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Biochemical mechanisms of signaling: Perspectives in plants under arsenic stress

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ABSTRACT

Plants are the ultimate food source for humans, either directly or indirectly. Being sessile in nature, they are exposed to various biotic and abiotic stresses because of changing climate that adversely effects their growth and development. Contamination of heavy metals is one of the major abiotic stresses because of anthropogenic as well as natural factors which lead to increased toxicity and accumulation in plants. Arsenic is a naturally occurring metalloid toxin present in the earth crust. Due to its presence in terrestrial and aquatic environments, it effects the growth of plants. Plants can tolerate arsenic using several mechanisms like phytochelation, vacuole sequestration and activation of antioxidant defense systems. Several signaling mechanisms have evolved in plants that involve the use of proteins, calcium ions, hormones, reactive oxygen species and nitric oxide as signaling molecules to cope with arsenic toxicity. These mechanisms facilitate plants to survive under metal stress by activating their defense systems. The pathways by which these stress signals are perceived and responded is an unexplored area of research and there are lots of gaps still to be filled. A good understanding of these signaling pathways can help in raising the plants which can perform better in arsenic contaminated soil and water. In order to increase the survival of plants in contaminated areas there is a strong need to identify suitable gene targets that can be modified according to needs of the stakeholders using various biotechnological techniques. This review focuses on the signaling mechanisms of plants grown under arsenic stress and will give an insight of the different sensory systems in plants. Furthermore, it provides the knowledge about several pathways that can be exploited to develop plant cultivars which are resistant to arsenic stress or can reduce its uptake to minimize the risk of arsenic toxicity through food chain thus ensuring food security.

Contents

Abbreviations: ; ABA, abscisic acid; APX, ascorbate peroxidase; CaM, calmodulin; CAT, catalase; CBL, calcineurin B-like protein; CDPK, calcium dependent protein kinase; CIPK, CBL-interacting protein kinase; CRK, CT10 regulator of kinase; EIN3, ethylene insensitive 3; ET, ethylene; G proteins, guanosine nucleotide-binding proteins; GR, glutathione reductase; GSH, glutathione; GST, glutathione S-transferase; JA, jasmonic acid; JAZ, jasmonate ZIM-domain; MAP, mitogen-activated protein; MAP4K, mitogen activated protein kinase kinase kinase kinase; MAPK, mitogen activated protein kinase; MAPKK, mitogen activated protein kinase kinase; MAPKKK, mitogen activated protein kinase kinase kinase; NADPH, nicotinamide adenine dinucleotide phosphate; NDP, nucleotide diphosphate; NO, nitric oxide; PCs, phytochelatins; PI3K, phosphoinositide 3-kinase; PP2C, protein phosphatase 2C; Prx, class III peroxidase; RLCKs, receptor like cytoplasmic kinases; ROS, reactive oxygen species; SH2 Phosphotyrosine, Src homology 2 domain phosphotyrosine; SIPK, salicylic acid (SA)-induced protein kinase; TDT, telurite-resistance/dicarboxylate transporter; TdT, terminal deoxynucleotidyl transferase; T–D–Y, threonine–aspartic acid–tyrosine; T–E–Y, threonine–glutamic acid–tyrosine; TFs, transcription factors; TKL, tyrosine kinase-like; WAK, wall-associated kinase; WRKY53, transcription factors which regulate leaf senescence; ZIM family proteins, zinc-finger protein which is expressed in inflorescence meristem

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1. Introduction

Metals and their compounds are essential components of biological and non-biological parts of ecosystems. Among all elements of periodic table, seventeen nutrient elements are vital for higher plants out of which 14 mineral elements are present in the soil. Heavy metals, such as iron (Fe), cobalt (Co), copper (Cu), manganese (Mn), molybdenum (Mo), and zinc (Zn) are required for plants as essential micronutrients because they act as cofactors for several enzymes and take part in vital biological reactions (Epstein and Bloom, 2004).

A broad range of cellular responses such as shift in expression of certain genes and synthesis of peptides to detoxify the metal ions get stimulated due to the increased level of non-nutritional metal ions leading to cellular damage. Although, many of these metal ions are essential in very minute quantity for the proper execution of metabolism, growth, and development, however it is challenging for cell to tackle surplus amount of these ions (Avery, 2001; Schutzendubel and Polle, 2002; Sarwat et al., 2013). Besides these essential micronutrients some other heavy metals such as cadmium (Cd), mercury (Hg), lead (Pb), aluminum (Al) and arsenic (As) are not required for any function and are very lethal for the plants leading to decline in photosynthesis, start of leaf senescence, production of ROS, inactivation of enzymes, reduced root and shoot growth thus leading to growth inhibition. Several studies have reported that increased uptake of heavy metals can affect the development, water potential, physiological, biochemical and molecular processes of plants (Malec et al., 2008, 2009; Maleva et al., 2009; Wan et al., 2011; Gangwar et al., 2011; Islam et al., 2011; Yusuf et al., 2012; Kumar et al., 2012).

