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Arsenic Stress Responses and Tolerance in Rice: Physiological, Cellular and Molecular Approaches

Jyotirmay KALITA, Amit Kumar PRADHAN, Zina Moni SHANDILYA, Bhaben TANTI

(*Department of Botany, Gauhati University, Guwahati 781014, Assam, India*)

Abstract: Arsenic (As), a potentially toxic metalloid released in the soil environment as a result of natural as well as anthropogenic processes, is subsequently taken up by crop plants. In rice grains, As has been reported in Asia, North America and Europe, suggesting a future threat to food security and crop production. As^{3+} by dint of its availability, mobility and phytotoxicity, is the most harmful species of As for the rice crop. Specific transporters mediate the transport of different species of As from roots to the aboveground parts of the plant body. Accumulation of As leads to toxic reactions in plants, affecting its growth and productivity. Increase in As uptake leads to oxidative stress and production of antioxidants to counteract this stress. Cultivars tolerant to As stress are efficient in antioxidant metabolism compared to sensitive ones. Iron and selenium are found to have ameliorating effect on the oxidative stress caused by As. Microbes, even many indigenous ones, in the plant rhizosphere are also capable of utilizing As in their metabolism, both independently and in association. Some of these microbes impart tolerance to As-stress in plants grown in As contaminated sites.

Key words: arsenic; rice; phytotoxicity; hyperaccumulator; phytochelatin; antioxidant; mitigation

Arsenic (As), a potentially toxic metalloid, is a naturally occurring element ubiquitous to all soils (Smedley and Kinniburgh, 2002; William et al, 2005). It is the 20th most common element in the earth's crust (Mandal and Suzuki, 2002). Soil contains 1.5–3.0 mg/kg As. As is present in inorganic forms in various minerals in soil, the important ones being realgar, arsenopyrite, etc. From the minerals, As in both inorganic and organic forms, gets mobilized due to natural and human activities, and becomes more readily available to living organisms.

Among the natural sources of mobilization of As, weathering of As-containing minerals (Woolson, 1977; Smedley, 2006) and the activities of microorganisms (Bentley and Chasteen, 2002; Turpeinen et al, 2002) are prominent. On methylation by microbes, As is released as monomethyl arsenate (MMA) or dimethyl arsenate (DMA) (Bentley and Chasteen, 2002). Some microbes utilize As in their metabolism, and release the toxic trimethyl arsine oxide (TMAsO) gas which is subsequently released to the atmosphere (Mandal and Suzuki, 2002).

Human activities that release more As in bio-available forms include application of As pesticides, use of As in paints to be subsequently released by molds and bacteria, mining of metals and heavy extraction of groundwater. Insecticides [calcium arsenate ($Ca_3As_2O_8$) and lead arsenate ($PbHAsO_4$)], herbicide [sodium arsenite ($NaAsO_2$)], rodenticides arsenious oxide (As_2O_3) and sodium arsenite ($NaAsO_2$) contain As (ICAR, 2009). Their residues remain in the soil, get dissolved in the groundwater and become easily available to living organisms. As-containing wallpaper paints, fed upon by molds and bacteria, led to release of the 'Gosio' gas, which was identified to be trimethyl arsine (Woolson, 1977). Metal mining,

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Corresponding author: Bhaben TANTI (btanti@gauhati.ac.in)

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processing of ores and related activities, has contributed to the release of As in the soil and groundwater (Smedley, 2006) in several countries including Thailand, Ghana, Turkey, England, Serbia, Bosnia, Poland, USA and Canada (Barringer and Reilly, 2013).

