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Review

Arsenic accumulation in rice (*Oryza sativa* L.) is influenced by environment and genetic factors

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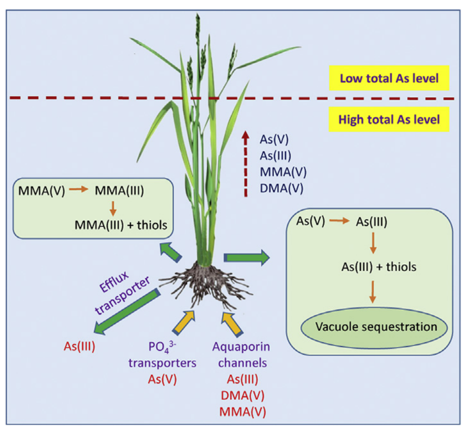
HIGHLIGHTS

- Biogeochemical factors govern As speciation in paddy soil-water systems.
- PO_4^{3-} and Si transporters involve As(III), As(V), MMA(V), and DMA(V) uptake.
- As(III) efflux and complexation with thiols limit As(III) translocation.
- DMA(V) possesses the highest translocation efficiency (grain-to-root).

GRAPHICAL ABSTRACT



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ABSTRACT

Arsenic (As) elevation in paddy soils will have a negative impact on both the yield and grain quality of rice (*Oryza sativa* L.). The mechanistic understanding of As uptake, translocation, and grain filling is an important aspect to produce rice grains with low As concentrations through agronomical, physico-chemical, and breeding approaches. A range of factors (i.e. physico-chemical, biological, and environmental) govern the speciation and mobility of As in paddy soil-water systems. Major As uptake transporters in rice roots, such as phosphate and aquaglyceroporins, assimilate both inorganic (As(III) and As(V)) and organic As (DMA(V) and MMA(V)) species from the rice rhizosphere. A number of metabolic pathways (i.e. As (V) reduction, As(III) efflux, and As(III)-thiol complexation and subsequent sequestration) are likely to play a key role in determining the translocation and substantial accumulation of As species in rice tissues. The order of translocation efficiency (caryopsis-to-root) for different As species in rice plants is comprehensively evaluated as follows: DMA(V) > MMA(V) > inorganic As species. The loading patterns of both inorganic and organic As species into the rice grains are largely dependent on the genetic makeup and maturity stage of the rice plants together with environmental interactions. The knowledge of As metabolism in rice plants and how it is affected by plant genetics and environmental factors would pave the way to develop adaptive strategies to minimize the accumulation of As in rice grains.

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Contents

1. Introduction

Rice (*Oryza sativa*) consumption is a dominant dietary exposure route to arsenic (As), a non-threshold carcinogen. Rice grains can contain approximately 10-times as much as the baseline total As level when compared to other cereal grains (Williams et al., 2007). Rice and rice-based products can lead to an intake of excessive amounts of inorganic As, particularly in the populations in South and South-East Asia (Kile et al., 2007; Meharg et al., 2009). Rice is the primary source of As in a non-seafood diet in Europe and the United States (Fu et al., 2011). Ohno et al. (2007) demonstrated that the consumption of rice has contributed 56% of the total As intake in humans; the corresponding figure for drinking water, solid food, liquid food, and cereals were 13%, 11%, 4%, and 16%, respectively. Contrasting results have also been reported elsewhere suggesting that drinking water has mainly contributed to total As intake (93.5%), and the consumption of rice and vegetables has only contributed to 6.2% and 0.3% of total As intake in humans, respectively, in a groundwater contaminated Bangladeshi setting (Rahman et al., 2013).

Arsenic in the geological environment is mainly associated with sulfur (S) rich minerals such as arsenopyrite (FeAsS), realgar (As_4S_4), and orpiment (As_2S_3) (Majzlan et al., 2014). Natural processes such as rock weathering and alluvial deposits may contribute As release into the paddy environment (Bundschuh and Maity, 2015; Herath et al., 2016). Anthropogenic processes (i.e. mining activities and use of As-contaminated groundwater in the form of irrigation water) promote the accumulation of natural As in paddy ecosystems. Moreover, As-containing insecticides, herbicides, feed additives, and wood preservatives are the potential anthropogenic sources of As in rice ecosystems (W.Q. Chen et al., 2016; Zhao et al., 2009).