There are certain plants which are able to grow in contaminated areas and have adopted an array of approaches enabling them to eliminate, accumulate or hyperaccumulate toxic heavy metals (Sharma and Dietz, 2006; Ahmad and Prasad, 2012; Anjum et al., 2012). In response to heavy metals, plants might respond via increased expression of reactive oxygen species (ROS) and reactive nitrogen species (NO) as well as substitution/inhibition of transcription factors, enzyme cofactors, antioxidative enzymes, cellular redox imbalance, ionic transport imbalance, oxidation of proteins and DNA damage (Islam et al., 2008; Aravind et al., 2009; Cuypers et al., 2011; Gangwar et al., 2011; Huang et al., 2012; Sytar et al., 2013).

Arsenic is a naturally occurring metalloid toxin in the earth crust (Zhao et al., 2010; Gupta et al., 2013) and is often coupled with other elements (Au, Ag, Cu and Sn in particular) in the environment. Increasing demand of these metals led to extensive mining and processing of ores causing widespread arsenic pollution of mining areas throughout the world (Nriagu, 1994). Use of arsenic based pesticides and herbicides in lawns and agricultural fields cause the contamination of agricultural and domestic lands (Woolson et al., 1971; Murphy and Aucott, 1998). Inorganic arsenic has been classified as group 1 carcinogen (IARC, 2004). According to the World Health Organization (WHO) standards arsenic concentrations should not exceed more than 10 $\mu g l^{-1}$ in drinking water. It is causing a global poisoning threat with severe diseases like skin lesions, cancers, and many other (Pearce, 2003), and people all around the world are at risk due to its presence in the food chain (Rahman et al., 2001; Chakraborti et al., 2003).

Solubility of arsenic is dependent on pH and ionic conditions and it can exist in four valence states (−3, 0, +3, +5) arsenate (As V) and arsenite (As III). Among these, arsenite is the most toxic form of arsenic (Payne and Abdel-Fattah, 2005; Zhao et al., 2010; Gupta et al., 2013). Human exposure of arsenic occurs through contaminated drinking water and food chain that may be due to natural geochemical systems or anthropogenic activities. The problem of arsenic contamination in food chain and human exposure to this toxin is a global issue (Finnegan and Chen, 2012). Due to the presence of arsenic in soil and water it effects the growth and yield of crops, posing threats to human health as well as global food security (Flora, 2011; Sharma, 2012).

It is hard for plants to escape the stress conditions due to their sessile nature, therefore to combat arsenic toxicity; plants have acquired certain protective systems which activate in response to cell signaling in stress conditions. Plants are equipped with composite mechanisms that perceive, transduce and broadcast the stress signals in order to adapt their metabolism in the changing climate (Turner et al., 2002; Xiong et al., 2002; Kopyra and GwÃ³ d, 2004). The mechanism responsible to perceive the stimulus in organ and its expansion to the organism is based on various biochemical processes, which can activate the defense even in response to small stimulus. The stress reaction response is enhanced by several enzymes that take part in biosynthesis of specific signaling molecules (Maksymiec, 2007).

Cell signaling is the feature of a multifarious coordination of communication that directs and harmonizes crucial cellular actions. Factors like process of development, resistance against stress and tissue homeostasis determine the potential that how cell will choose and respond to its environment (Sarwat et al., 2013). In order to avoid the effects of stress and to adapt under stress conditions, expression pattern of certain genes has been changed in plants which resulted in an altered metabolic profile (Tuteja and Sopory, 2008a, 2008b).

Presence of arsenic can activate a chain of events that can impede the growth, interrupt photosynthesis and respiration, and stimulate the secondary metabolism resulting in yield losses (Jiang and Singh, 1994; Cozzolino et al., 2010). Phytochelations, hyper accumulation and initiation of antioxidant defense system are known mechanisms that play a part in response to arsenic toxicity in plants (Garg and Singla, 2011). As(V), analog of phosphate, interferes with vital cellular practices inside the plant cell replacing the phosphate moiety, being used in oxidative phosphorylation and ATP synthesis in mitochondria (Wickes and Wiskish, 1976). On the other hand transport of As(III) and un-dissociated methylated arsenic species occurs by nodulin 26-like intrinsic (NIP) aquaporin channels (Zhao et al., 2010; Mosa et al., 2012; Ali et al., 2009). Inorganic forms of arsenic are extremely toxic as As(V) hamper the metabolism of phosphate (such as phosphorylation and synthesis of ATP) while As(III) change the configuration or catalytic functioning of proteins by binding to vicinal sulfhydryl groups (Tripathi et al., 2007; Zhao et al., 2010; Ali et al., 2009). In plants