water. The manipulation of Si is a way to abate As uptake by rice. This approach takes advantage of the fact that AsIII, the most prevalent As species in flooded porewater, shares the silicic acid uptake pathway in rice [97]. Liu et al. [98] reported that foliar using SiO₂ nanoparticles in As-polluted paddy soil increases the dry weight of rice and obviously reduces As accumulation in grains and shoots. The addition of SiO₂ nanoparticles increases pectin content and advances the mechanical force of the cell wall, resulting in decreased As uptake into rice cells [99]. Rice planted along with accumulators has received growing research attention due to the reduced As uptake by rice. Parveen et al. [100] stated that rice accompanied by accumulators in As-amended plots shows reduced As uptake in grains and shoots. Thus, certain accumulator plants, such as *Pteris vittata*, *Vetiveria zizanioides* and *Phragmites australis*, have been cultivated along with rice. The use of algae or bacteria to reduce As uptake by plants has also been reported [101]. Flooded rice fields offer ideal conditions for microbial and algal growth and regulate As bioavailability through precipitation, redox reactions, complexation and nutrient availability [95].

Table 3. Reported ways for reducing the uptake of As by rice plants.

Decreasing of As Uptake	Method	Remarks	Reference
43% to 70%	Using <i>Anabaena azotica</i> (Microalgae)	(i) Decreasing translocation of As from root to grains; (ii) decreasing DMA in grains and roots and (iii) enhancing nutrient uptake and rice growth	[102]
40%	Using <i>Chlorella vulgaris</i> and <i>Nannochloropsis</i> sp. (Microalgae)	(i) Increasing root and shoot length and biomass and (ii) reduction in cellular toxicity and antioxidant enzyme	[103]
48.1% to 77.7%	Using <i>Chlorella vulgaris</i> (Microalgae) and <i>Pseudomonas putida</i> (Bacteria)	(i) Reducing As accessibility; (ii) modulating the As uptake and (iii) enhancing detoxification mechanism.	[95]
3.5% to 26.0%	Using rhizobacteria (PGPR)	(i) Improving rice growth and (ii) decreasing As accumulation	[104]
79% (in shoots)	Using <i>Pantoea</i> sp (Bacteria; EA106)	(i) improving Fe uptake by root; (ii) decreasing As accumulation	[105]
52.3% to 64.5%	Using <i>Rhodopseudomonas palustris</i> C1 and <i>Rubrivivax benzoatilyticus</i> C31 (Nonsulfur bacteria)	(i) Improving the rice growth; (ii) increasing chlorophyll a and b and (iii) reducing As accumulation	[106]
31% (in grains; just leonardite); 92% (in grains; leonardite + <i>Bacillus pumilus</i>) 91% (in grains; leonardite + <i>Pseudomonas</i> sp) 91% (in grains; leonardite + <i>Bacillus thuringiensis</i>)	Using leonardite + <i>Bacillus pumilus</i> , <i>Pseudomonas</i> sp and <i>Bacillus thuringiensis</i>	(i) High efficiency of leonardite in adsorption of arsenic and (ii) increasing productivity and reducing arsenic in grains	[107]
17% to 82% (in straw)	Using <i>Pteris vittata</i> (Plant)	(i) Decreasing phosphate extractable; (ii) decreasing methylated As in grains more than inorganic As	[108]
22% to 58% (in grains)			
179% (in root)	Using selenium amendments	(i) Enhancing the essential amino acids; and (ii) increasing non-protein thiols and phytochelatins in rice	[109]
144% (in shoot)			
46% (in straw)	Using Si-rich amendments	(i) Decreasing As accumulation and (ii) reducing CH ₄ emissions from soil (i) Decreasing the soil solution As in flooded condition; (ii) decreasing As uptake by rice in aerobic and (iii) decreasing the proportion of As in rice shoots.	[97]
27.5 (in grains)	Using selenite fertilization	(i) Increasing the Si, Fe and P in soil solution	[110]
50% (straw, flag leaf and husk)	Using silicon	(i) Increasing the Fe and Mn plaque content and (ii) improving the biomass weight of the rice	[111]
68.9% to 78.3% (in grains)	Using ferromanganese oxide and biochar	(i) Increasing percentage productive tillers and grain yield and (ii) reducing the cadmium bioaccumulation in rice grains	[112]
32% (in grains under low water)	Using zero valent iron		[113]

As shown in Table 3, using microalgae and bacteria are efficient in reducing As accumulation in rice.

5. Conclusions

Rice is a major dietary source of As; therefore, researchers have tried to reduce As uptake by rice plants. In the present study, several research papers were reviewed to investigate the journey of arsenic in rice. The key conclusions of the present study are as follows:

1. The accumulation of As in soils in Bangladesh (51,900 µg/L in root) and Taiwan (157,000 µg/L in root) is higher than that in other countries.

2. AsV enters the root via Pi transporters, and AsIII, DMA and MMA enter the root through NIPs.
3. AsV can be reduced to AsIII by HAC1. In addition, DMA is more mobile than other As species.
4. Soil properties, such as pH, OM and the amounts of Fe, Mn, N, P and S, can affect As uptake by rice.
5. Amongst the agronomic strategies for reducing the uptake and accumulation of As in rice, the use of microalgae and bacteria is the most efficient.

Author Contributions: T.A. was responsible for writing the initial draft of the manuscript. A.M. modified the manuscript and contributed to the literature search. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the Institute of Scientific Research Amin-Azma grant with the reference number A20191.