Natural soils can typically contain the level range of 0.1–10 mg kg^{-1} of total As (Zhao et al., 2010a). European Community (EU) recommends that soils must contain <20 mg kg^{-1} of total As to be used for agricultural purposes (Bhattacharya et al., 2009; Shrivastava et al., 2017). Arsenite (As(III)) and arsenate (As(V)) are the most commonly found inorganic As species whereas monomethylarsonoic acid (MMA(V)) and dimethylarsinic acid (DMA(V)) are the frequently reported organic As species in paddy soil-water systems (Honma et al., 2016; Jia et al., 2012). Both inorganic and organic As species in the rice rhizosphere are acquired by rice roots through the various nutrient assimilatory pathways and they are translocated via a variety of mechanisms (Ma et al., 2008; P. Wang et al., 2016).

Attention is therefore required to understand how rice plants acquire and metabolize As species so as to develop mitigation measures against this global contamination in the food chain. Taking these demands into account, this review presents recent progress in As dynamics in the rice ecosystem, and its uptake by rice roots and translocation to the rice grains. Further, mechanisms (i.e. metabolism/detoxification) that have evolved to mitigate the accumulation of As in rice tissues are discussed highlighting the major knowledge gaps that need to be addressed in future research.

2. Arsenic phytoavailability in paddy soil-water system

Paddy soils under conventional paddy management practices are subjected to flooded and non-flooded conditions, during initial and final stages of the growth of rice, respectively. The changes in water management regimes may alter the redox potential (Eh) of paddy soil-water systems (Kumarathilaka et al., 2018; Pan et al., 2014). During flooded conditions, water replaces the gaseous phase in the soil matrix. A number of redox reactions (from high Eh (~+700 mV) to low Eh (~−300 mV): reduction of Mn(IV), Fe(III), and SO_4^{2-}, and methanogenesis) take place either sequentially or simultaneously during the flooded conditions (Sahrawat, 2015). Arsenate in the soil matrix is converted to As(III), which has a higher mobility than As(V), when Eh turns more negative. The As(III)/As(V) ratio is high in the soil solution during flooded conditions and reverses for non-flooded conditions (Yamaguchi et al., 2014).

Iron (III) plaque, consisting of amorphous or crystalline Fe (hydro)oxides, was found to have a significant effect on the sequestration of both As(V) and As(III) (Eqs. (1) and (2)) (Liu et al., 2004). A higher ratio of As/Fe in Fe(III) plaque around rice roots compared to that of Fe minerals in the soil matrix indicates the high capacity of Fe (III) plaque for retention of As in the rhizosphere (Yamaguchi et al., 2014). Radial oxygen loss (ROL), the process that diffuses O_2 into the rhizosphere through root aerenchyma, can promote the formation of Fe(III) plaque even under flooded conditions (Mei et al., 2009). The root anatomy (i.e. root porosity) in different rice genotypes strongly correlates with ROL and substantial formation of Fe (III) plaque (Mei et al., 2009; C. Wu et al., 2011). In addition, the growth stage of rice plants and background Fe concentrations in paddy soils have effects on the quantities of Fe(III) plaque in rice roots (Li et al., 2015). Therefore, As retention by Fe(III) plaque and subsequent accumulation of As in rice plant tissues (i.e. root, shoot, husk, and grain) of different rice genotypes are remarkably varied (Lee et al., 2013; Liu et al., 2006).

$$\equiv FeOH_{(s)} + AsO_4^{3-}{}_{(aq)} + 3H^+{}_{(aq)} \rightarrow FeH_2AsO_{4(s)} + H_2O_{(l)} \quad (1)$$

$$\equiv FeOH_{(s)} + AsO_3^{3-}{}_{(aq)} + 3H^+{}_{(aq)} \rightarrow FeH_2AsO_{3(s)} + H_2O_{(l)} \quad (2)$$