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Review

Omics and biotechnology of arsenic stress and detoxification in plants: Current updates and prospective

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ABSTRACT

Arsenic (As), a naturally occurring metallic element, is a dreadful health hazard to millions of people across the globe. Arsenic is present in low amount in the environment and originates from anthropogenic impact and geogenic sources. The presence of As in groundwater used for irrigation is a worldwide problem as it affects crop productivity, accumulates to different tissues and contaminates food chain. The consumption of As contaminated water or food products leads to several diseases and even death. Recently, studies have been carried out to explore the biochemical and molecular mechanisms which contribute to As toxicity, accumulation, detoxification and tolerance acquisition in plants. This information has led to the development of the biotechnological tools for developing plants with modulated As tolerance and detoxification to safeguard cellular and genetic integrity as well as to minimize food chain contamination. This review aims to provide current updates about the biochemical and molecular networks involved in As uptake by plants and the recent developments in the area of functional genomics in terms of developing As tolerant and low As accumulating plants.

Contents

1. Introduction

Arsenic is ubiquitous environmental contaminant, present naturally in rocks, soil, water, air, plants and animals. Studies suggest that more than two hundred mineral species contain As, of which arsenopyrite is

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the most common (Zhao et al., 2010). About one-third of the atmospheric flux of As is of the natural origin which is released into the environment through activities such as volcanic action, low-temperature volatilization, erosion of rocks and forest fires, or through human actions (Tripathi et al., 2007; Neumann et al., 2010). Industrial processes and use of agricultural pesticides and chemicals for timber preservation also contribute to the presence of As in the environment (Zhao et al., 2010). Arsenic exists in different oxidation states and forms; of these inorganic forms include the trivalent As trioxide, As trichloride, As trisulphide, sodium arsenite and pentavalent form including As pentafluoride. Organic form includes arsenobetaine, arsenocholine, tetramethylarsonium salts, arsenosugars and As containing lipids. Of these, inorganic forms are more toxic, of geological origin and present in groundwater and contaminate drinking water in several parts of the world (Lizama et al., 2011). Organic As compounds mainly arsenobetaine are found in marine organisms although some of these compounds have also been found in terrestrial species (Newcombe et al., 2010; Zhao et al., 2013). In soil, organic form, arsenobetaine, is rapidly demethylated to DMA and leads to toxic end product arsenate As(V) (Huang et al., 2007). Various reports suggest the presence of methylated forms of As including monomethylarsonic acid (MMA), dimethylarsinic acid (DMA) and trimethylarsine oxide (TMAO) in nature (Tripathi et al., 2012) however, capacity of plants to methylate As has not been reported as yet.

Arsenic, in addition to adversely affecting plant growth and productivity, also causes severe human health hazards due to its contamination in the food chain (Zhao et al., 2010; Banerjee et al., 2013). In humans, exposure to As has been associated with an increased risk of malignant arsenical skin lesions, and carcinomas (Santra et al., 2013). Chronic exposure to inorganic As affects different biological systems within the body and signs of a typical cutaneous As exposure have been reported in different organs mainly the liver (Banerjee et al., 2013). In addition to this, As is known to modulate multiple pathways including those associated with growth factor, suppression of cell cycle check point proteins, inhibition of DNA repair system and DNA methylation (Reichard and Puga, 2010; Sinha et al., 2013). Studies also suggest that As alters signal transduction pathways, induces ROS synthesis and inhibits DNA repair machinery which ultimately lead to the tumor development (Rodriguez-Gabriel and Russell, 2005). Animals have the capacity to biotransform inorganic As to methylated forms such as methylarsonic acid and dimethylarsenic acid which are less toxic and more readily excreted in urine, however, this process cannot sustain long term exposure (Vahter, 2002). Understanding of biotransformation in animals and use of this information for the long term exposure can be one of the effective strategies to combat toxic effects of As to human health.

The deleterious effects of As to the plants and human led to initiate studies to understand mechanisms related to As uptake from soil and transport in different plant parts. Studies were started with the objective to understand As homeostasis in plants and the basis for inclusion of As in food chain and related hazards. In addition, a series of events that occur at molecular, metabolic and physiological levels need to be explored by utilizing biotechnological advancements and systems biology approach (Tuli et al., 2010). In recent past, various studies have been carried out which provided information related to biochemical, physiological and molecular responses of the plant under As exposure. In addition, the biotechnological advancements have helped to develop transgenic plants which can combat As stress and have modulated mobilization of the metal in plant parts. Here, we have reviewed and carried out in-depth analysis of established understanding as well as identified key thrust areas where further research is required to develop As resistant and low As accumulating plant varieties to minimize food chain contamination.

