World J Microbiol Biotechnol (2011) 27:1231–1240
DOI 10.1007/s11274-010-0572-7

ORIGINAL PAPER

# Role of microorganisms in adaptation of agriculture crops to abiotic stresses

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Received: 26 July 2010 / Accepted: 16 September 2010 / Published online: 5 October 2010


**Abstract** Increased incidences of abiotic and biotic stresses impacting productivity in principal crops are being witnessed all over the world. Extreme events like prolonged droughts, intense rains and flooding, heat waves and frost damages are likely to further increase in future due to climate change. A wide range of adaptations and mitigation strategies are required to cope with such impacts. Efficient resource management and crop/livestock improvement for evolving better breeds can help to overcome abiotic stresses to some extent. However, such strategies being long drawn and cost intensive, there is a need to develop simple and low cost biological methods for the management of abiotic stress, which can be used on short term basis. Microorganisms could play a significant role in this respect, if we can exploit their unique properties of tolerance to extremities, their ubiquity, genetic diversity, their interaction with crop plants and develop methods for their successful deployment in agriculture production. Besides influencing the physico-chemical properties of rhizospheric soil through production of exopolysaccharides and formation of biofilm, microorganisms can also influence higher plants response to abiotic stresses like drought, chilling injury, salinity, metal toxicity and high temperature, through different mechanisms like induction of osmo-protectants and heat shock proteins etc. in plant cells. Use of these microorganisms per se can alleviate stresses in crop plants thus opening a new and emerging application in agriculture. These microbes also provide excellent models for understanding the stress tolerance, adaptation and response mechanisms that can be subsequently engineered into crop plants to cope with climate change induced stresses.

**Keywords** Abiotic stress tolerance · Microorganisms · Crop production · Climate change

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## Introduction

Agriculture is considered to be one of the most vulnerable sectors to climate-change. Crop production, particularly in tropical regions is facing increasing stresses caused due to natural and anthropogenic factors. Increased incidence of abiotic and biotic stresses has become major cause for stagnation of productivity in principal crops. There are evidences of yield declines in wheat and paddy crops in many parts of South Asia due to increasing water stress, reduction in number of rainy days and increased air temperature. The average temperature in the Indian sub-continent has risen by 0.57°C in the last 100 years and models project that it is likely to rise further to a maximum of 2.5°C by 2050 and 5.8°C by 2100 (Kumar et al. 2006). Irrigation requirement in arid and semi-arid regions is estimated to increase by 10% with every 1°C rise in temperature. Besides high temperature, droughts, elevated $CO_2$, extreme rainfall events, more floods, cold waves, heat waves, and cyclones are the other important natural disasters that cause serious economic losses, are likely to be witnessed as a result of global warming. These factors are likely to cause serious negative impacts on crop growth and yields and impose severe pressure on our land and water resources.

The principal abiotic stresses in India are drought or soil moisture stress that affect nearly two-thirds area forming parts of the arid and semi arid eco systems, high

temperatures, soil salinity/alkalinity, low pH and metal toxicity. Nearly 11 m ha area is affected by salinity, a chemical stress and another 16 m ha by water logging, a physical stress.

Evolving efficient, low cost, easily adaptable methods for the abiotic stress management is a major challenge. Worldwide, extensive research is being carried out, to develop strategies to cope with abiotic stresses, through development of heat and drought tolerant varieties, shifting the crop calendars, resource management practices etc. (Venkateswarlu and Shanker 2009). While most of these technologies are cost-intensive, recent studies indicate that microorganisms can also help crops cope with abiotic stresses. The role of microorganisms in plant growth promotion, nutrient management and disease control is well known. These beneficial microorganisms colonize the rhizosohere/endorhizosphere of plants and promote growth of the plants through various direct and indirect mechanisms (Saxena et al. 2005). However, of late, the role of microbes in management of biotic and abiotic stresses is gaining importance. The subject of PGPR elicited tolerance to abiotic stresses has been reviewed recently (Venkateswarlu et al. 2008; Yang et al. 2009). The term Induced Systemic Tolerance (IST) has been proposed for PGPR-induced physical and chemical changes that result in enhanced tolerance to abiotis stress.