Acknowledgments: The authors would like to express their gratitude to the Institute of Scientific Research Amin-Azma.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Hoang, T.V.; Xuan, V.K.T.; Rahman, M.M.; Choi, S.H.; Jeon, J.S. Heat stress transcription factor OsSPL7 plays a critical role in reactive oxygen species balance and stress responses in rice. *Plant Sci.* **2019**, *289*, 110273. [[CrossRef](#)]
2. Mousavian, M.T.H.; Karizaki, V.M. Determination of Mass Transfer Parameters during Deep Fat Frying of Rice Crackers. *Rice Sci.* **2012**, *19*, 64–69. [[CrossRef](#)]
3. Ma, X.; Han, B.; Tang, J.; Zhang, J.; Cui, D.; Geng, L.; Zhou, H.; Li, M.; Han, L. Construction of chromosome segment substitution lines of Dongxiang common wild rice (*Oryza rufipogon* Griff.) in the background of the japonica rice cultivar Nipponbare (*Oryza sativa* L.). *Plant Physiol. Biochem.* **2019**, *144*, 274–282. [[CrossRef](#)] [[PubMed](#)]
4. Pathaichindachote, W.; Panyawut, N.; Sikaewtung, K.; Patarapuwadol, S.; Muangprom, A. Genetic Diversity and Allelic Frequency of Selected Thai and Exotic Rice Germplasm Using SSR Markers. *Rice Sci.* **2019**, *26*, 393–403. [[CrossRef](#)]
5. Chen, Y.; Han, Y.H.; Cao, Y.; Zhu, Y.G.; Rathinasabapathi, B.; Ma, L.Q. Arsenic Transport in Rice and Biological Solutions to Reduce Arsenic Risk from Rice. *Front. Plant Sci.* **2017**, *8*, 268. [[CrossRef](#)]
6. Kobya, M.; Soltani, R.D.C.; Omwene, P.I.; Khataee, A. A review on decontamination of arsenic-contained water by electrocoagulation: Reactor configurations and operating cost along with removal mechanisms. *Environ. Technol. Innov.* **2020**, *17*, 100519. [[CrossRef](#)]
7. Sodhi, K.K.; Kumar, M.; Agrawal, P.K.; Singh, D.K. Perspectives on arsenic toxicity, carcinogenicity and its systemic remediation strategies. *Environ. Technol. Innov.* **2019**, *16*, 100462. [[CrossRef](#)]
8. Rahaman, M.S.; Akter, M.; Rahman, M.M.; Sikder, M.T.; Hosokawa, T.; Saito, T.; Kurasaki, M. Investigating the protective actions of D-pinitol against arsenic-induced toxicity in PC12 cells and the underlying mechanism. *Environ. Toxicol. Pharm.* **2020**, *74*, 103302. [[CrossRef](#)]
9. Anwar, H.M.; Rengel, Z.; Damon, P.; Tibbett, M. Arsenic-phosphorus interactions in the soil-plant-microbe system: Dynamics of uptake, suppression and toxicity to plants. *Environ. Pollut.* **2018**, *233*, 1003–1012. [[CrossRef](#)]
10. Yun, S.W.; Kim, D.H.; Kang, D.H.; Son, J.; Lee, S.Y.; Lee, C.K.; Lee, S.H.; Ji, W.H.; Baveye, P.C.; Yu, C. Effect of farmland type on the transport and spatial distribution of metal(loid)s in agricultural lands near an abandoned gold mine site: Confirmation of previous observations. *J. Geochem. Explor.* **2017**, *181*, 129–137. [[CrossRef](#)]
11. Shrivastava, A.; Barla, A.; Majumdar, A.; Singh, S.; Bose, S. Arsenic mitigation in rice grain loading via alternative irrigation by proposed water management practices. *Chemosphere* **2020**, *238*, 124988. [[CrossRef](#)] [[PubMed](#)]
12. Awasthi, S.; Chauhan, R.; Srivastava, S.; Tripathi, R.D. The Journey of Arsenic from Soil to Grain in Rice. *Front. Plant Sci.* **2017**, *8*, 1007. [[CrossRef](#)] [[PubMed](#)]