A very significant means of mobilization of As is the extraction of groundwater from shallow aquifers in various countries, where surface water is contaminated by disease causing microorganisms. Groundwater is generally more vulnerable to As contamination than surface water because of the interaction of groundwater with aquifer minerals and the increased potential in aquifers for the generation of the physicochemical conditions favourable for As release (Smedley, 2006). Groundwater obtained from shallow aquifers is more likely to contain higher amount of As than that obtained from deep aquifers (Smedley, 2006). As contaminated groundwater is found in many countries like Bangladesh, India, China, Argentina, Chile, Vietnam, Hungary and Mexico (Smedley and Kinniburgh, 2002; Smedley, 2006; Chakraborti et al, 2012). Deep aquifers containing high As levels have also been reported in the Mekong Valley, Vietnam, where high amount of groundwater extraction has resulted in subsidence of the land level by almost 3 cm per year as measured by satellite based radar images from 2007 to 2010 (Erban et al, 2013), leading to speculations that similar deep aquifers of groundwater may not remain As free over the years to come.

In soil, As exhibits a number of oxidation states, the common ones being As^{5+}, As^{3+} and As^{3-}. In aerobic soils, As is mainly present in the oxidized form as arsenate (As^{5+}). While in anaerobic environments like paddy soil, it mainly exists in the reduced form as arsenite (As^{3+}) (Takahashi et al, 2004).

With the use of As-contaminated water in irrigation and due to the various processes of its mobilization, the levels of As in soils have escalated, affecting the agricultural system and resulting in the uptake of the element by crop plants. The translocation factor (TF) for As is higher in rice (0.8) compared to the other crops like wheat (0.1) and barley (0.2) (Xu et al, 2008). The amount of As in paddy soil and soil solution stand elevated (Brammer and Ravenscroft, 2009). The scenario is the worst in rice fields in affected areas such as Bangladesh, India, China and Thailand, where rice is the staple food for most of the people (Abedin et al, 2002; Williams et al, 2006; Garnier et al, 2010). Humans also have been exposed to As through drinking of As-contaminated water and consumption of As-contaminated crops. The contaminated groundwater used to cultivate vegetables and rice for human consumption may be an important pathway of As ingestion and exposure to chronic As (Chakraborti et al, 2004). Food imported into the United Kingdom from Bangladesh has a 2- to 100-fold higher As concentration than vegetables cultivated in the United Kingdom and North America (Al Rmalli et al, 2005). In the South Punjab and Sindh provinces of Pakistan, As is a major contaminant of soil, water and fodder, thereby making its way into the food chain of cattle and subsequently the humans (Zubair et al, 2017). Thus, food is an important route of As exposure in some regions and these exposures can have long-term negative health effects in humans. Even, raised air-As concentration, caused by smelter contaminants in Yunnan (China) poisoning incident in 1993, has been found to contaminate crops grown in the area, where 90% of the human As intake is from the food (rice and corn), and only 10% or less from direct inhalation (Mandal and Suzuki, 2002).

The World Health Organization (WHO) certified that the maximum contaminant level (MCL) of As in drinking water is 10 μg/L (reduced from 50 μg/L) in 1993. Regulations in different countries have recommended different values of the MCL (Smedley, 2006; Barringer and Reilly, 2013). Countries like USA, New Zealand, Japan, Argentina, Brazil, Chile and Colombia place 10 μg/L as MCL in drinking water. Australia uses a standard of 7 μg/L. The New Jersey state in USA places 5 μg/L as the MCL. Mexico has adopted a standard of 25 μg/L, whereas some developing countries like Bangladesh have maintained the earlier 50 μg/L MCL standard. In July 2014, the WHO set worldwide guidelines for what it considers to be safe levels of As in rice, suggesting the maximum of 200 μg/kg for white rice and 400 μg/kg for brown rice (Sohn, 2014). Safety measures can be taken for removing As from drinking water (Ghosh and Singh, 2009) by various methods even at household levels (Chaurasia et al, 2012). However, removal of As from food or crop fields after its incorporation is not economically viable.

As is considered to be one of the most highly toxic and carcinogenic elements. According to the US Environmental Protection Agency (EPA) and the International Agency for Research on Cancer (IARC), As and its compounds have been ranked as a Group 1 human carcinogen. As present in drinking water or contaminated crops can have severe impact on the