The present review captures the recent work on the role of microorganisms in helping crops cope with various abiotic stresses like heat stress, salt stress, drought, chilling injury and water-logging, the most common stresses caused due to climate change.

## Abiotic stresses: adaptation of microorganisms at cellular level

The different stress factors have a significant influence on the performance of microorganisms. The selection and deployment of microorganisms in stressed ecosystems therefore requires concerted research and technology development. Extensive research has been carried out on occurance and functional diversity of agriculturally important microbes in stressed environments as reviewed by several authors (Grahm 1992; Zahran 1999; Venkateswarlu et al. 2008). The occurance of *Rhizobium, Bradyrhizobium, Azotobacter, Azospirillum, Pseudomonas* and *Bacillus* has been reported from desert ecosystems, acid soils, saline and alkaline areas and highly eroded hill slopes of India (Tilak et al. 2005, Selvakumar et al. 2009, Upadhyay et al. 2009).

Adaptation of microorganisms to stress is a complex multilevel regulatory process in which many genes may be involved (Srivastava et al. 2008). In certain species living under extreme environments (thermophiles and halophiles), optimum metabolic process like enzymatic activities and membrane stability occur at high temperature or salinity respectively (Madigen 1999), whereas other microorganisms develop different adaptation mechanisms to combat the stress.

Under stress, most of the rhizobacteria produce osmoprotectants ($K^+$, glutamate, trehalose, proline, glycine beatine, proline betaine and ectoine etc.) to modulate their cytoplasmic osmolarity (Blanco and Bernard 1994; Magdy et al. 1990). The periplasmic space of bacteria contains large quantities of highly anionic polysaccharides known as membrane derived oligosaccharides, which are too large to diffuse through the porin proteins and probably function to maintain the turgor pressure of the periplasm of these organisms. Several reviews have focused on the response of bacteria to variations in the solute content of their aqueous environment (Chang et al. 1996, 2007, Sandhya et al. 2009a, b). Vriezen et al. (2006) studied the physiological factors that determine the survival of rhizobia during desiccation and found that survival of *Sinorhizobium meliloti* USDA 1021 during desiccation was enhanced, when cells were dried in stationary phase with an increasing drying temperature and availability of chloride and sulphate. Such studies may help in development of improved strains for stress conditions.

Certain bacteria like *Pseudomonas* survive under stress conditions due to the production of exopolysaccharides (EPS), which protects microorganisms from hydric stress and fluctuations in water potential by enhancing water retention and regulating the diffusion of carbon sources in microbial environment (Sandhya et al. 2009a, b). Exopolysaccharides possess unique water holding and cementing properties, thus play a vital role in the formation and stabilization of soil aggregates and regulation of nutrients and water flow across plant roots through biofilm formation (Roberson and Firestone 1992; Tisdall and Oadea 1982).

High soil temperatures in tropical and subtropical areas, is a major problem for crop production and microbial colonization. Protein denaturation and aggregation are the major types of cellular damage that result from higher temperatures. All organisms respond to a sudden increase in temperature by inducing the synthesis of specific group of polypeptides known as heat shock proteins (HSPs). HSPs consist of chaperons (such as GroEL, DnaK, DnaJ, GroES, ClpB, ClpA, ClpX, small heat shock proteins (sHSP) and proteases). Chaperons are involved in the proper folding of denatured proteins and proteases are required for the degradation of irreversibly damaged proteins (Munchbach et al. 1999). A thermotolerant *P. aeruginosa* strain AMK-P6 isolated from semi-arid location showed induction of HSPs when exposed to high temperature (Ali et al. 2009). The activity of such chaperones is essential for cell survival during heat shock and for

subsequent recovery. Similarly cold tolerant bacteria respond to a decrease in temperature by induction of cryoprotective protein (Koda et al. 2001).