13. Li, N.; Wang, J.; Song, W.Y. Arsenic Uptake and Translocation in Plants. *Plant Cell Physiol.* **2016**, *57*, 4–13. [[CrossRef](#)]
14. Mitra, A.; Chatterjee, S.; Moogouei, R.; Gupta, D.K. Arsenic Accumulation in Rice and Probable Mitigation Approaches: A Review. *Agronomy* **2017**, *7*, 67. [[CrossRef](#)]
15. Kabir, M.S.; Salam, M.A.; Paul, D.N.R.; Hossain, M.I.; Rahman, N.M.F.; Aziz, A.; Latif, M.A. Spatial Variation of Arsenic in Soil, Irrigation Water, and Plant Parts: A Microlevel Study. *Sci. World J.* **2016**, 2186069. [[CrossRef](#)] [[PubMed](#)]
16. Chakma, S.; Rahman, M.M.; Islam, P.; Awal, M.A.; Roy, U.K.; Haq, M.R. Arsenic in rice and rice straw. *Bangladesh Vet.* **2012**, *29*, 1–6. [[CrossRef](#)]
17. Rahman, M.A.; Hasegawa, H.; Rahman, M.M.; Rahman, M.A.; Miah, M.A.M. Accumulation of arsenic in tissues of rice plant (*Oryza sativa* L.) and its distribution in fractions of rice grain. *Chemosphere* **2007**, *69*, 942–948. [[CrossRef](#)]
18. Islam, S.; Rahman, M.M.; Islam, M.R.; Naidu, R. Geographical variation and age-related dietary exposure to arsenic in rice from Bangladesh. *Sci. Total Environ.* **2017**, *601*, 122–131. [[CrossRef](#)]
19. Shah, A.L.; Naher, U.A.; Hasan, Z.; Islam, S.M.M.; Rahman, M.S.; Panhwar, Q.A.; Shamshuddin, J. Arsenic Management in Contaminated Irrigation Water for Rice Cultivation. *Trop. Agric. Sci.* **2016**, *39*, 155–166.
20. Ma, L.; Wang, L.; Jia, Y.; Yang, Z. Arsenic speciation in locally grown rice grains from Hunan Province, China: Spatial distribution and potential health risk. *Sci. Total Environ.* **2016**, *557*, 438–444. [[CrossRef](#)]
21. Li, J.; Dong, F.; Lu, Y.; Yan, Q.; Shim, H. Mechanisms Controlling Arsenic Uptake in Rice Grown in Mining Impacted Regions in South China. *PLoS ONE* **2014**, *9*, e108300. [[CrossRef](#)] [[PubMed](#)]
22. Li, X.; Xie, K.; Yue, B.; Gong, Y.; Shao, Y.; Shang, X.; Wu, Y. Inorganic arsenic contamination of rice from Chinese major rice-producing areas and exposure assessment in Chinese population. *Sci. China Chem.* **2015**, *58*, 1898–1905. [[CrossRef](#)]
23. Lu, Y.; Dong, F.; Deacon, C.; Chen, H.J.; Raab, A.; Meharg, A.A. Arsenic accumulation and phosphorus status in two rice (*Oryza sativa* L.) cultivars surveyed from fields in South China. *Environ. Pollut.* **2010**, *158*, 1536–1541. [[CrossRef](#)]
24. Lin, S.C.; Chang, T.K.; Huang, W.D.; Lur, H.S.; Shyu, G.S. Accumulation of arsenic in rice plant: A study of an arsenic-contaminated site in Taiwan. *Paddy Water Environ.* **2015**, *13*, 11–18. [[CrossRef](#)]
25. Patel, K.S.; Shirvas, K.; Brandt, R.; Jakubowski, N.; Hoffmann, P. Arsenic contamination in water, soil, sediment and rice of central India. *Environ. Geochem. Health* **2005**, *27*, 131–145. [[CrossRef](#)] [[PubMed](#)]
26. Singh, V.; Brar, M.S.; Sharma, P.; Malhi, S.S. Arsenic in water, soil and rice plants in the Indo-Gangetic Plains of Northwestern India. *Commun. Soil Sci. Plant Anal.* **2010**, *41*, 1350–1360. [[CrossRef](#)]
27. Bhattacharya, P.; Samal, A.C.; Majumdar, J.; Santra, S.C. Arsenic Contamination in Rice, Wheat, Pulses, and Vegetables: A Study in an Arsenic Affected Area of West Bengal, India. *Water Air Soil Pollut.* **2010**, *213*, 3–13. [[CrossRef](#)]
28. Sidhu, S.S.; Brar, J.S.; Biswas, A.; Banger, K.; Saroa, G.S. Arsenic Contamination in Soil–Water–Plant (Rice, *Oryza sativa* L.) Continuum in Central and Sub-mountainous Punjab, India. *Bull. Environ. Contam. Toxicol.* **2012**, *89*, 1046–1050. [[CrossRef](#)]
29. Juen, L.L.; Aris, A.Z.; Ying, L.W.; Haris, H. Bioconcentration and Translocation Efficiency of Metals in Paddy (*Oryza sativa*): A Case Study from Alor Setar, Kedah, Malaysia. *Sains Malays.* **2014**, *43*, 521–528.
30. Zulkafflee, N.S.; Redzuan, N.A.M.; Hanafi, Z.; Selamat, J.; Ismail, M.R.; Praveena, S.M.; Razis, A.F.A. Heavy Metal in Paddy Soil and its Bioavailability in Rice Using In Vitro Digestion Model for Health Risk Assessment. *Int. J. Environ. Res. Public Health* **2019**, *16*, 4769. [[CrossRef](#)]
31. Ruangwises, S.; Saipan, P.; Tengjaroenku, B.; Ruangwises, N. Total and Inorganic Arsenic in Rice and Rice Bran Purchased in Thailand. *J. Food Prot.* **2012**, *75*, 771–774. [[CrossRef](#)] [[PubMed](#)]
32. Kuramata, M.; Abe, T.; Matsumoto, S.; Ishikawa, S. Arsenic accumulation and speciation in Japanese paddy rice cultivars. *Soil Sci. Plant Nutr.* **2011**, *57*, 248–258. [[CrossRef](#)]
33. Makino, T.; Ishikawa, S.; Murakami, M.; Arao, T. Spatial Distribution and Risk Management of Heavy Metal Contamination in Japan. In Proceedings of the Monsoon Asia Agro-Environmental Research Consortium (MARCO) Symposium, Tsukuba, Japan, 26–28 August 2015; Available online: https://www.naro.affrc.go.jp/archive/niaes/marco/marco2015/text/ws3-6_t_makino.pdf (accessed on 22 December 2019).