2. Contamination of food chain: arsenic accumulation in plants

2.1. Arsenic uptake and accumulation in plants

Uptake and accumulation of As in different plant parts affects the growth and productivity of the plants (Fig. 1). Arsenic uptake, translocation and biomagnifications in various crop plants and vegetable species have increased the threat to humans. Accumulation of As in agricultural plants depends on two factors: As availability in the soil and the physiological properties of the plant (Santra et al., 2013). Arsenic uptake by plants occurs primarily through the root system. After uptake by the root system, As distribution is highly variable among various plant parts. Generally, roots and tubers are known to accumulate As in large amount (Peryea, 2001), however, this varies among different plant species. Toxicity and accumulation of As in few crop plants have been studied to predict and reduce the risk of As entrance into the plants as well as to determine the effects on plant biomass and yield (Pickering et al., 2000; Takahashi et al., 2004; Zhang et al., 2009). Studies suggest that As is not readily translocated to the shoots and edible plant parts are generally low in As (<2 mg kg^{-1}). However, some plants accumulate high levels (5–40 mg As kg^{-1}) of As even at soil concentrations near the background level (Gulz et al., 2005). In rice straw, As accumulates up to 149 mg kg^{-1} which is a major cause of As related health hazards (Tripathi et al., 2012). Recently, Wilson et al. (2014) investigated the accumulation of antimony (Sb) and As in vegetable crops such as lettuce, spinach, raddish, carrot and silverbeet for the oral bioaccessibility of these toxic metalloids to humans. Analysis showed that fraction of metalloids was soluble under typical conditions of crop production and As was accumulated in all the glasshouse grown vegetable species. Studies have demonstrated that the phytotoxicity of As in crop plants is influenced by Fe and P which affect the phytoavailability and translocation of As in maize (Rosas-Castor et al., 2014). Among all of the As contaminated food, seafood is reported to be containing higher As concentrations. However, seafood contains only a small proportion of inorganic As forms. The majority of As in seafood is present in the form of complex organic compounds that are generally regarded as less toxic (Borak and Hosgood, 2007).

2.2. Hyperaccumulator plants for arsenic

Naturally, several plant species are able to accumulate and detoxify extraordinarily high levels of heavy metals. In this context, more than 450 hyperaccumulator plant species from 45 families have been reported (Prasad et al., 2010; Sebastian and Prasad, 2014). Studies suggest that few members of the Pteridaceae family show tolerance as well as hyperaccumulation of As in their fronds (Ma et al., 2001; Zhao et al., 2002). Chinese Brake fern, *Pteris vittata* is an efficacious As hyperaccumulator, and accumulates large amount of As in the fronds. *P. vittata* is known to tolerate maximum As concentration in the soil (Zhang et al., 2002). Arsenic tolerance mechanism of *P. vittata* involves As uptake, and detoxification by cellular compartmentalization into different tissues including minor veins (Bondada and Ma, 2003). Arsenic speciation analysis of *P. vittata* grown in an As contaminated soil shows that majority of the total As in the above ground biomass is present in the form of As(III), which is considered to be the more toxic form as compared to As(V) (Fayiga et al., 2005).

A number of other fern species including *Pitrogram macalomelanos*, *Pteris criteca*, *Pteris longifolia and Pteris umbrosa* are known to be As hyperaccumulators (Francesconi et al., 2002; Zhao et al., 2002; Meharg, 2003). Interestingly, As response, accumulation and elemental distribution also identified few hyperaccumulator fern species which are sensitive to As (Sridokchan et al., 2005). Other plant species such as *Silene vulgaris* (Schmidt et al., 2004) are also known to accumulate large amount of As and show As tolerance. Some aquatic macrophytes like, *Hydrilla verticillata*, *Potamogeton pectinatus*, *Eichhornia crassipes*, *Egeriadensa*, *Ceratophyllum demersum*, and watercress *Lepidium sativum*