Microorganisms could play a significant role in stress management, once their unique properties of tolerance to extremities, their ubiquity, genetic diversity are understood and methods for their successful deployment in agriculture production are developed. These organisms also provide excellent models for understanding stress tolerance mechanisms that can be subsequently engineered into crop plants.

## Alleviation of abiotic stress in plants by rhizosphere and endophytic bacteria

Besides developing mechanisms for stress tolerance, microorganisms can also impart some degree of tolerance to plants towards abiotic stresses like drought, chilling injury, salinity, metal toxicity and high temperature. In the last decade, bacteria belonging to different genera including *Rhizobium, Bacillus, Pseudomonas, Pantoea, Paenibacillus, Burkholderia, Achromobacter, Azospirillum, Microbacterium, Methylobacterium, variovorax, Enterobacter* etc. have been reported to provide tolerance to host plants under different abiotic stress environments (Table 1). Use of these microorganisms per se can alleviate stresses in agriculture thus opening a new and emerging application of microorganisms.

A variety of mechanisms have been proposed behind microbial elicited stress tolerance in plants (Fig. 1). Production of indole acetic acid, gibberellins and some unknown determinants by PGPR, result in increased root length, root surface area and number of root tips, leading to enhanced uptake of nutrients thereby improving plant health under stress conditions (Egamberdieva and Kucharova 2009). Plant growth promoting bacteria have been found to improve growth of tomato, pepper, canola, bean and lettuce under saline conditions (Barassi et al. 2006; Glick et al. 1997; Yildirim and Taylor 2005). Some PGPR strains produce cytokinin and antioxidants, which result in abscisic acid (ABA) accumultion and degradation of reactive oxygen species. High activities of antioxdant enzymes are linked with oxidative stress tolerance (Stajner et al. 1997). Timmusk and Wagner (1999)were among the firsts to show that inoculation of *Paenibacillus polymyxa* confers drought tolerance in *A. thaliana* through the induction of drought responsive gene, *ERD15 (EARLY RESPONSE TO DEHYDRATION 15*). Inoculation of *Azospirillum brasilense* Sp245 in wheat (*Triticum aestivum*) under drought stress resulted in a better water status and an additional "elastic adjustment"resulting in better grain yield and mineral quality (Mg, K and Ca) at harvest. Another PGPR starin, *Achromobacter piechaudii* ARV8 which produced 1-aminocyclopropane-1-carboxylate (ACC) deaminase, conferred IST against drought and salt in pepper and tomato (Mayak et al. 2004). Many aspects of plant life are regulated by ethylene levels and the biosynthesis of ethylene is subjected to tight regulation, involving transcriptional and post-transcriptional factors regulated by environmental cues, including biotic and abiotic stresses (Hardoim et al. 2008). In the biosynthetic pathway of ethylene, S-adenosylmethionine (S-AdoMet) is converted by 1-aminocyclopropane-1-carboxylate synthase (ACS) to 1-aminocyclopropane-1-carboxylate (ACC), the immediate precursor of ethylene. Under stress conditions, the plant hormone ethylene endogenously regulates plant homoeostasis and results in reduced root and shoot growth. In the presence of ACC deaminase producing bacteria, plant ACC is sequestered and degraded by bacterial cells to supply nitrogen and energy. Furthermore, by removing ACC, the bacteria reduce the deleterious effect of ethylene, ameliorating plant stress and promoting plant growth (Glick 2007). Saleem et al. (2007) have reviewed the role of PGPR containing ACC deaminase, in stress agriculture. Inoculation with ACC deaminase containing bacteria induce longer roots which might be helpful in the uptake of relatively more water from deep soil under drought stress conditions, thus increasing water use efficiency of the plants under drought conditions (Zahir et al. 2008).