34. Rahman, M.A.; Rahman, M.M.; Reichman, S.M.; Lim, R.P.; Naidu, R. Arsenic Speciation in Australian-Grown and Imported Rice on Sale in Australia: Implications for Human Health Risk. *J. Agric. Food Chem.* **2014**, *62*, 6016–6024. [[CrossRef](#)] [[PubMed](#)]
35. Fransisca, Y.; Small, D.M.; Morrison, P.D.; Spencer, M.J.S.; Ball, A.S.; Jones, O.A.H. Assessment of arsenic in Australian grown and imported rice varieties on sale in Australia and potential links with irrigation practises and soil geochemistry. *Chemosphere* **2015**, *138*, 1008–1013. [[CrossRef](#)]
36. Williams, P.N.; Villada, A.; Deacon, C.; Raab, A.; Figuerola, J.; Green, A.J.; Feldmann, J.; Meharg, A.A. Greatly Enhanced Arsenic Shoot Assimilation in Rice Leads to Elevated Grain Levels Compared to Wheat and Barley. *Environ. Sci. Technol.* **2007**, *41*, 6854–6859. [[CrossRef](#)]
37. Sommella, A.; Deacon, C.; Norton, G.; Pigna, M.; Violante, A.; Meharg, A.A. Total arsenic, inorganic arsenic, and other elements concentrations in Italian rice grain varies with origin and type. *Environ. Pollut.* **2013**, *181*, 38–43. [[CrossRef](#)]
38. Atiaga-Franco, O.L.; Otero, X.L.; Gallego-Picó, A.; Escobar-Castañeda, L.A.; Bravo-Yagüe, J.C.; Carrera-Villacrés, D. Analysis of total arsenic content in purchased rice from Ecuador. *Czech J. Food Sci.* **2019**, *37*, 1–7. [[CrossRef](#)]
39. Mondal, D.; Periche, R.; Tineo, B.; Bermejo, L.A.; Rahman, M.M.; Siddique, A.B.; Rahman, M.A.; Solis, J.L.; Cruz, G.J.F. Arsenic in Peruvian rice cultivated in the major rice growing region of Tumbes river basin. *Chemosphere* **2020**, *241*, 125070. [[CrossRef](#)]
40. Abedin, M.J.; Feldmann, J.; Meharg, A.A. Uptake Kinetics of Arsenic Species in Rice Plants. *Plant Physiol.* **2002**, *128*, 1120–1128. [[CrossRef](#)]
41. Luan, M.; Liu, J.; Liu, Y.; Han, X.; Sun, G.; Lan, W.; Luan, S. Vacuolar Phosphate Transporter 1 (VPT1) Affects Arsenate Tolerance by Regulating Phosphate Homeostasis in Arabidopsis. *Plant Cell Physiol.* **2018**, *59*, 1345–1352. [[CrossRef](#)]
42. Mishra, S.; Mattusch, J.; Wennrich, R. Accumulation and transformation of inorganic and organic arsenic in rice and role of thiol-complexation to restrict their translocation to shoot. *Sci. Rep.* **2017**, *7*, 40522. [[CrossRef](#)] [[PubMed](#)]
43. Ye, Y.; Yuan, J.; Chang, X.; Yang, M.; Zhang, L.; Lian, X. The Phosphate Transporter Gene OsPht1;4 Is Involved in Phosphate Homeostasis in Rice. *PLoS ONE* **2015**, *10*, e0126186. [[CrossRef](#)] [[PubMed](#)]
44. Pommerrenig, B.; Diehn, T.A.; Bienert, G.P. Metalloido-porins: Essentiality of Nodulin 26-like intrinsic proteins in metalloid transport. *Plant Sci.* **2015**, *238*, 212–227. [[CrossRef](#)] [[PubMed](#)]
45. Mitani, N.; Yamaji, N.; Ma, J.F. Characterization of substrate specificity of a rice silicon transporter, Lsi1. *Pflüg. Arch. Eur. J. Physiol.* **2008**, *456*, 679–686. [[CrossRef](#)]
46. Pommerrenig, B.; Diehn, T.A.; Bernhardt, N.; Bienert, D.; Mitani-Ueno, N.; Fuge, J.; Bieber, A.; Spitzer, C.; Bräutigam, A.; Ma, J.F.; et al. Functional evolution of nodulin 26-like intrinsic proteins: From bacterial arsenic detoxification to plant nutrient transport. *New Phytol.* **2019**, in press. [[CrossRef](#)]
47. Bienert, G.P.; Thorsen, M.; Schüssler, M.D.; Nilsson, H.R.; Wagner, A.; Tamás, M.J.; Jahn, T.P. A subgroup of plant aquaporins facilitate the bi-directional diffusion of As(OH)₃ and Sb(OH)₃ across membranes. *BMC Biol.* **2008**, *6*, 26. [[CrossRef](#)]
48. Suriyagoda, L.D.B.; Ditteret, K.; Lambers, H. Mechanism of arsenic uptake, translocation and plant resistance to accumulate arsenic in rice grains. *Agric. Ecosyst. Environ.* **2018**, *253*, 23–37. [[CrossRef](#)]
49. Zhao, F.J.; Zhu, Y.G.; Meharg, A.A. Methylated Arsenic Species in Rice: Geographical Variation, Origin, and Uptake Mechanisms. *Environ. Sci. Technol.* **2013**, *47*, 3957–3966. [[CrossRef](#)]
50. Guillod-Magnin, R.; Brüsweiler, B.J.; Aubert, R.; Haldimann, M. Arsenic species in rice and rice-based products consumed by toddlers in Switzerland. *Food Addit. Contam. Part A* **2018**, *35*, 1164–1178. [[CrossRef](#)]
51. Muehe, E.M.; Wang, T.; Kerl, C.F.; Planer-Friedrich, B.; Fendorf, S. Rice production threatened by coupled stresses of climate and soil arsenic. *Nat. Commun.* **2019**, *10*, 4985. [[CrossRef](#)]
52. Kalita, J.; Pradhan, A.K.; Shandilya, Z.M.; Tanti, B. Arsenic Stress Responses and Tolerance in Rice: Physiological, Cellular and Molecular Approaches. *Rice Sci.* **2018**, *25*, 235–249. [[CrossRef](#)]
53. Ye, Y.; Li, P.; Xu, T.; Zeng, L.; Cheng, D.; Yang, M.; Luo, J.; Lian, X. OsPT4 Contributes to Arsenate Uptake and Transport in Rice. *Front. Plant Sci.* **2017**, *8*, 2197. [[CrossRef](#)]
54. Zhao, F.J.; Ago, Y.; Mitani, N.; Li, R.L.; Sy, Y.H.; Yamaji, N.; McGrath, S.P.; Ma, J.F. The role of the rice aquaporin Lsi1 in arsenite efflux from roots. *New Phytol.* **2010**, *186*, 392–399. [[CrossRef](#)] [[PubMed](#)]

55. Lin, Y.; Sun, Z.; Li, Z.; Xue, R.; Cui, W.; Sun, S.; Liu, T.; Zeng, R.; Song, Y. Deficiency in Silicon Transporter Lsi1 Compromises Inducibility of Anti-herbivore Defense in Rice Plants. *Front. Plant Sci.* **2019**, *10*, 652. [[CrossRef](#)] [[PubMed](#)]
56. Detmann, K.C.; Araújo, W.L.; Martins, S.C.V.; Sanglard, L.M.V.; Reis, J.V.; Detmann, E.; Rodrigues, F.A.; Nunes-Nesi, A.; Fernie, A.R.; DaMatta, F.M. Silicon nutrition increases grain yield, which, in turn, exerts a feed-forward stimulation of photosynthetic rates via enhanced mesophyll conductance and alters primary metabolism in rice. *New Phytol.* **2012**, *196*, 752–762. [[CrossRef](#)]
57. Cao, Y.; Sun, D.; Mei, H.; Liu, X.; Sun, S.; Xu, G.; Liu, Y.; Chen, Y. Knocking Out OsPT4 Gene Decreases Arsenate Uptake by Rice Plants and Inorganic Arsenic Accumulation in Rice Grains. *Environ. Sci. Technol.* **2017**, *51*, 12131–12138. [[CrossRef](#)]
58. Yang, W.T.; Baek, D.; Yun, D.J.; Lee, K.S.; Hong, S.Y.; Bae, K.D.; Chung, Y.S.; Kwon, Y.S.; Kim, D.H.; Jung, K.H.; et al. Rice OsMYB5P improves plant phosphate acquisition by regulation of phosphate transporter. *PLoS ONE* **2018**, *13*, e0194628. [[CrossRef](#)]
59. Carey, A.M.; Scheckel, K.G.; Lombi, E.; Newville, M.; Choi, Y.; Norton, G.J.; Charnock, J.M.; Feldmann, J.; Proce, A.H.; Meharg, A.A. Grain Unloading of Arsenic Species in Rice. *Plant Physiol.* **2010**, *152*, 309–319. [[CrossRef](#)]
60. Chen, Y.; Sun, S.K.; Tang, Z.; Liu, G.; Moore, K.L.; Maathuis, J.M.; Miller, A.J.; McGrath, S.P.; Zhao, F.J. The Nodulin 26-like intrinsic membrane protein OsNIP3;2 is involved in arsenite uptake by lateral roots in rice. *J. Exp. Bot.* **2017**, *68*, 3007–3016. [[CrossRef](#)]
61. Chao, D.Y.; Chen, Y.; Chen, J.; Shi, S.; Chen, Z.; Wang, C.; Danku, J.M.; Zhao, F.J. Genome-wide Association Mapping Identifies a New Arsenate Reductase Enzyme Critical for Limiting Arsenic Accumulation in Plants. *PLoS ONE* **2014**, *12*, e1002009. [[CrossRef](#)]
62. Tang, Z.; Chen, Y.; Chen, F.; Ji, Y.; Zhao, F.J. OsPTR7 (OsNPF8.1), a Putative Peptide Transporter in Rice, is Involved in Dimethylarsenate Accumulation in Rice Grain. *Plant Cell Physiol.* **2017**, *58*, 904–913. [[CrossRef](#)] [[PubMed](#)]
63. Kumarathilaka, P.; Seneweera, S.; Meharg, A.; Bundschuh, J. Arsenic accumulation in rice (*Oryza sativa* L.) is influenced by environment and genetic factors. *Sci. Total Environ.* **2018**, *642*, 485–496. [[CrossRef](#)] [[PubMed](#)]
64. Duan, G.L.; Hu, Y.; Schneider, S.; McDermott, J.; Chen, J.; Sauer, N.; Rosen, B.P.; Daus, B.; Liu, Z.; Zhu, Y.G. Inositol transporters AtINT2 and AtINT4 regulate arsenic accumulation in Arabidopsis seeds. *Nat. Plants* **2016**, *2*, 15202. [[CrossRef](#)] [[PubMed](#)]
65. Mosa, K.A.; Kumar, K.; Chhikara, S.; McDermott, J.; Liu, Z.; Musante, C.; White, J.C.; Dhankher, O.P. Members of rice plasma membrane intrinsic proteins subfamily are involved in arsenite permeability and tolerance in plants. *Transgen. Res.* **2012**, *21*, 1265–1277. [[CrossRef](#)]
66. Song, W.Y.; Yamaki, T.; Yamaji, N.; Ko, D.; Jung, K.H.; Fujii-Kashino, M.; An, G.; Martinoia, E.; Lee, Y.; Ma, F.J. A rice ABC transporter, OsABCC1, reduces arsenic accumulation in the grain. *PNAS* **2014**, *111*, 15699–15704. [[CrossRef](#)]
67. Shakoob, M.B.; Riaz, M.; Niazi, N.K.; Ali, S.; Rizwan, M.; Arif, M.S.; Arif, M. Chapter 18—Recent Advances in Arsenic Accumulation in Rice. In *Advances in Rice Research for Abiotic Stress Tolerance*; Hasanuzzaman, M., Fujita, M., Nahar, K., Biswas, J.K., Eds.; Elsevier: Amsterdam, The Netherlands, 2019. [[CrossRef](#)]
68. Abbas, G.; Murtaza, B.; Bibi, I.; Shahid, M.; Niazi, N.K.; Khan, M.I.; Amjad, M.; Hussain, M. Arsenic Uptake, Toxicity, Detoxification, and Speciation in Plants: Physiological, Biochemical, and Molecular Aspects. *Int. J. Environ. Res. Public Health* **2018**, *15*, 59. [[CrossRef](#)]
69. Sun, S.K.; Chen, Y.; Che, J.; Konishi, N.; Tang, Z.; Miller, A.J.; Ma, J.F.; Zhao, F.J. Decreasing arsenic accumulation in rice by overexpressing OsNIP1;1 and OsNIP3;3 through disrupting arsenite radial transport in roots. *New Phytol.* **2018**, *219*, 641–653. [[CrossRef](#)]
70. Chang, Z.; Jin, M.; Yan, W.; Chen, H.; Qiu, S.; Fu, S.; Xia, J.; Liu, Y.; Chen, Z.; Wu, J.; et al. The ATP-binding cassette (ABC) transporter OsABCG3 is essential for pollen development in rice. *Rice* **2018**, *11*, 58. [[CrossRef](#)]
71. Meadows, R. How Plants Control Arsenic Accumulation. *PLoS Biol.* **2014**, *12*, e1002008. [[CrossRef](#)]
72. Salt, D.E. Would the real arsenate reductase please stand up? *New Phytol.* **2017**, *215*, 1090–1101. [[CrossRef](#)]
73. Shri, M.; Singh, P.K.; Kidiwai, M.; Gautam, N.; Dubey, S.; Verma, G.; Chakrabarty, D. Recent advances in arsenic metabolism in plants: Current status, challenges and highlighted biotechnological intervention to reduce grain arsenic in rice. *Metallomics* **2019**, *11*, 519–532. [[CrossRef](#)]

74. Brinke, A.; Reifferscheid, G.; Klein, R.; Feiler, U.; Buchinger, S. Transcriptional changes measured in rice roots after exposure to arsenite-contaminated sediments. *Environ. Sci. Pollut. Res.* **2018**, *25*, 2707–2717. [[CrossRef](#)] [[PubMed](#)]
75. Jung, H.I.; Kong, M.S.; Lee, B.R.; Kim, T.H.; Cae, M.J.; Lee, E.J.; Jung, G.B.; Lee, C.H.; Sung, J.K.; Kim, Y.H. Exogenous Glutathione Increases Arsenic Translocation into Shoots and Alleviates Arsenic-Induced Oxidative Stress by Sustaining Ascorbate–Glutathione Homeostasis in Rice Seedlings. *Front. Plant Sci.* **2019**, *10*, 1089. [[CrossRef](#)] [[PubMed](#)]
76. Hossain, K.; Quaik, S.; Pant, G.; Yada, S.; Maruthi, Y.A.; Rafatullah, M.; Nasir, M.; Ismail, N. Arsenic Fate in the Ground Water and its Effect on Soil-Crop Systems. *Res. J. Environ. Toxicol.* **2015**, *9*, 231–240. [[CrossRef](#)]
77. Bakhat, H.F.; Zia, Z.; Abbas, S.; Hammad, H.M.; Shah, G.M.; Khalid, S.; Shahid, N.; Sajjad, M.; Fahad, S. Factors controlling arsenic contamination and potential remediation measures in soil-plant systems. *Groundw. Sustain. Dev.* **2019**, *9*, 100263. [[CrossRef](#)]
78. Quazi, S.; Datta, R.; Sarkar, D. Effects of soil types and forms of arsenical pesticide on rice growth and development. *Int. J. Environ. Technol.* **2011**, *8*, 445–460. [[CrossRef](#)]
79. Tu, S.; Ma, L.Q. Interactive effects of pH, arsenic and phosphorus on uptake of As and P and growth of the arsenic hyperaccumulator *Pteris vittata* L. under hydroponic conditions. *Environ. Exp. Bot.* **2003**, *50*, 243–251. [[CrossRef](#)]
80. Moreno-Jiménez, E.; Esteban, E.; Peñalosa, J.M. The Fate of Arsenic in Soil-Plant Systems. In *Reviews of Environmental Contamination and Toxicology*; Whitacre, D.M., Ed.; Springer: Berlin, Germany, 2015. [[CrossRef](#)]
81. Syu, C.H.; Wu, P.R.; Lee, C.H.; Juang, L.W.; Lee, D.Y. Arsenic phytotoxicity and accumulation in rice seedlings grown in arsenic-contaminated soils as influenced by the characteristics of organic matter amendments and soils. *J. Plant Nutr. Soil Sci.* **2019**, *182*, 60–71. [[CrossRef](#)]
82. Suda, A.; Makino, T. Effect of organic amendments on arsenic solubilization in soils during long-term flooded incubation. *Int. J. Environ. Sci. Technol.* **2016**, *13*, 2375–2382. [[CrossRef](#)]
83. Norton, G.J.; Adomako, E.E.; Deacon, C.M.; Carey, A.M.; Price, A.H.; Meharg, A.A. Effect of organic matter amendment, arsenic amendment and water management regime on rice grain arsenic species. *Environ. Pollut.* **2013**, *177*, 38–47. [[CrossRef](#)]
84. Qiao, J.T.; Li, X.M.; Hu, M.; Li, F.; Young, L.Y.; Sun, W.; Huang, W.; Cui, J. Transcriptional Activity of Arsenic-Reducing Bacteria and Genes Regulated by Lactate and Biochar during Arsenic Transformation in Flooded Paddy Soil. *Environ. Sci. Technol.* **2018**, *51*, 61–70. [[CrossRef](#)] [[PubMed](#)]
85. Srivastava, S.; Pathare, V.S.; Sounderajan, S.; Suprasanna, P. Nitrogen supply influences arsenic accumulation and stress responses of rice (*Oryza sativa* L.) seedlings. *J. Hazard. Mater.* **2019**, *267*, 599–606. [[CrossRef](#)] [[PubMed](#)]
86. Abedin, M.J.; Cotter-Howells, J.; Meharg, A.A. Arsenic uptake and accumulation in rice (*Oryza sativa* L.) irrigated with contaminated water. *Plant Soil* **2002**, *240*, 311–319. Available online: <https://www.jstor.org/stable/24121150> (accessed on 20 December 2019). [[CrossRef](#)]
87. Pigna, M.; Cozzolino, V.; Caporale, A.G.; Mora, M.L.; Meo, V.D.; Jara, A.A.; Violante, A. Effects of Phosphorus Fertilization on Arsenic Uptake by Wheat Grown in Polluted Soils. *J. Soil Sci. Plant Nutr.* **2010**, *14*, 428–442. [[CrossRef](#)]
88. Boye, K.; Lezama-Pacheco, J.; Fendorf, S. Relevance of Reactive Fe:S Ratios for Sulfur Impacts on Arsenic Uptake by Rice. *Soils* **2017**, *1*, 1. [[CrossRef](#)]
89. Srivastava, S.; Akkarakaran, J.J.; Sounderajan, S.; Shrivastava, M.; Suprasanna, P. Arsenic toxicity in rice (*Oryza sativa* L.) is influenced by sulfur supply: Impact on the expression of transporters and thiol metabolism. *Geoderma* **2016**, *270*, 33–42. [[CrossRef](#)]
90. Zhang, J.; Zhao, Q.Z.; Duan, G.L.; Huang, Y.C. Influence of sulphur on arsenic accumulation and metabolism in rice seedlings. *Environ. Exp. Bot.* **2011**, *72*, 34–40. [[CrossRef](#)]
91. Liu, W.L.; Zhu, Y.G.; Smith, F.A. Effects of iron and manganese plaques on arsenic uptake by rice seedlings (*Oryza sativa* L.) grown in solution culture supplied with arsenate and arsenite. *Plant Soil* **2005**, *277*, 127–138. [[CrossRef](#)]
92. Ultra, V.U.; Nakayama, A.; Tanaka, S.; Kang, Y.; Sakurai, K.; Iwasaki, K. Potential for the alleviation of arsenic toxicity in paddy rice using amorphous iron-(hydr)oxide amendments. *Soil Sci. Plant Nutr.* **2009**, *55*, 160–169. [[CrossRef](#)]

93. Lee, C.H.; Hsieh, Y.C.; Lin, T.H.; Lee, D.Y. Iron plaque formation and its effect on arsenic uptake by different genotypes of paddy rice. *Plant Soil* **2013**, *363*, 231–241. [[CrossRef](#)]
94. Yu, H.Y.; Li, F.B.; Liu, C.S.; Huang, W.; Liu, T.X.; Yu, W.M. Chapter Five—Iron Redox Cycling Coupled to Transformation and Immobilization of Heavy Metals: Implications for Paddy Rice Safety in the Red Soil of South China. *Adv. Agron.* **2016**, *137*, 279–317. [[CrossRef](#)]
95. Srivastava, S.; Srivastava, S.; Bist, V.; Awashti, S.; Chauhan, R.; Chaudhry, V.; Singh, P.C.; Dwivedi, S.; Niranjana, A.; Agrawal, L.; et al. *Chlorella vulgaris* and *Pseudomonas putida* interaction modulates phosphate trafficking for reduced arsenic uptake in rice (*Oryza sativa* L.). *J. Hazard. Mater.* **2018**, *351*, 177–187. [[CrossRef](#)] [[PubMed](#)]
96. Farquhar, M.L.; Charnock, J.M.; Livens, F.R.; Vaughan, D.J. Mechanisms of Arsenic Uptake from Aqueous Solution by Interaction with Goethite, Lepidocrocite, Mackinawite, and Pyrite: An X-ray Absorption Spectroscopy Study. *Environ. Sci. Technol.* **2002**, *36*, 1757–1762. [[CrossRef](#)] [[PubMed](#)]
97. Limmer, M.A.; Mann, J.; Amaral, D.C.; Vargas, R.; Seyfferth, A.L. Silicon-rich amendments in rice paddies: Effects on arsenic uptake and biogeochemistry. *Sci. Total Environ.* **2018**, *624*, 1360–1368. [[CrossRef](#)] [[PubMed](#)]
98. Liu, C.; Wei, L.; Zhang, S.; Xu, X.; Li, F. Effects of nanoscale silica sol foliar application on arsenic uptake, distribution and oxidative damage defense in rice (*Oryza sativa* L.) under arsenic stress. *RSC Adv.* **2014**, *4*, 57227–57234. [[CrossRef](#)]
99. Cui, J.; Li, Y.; Jin, Q.; Li, F. Silica nanoparticles inhibit arsenic uptake into rice suspension cells via improving pectin synthesis and the mechanical force of the cell wall. *Environ. Sci. Nano* **2019**, in press. [[CrossRef](#)]
100. Parveen, A.; Mehrotra, S.; Singh, N. Rice planted along with accumulators in arsenic amended plots reduced arsenic uptake in grains and shoots. *Chemosphere* **2017**, *184*, 1327–1333. [[CrossRef](#)]
101. Markley, C.T.; Herbert, B.E. Modeling Phosphate Influence on Arsenate Reduction Kinetics by a Freshwater Cyanobacterium. *Environ. Model. Assess.* **2009**, *15*, 361–368. [[CrossRef](#)]
102. Wang, Y.; Li, Y.Q.; Lv, K.; Cheng, J.J.; Chen, X.L.; Ge, Y.; Yu, X.Y. Soil microalgae modulate grain arsenic accumulation by reducing dimethylarsinic acid and enhancing nutrient uptake in rice (*Oryza sativa* L.). *Plant Soil* **2018**, *430*, 99–111. [[CrossRef](#)]
103. Upadhyay, A.K.; Singh, N.K.; Singh, R.; Rai, U.N. Amelioration of arsenic toxicity in rice: Comparative effect of inoculation of *Chlorella vulgaris* and *Nannochloropsis* sp. on growth, biochemical changes and arsenic uptake. *Ecotoxicol. Environ. Saf.* **2016**, *124*, 68–73. [[CrossRef](#)]
104. Xiao, A.W.; Li, W.C.; Ye, Z.H. The effect of plant growth-promoting rhizobacteria (PGPR) on arsenic accumulation and the growth of rice plants (*Oryza sativa* L.). *Chemosphere* **2020**, *242*, 125136. [[CrossRef](#)]
105. Lakshmanan, V.; Shanthyaraj, D.; Li, G.; Seyfferth, A.L.; Sherrier, D.J.; Bais, H.P. A natural rice rhizospheric bacterium abates arsenic accumulation in rice (*Oryza sativa* L.). *Planta* **2015**, *242*, 1037–1050. [[CrossRef](#)] [[PubMed](#)]
106. Nookongbut, P.; Kantachote, D.; Megharaj, M.; Naidu, R. Reduction in arsenic toxicity and uptake in rice (*Oryza sativa* L.) by As-resistant purple nonsulfur bacteria. *Environ. Sci. Pollut. Res.* **2018**, *25*, 36530–36544. [[CrossRef](#)] [[PubMed](#)]
107. Dolphen, R.; Thiravetyan, P. Reducing arsenic in rice grains by leonardite and arsenic-resistant endophytic bacteria. *Chemosphere* **2019**, *223*, 448–454. [[CrossRef](#)] [[PubMed](#)]
108. Ye, W.L.; Khan, M.A.; McGrath, S.P.; Zhao, F.J. Phytoremediation of arsenic contaminated paddy soils with *Pteris vittata* markedly reduces arsenic uptake by rice. *Environ. Pollut.* **2011**, *159*, 3739–3743. [[CrossRef](#)]
109. Kumar, A.; Dixit, G.; Singh, A.P.; Dwivedi, S.; Srivastava, S.; Mishra, K.; Tripathi, R.D. Selenate mitigates arsenite toxicity in rice (*Oryza sativa* L.) by reducing arsenic uptake and ameliorates amino acid content and thiol metabolism. *Ecotoxicol. Environ. Saf.* **2016**, *133*, 350–359. [[CrossRef](#)]
110. Wan, Y.; Camara, A.Y.; Huang, Q.; Yu, Y.; Wang, Q.; Li, H. Arsenic uptake and accumulation in rice (*Oryza sativa* L.) with selenite fertilization and water management. *Ecotoxicol. Environ. Saf.* **2018**, *156*, 67–74. [[CrossRef](#)]
111. Fleck, A.T.; Mattusch, J.; Schenk, M.K. Silicon decreases the arsenic level in rice grain by limiting arsenite transport. *J. Plant Nutr. Soil Sci.* **2013**, *176*, 785–794. [[CrossRef](#)]
112. Lin, L.; Gao, M.; Qiu, W.; Huang, Q.; Song, Z. Reduced arsenic accumulation in indica rice (*Oryza sativa* L.) cultivar with ferromanganese oxide impregnated biochar composites amendments. *Environ. Pollut.* **2017**, *231*, 479–486. [[CrossRef](#)]

113. Mlangeni, A.T.; Perez, M.; Raab, A.; Krupp, E.M.; Norton, G.J.; Feldmann, J. Simultaneous stimulation of arsenic methylation and inhibition of cadmium bioaccumulation in rice grain using zero valent iron and alternate wetting and drying water management. *Sci. Total Environ.* **2019**, in press. [[CrossRef](#)]



© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).