The complex and dynamic interactions among microorganisms, roots, soil and water in the rhizosphere induce changes in physicochemical and structural properties of the soil (Haynes and Swift 1990). Microbial polysaccharides can bind soil particles to form microaggregates and macroaggregates. Plant roots and fungal hyphae fit in the pores between microaggregates and thus stabilize macroaggregates. Plants treated with EPS producing bacteria display increased resistance to water stress due to improved soil structure (Sandhya et al. 2009b). EPS can also bind to cations including $Na^+$ thus making it unavailable to plants under saline conditions. Chen et al. (2007) correlated proline accumulation with drought and salt tolerance in plants. Introduction of *proBA* genes derived from *Bacillus subtilis* into *A. thaliana* resulted in production of higher levels of free proline resulting in increased tolerance to osmotic stress in the transgenic plants. Increased production of proline along with decreased electrolyte leakage, maintenance of relative water content of leaves and selective uptake of $K^+$ ions resulted in salt tolerance in *Zea mays* coinoculated with *Rhizobium* and *Pseudomonas* (Bano and Fatima 2009). Proline protects membranes and proteins against the adverse effects of high concentration of inorganic ions and temperature extremes. It also functions as a protein-compatible hydrotope, and as a hydroxyl radical scavanger (Smirnoff and Cumbes 1989).

**Table 1** Microorganisms conferring abiotic stress tolerance in crop plants

| Organism | Crop | Type of stress | Mechanism | References |
|---|---|---|---|---|
| *Pantoea agglomerans* | Wheat | Drought | *Rhizosphere* soil aggregation through EPS | Amellal et al. (1998) |
| *Paenibacillus polymyxa* | Arabiodopsis | Drought | Induction of stress resistant gene ERD 15 | Timmusk and Wagner (1999) |
| *Rhizobium* sp. | Sunflower | Drought | Soil aggregation through EPS | Alami et al. (2000) |
| *Pseudomonas putida*, *Enterobacter cloacae*, *P. putida* | Tomato | Flooding | Synthesis of ACC-deaminase | Grichko and Glick (2001) |
| PGPR | Chickpea | Metal toxicity | Sequestration of metal ions | Gupta et al. (2004) |
| *Azospirillum* sp. | Wheat | Drought | Improved Water relations | Creus et al. (2004) |
| *Achromobacter piechaudii* | Tomato | Salt, drought | Synthesis of ACC-deaminase | Mayak et al. (2004) |
| *Variovorax paradoxus* | Pea | Drought | Synthesis of ACC-deaminase | Dodd et al. (2005) |
| *Piriformaspora indica* | Barley | Salinity | Elevated antioxidative capacity | Waller et al. (2005) |
| AM Fungi | Sorghum | Drought, salinity | Improved Water relation | Cho et al. (2006) |
| *B. amylolequifaciens* | Wheat | Salinity | Restricted $Na^+$ influx | Ashraf et al. (2004) |
| *B. insolitus* | | | | |
| *Microbacterium sp.* | | | | |
| *P. syringae* | | | | |
| *Paraphaeosphaeria quadriseptata* | Arabiodopsis | Drought | Induction of HSP | McLellan et al. (2007) |
| (A rhizospheric fungi) | | | | |
| *Scytonema* | Rice | Coastal Salinity | Gibberellic acid & extra cellular products | Rodriguez et al. (2006) |
| *Burkholderia phytofirmans* PsJN | Grapevine | Low temperature | Synthesis of ACC-deaminase | Ait Bakra et al. (2006) |
| AM fungi & *Bradyrhizobium* | Dragonblood (*Pterocarpus officinalis*) | Flooding | Development of adv. roots, aerenchyma and hyper trophied lenticels | Fougnies et al. (2007) |
| *Brome mosaic virus* | Rice | Drought | Unknown | Marquez et al. (2007) |
| *Methylobacterium oryzae, Burkholderia sp.* | Tomato | Ni & Cd Toxicity | Reduced uptake and translocation | Madhaiyan et al. (2007) |
| *Pseudomonas fluorescens* | Groundnut | Salinity | Synthesis of ACC-deaminase | Saravanakumar and Samiyappan (2007) |
| *P. putida* | Canola | Low temperature | Synthesis of ACC-deaminase | Chang et al. (2007) |
| *P. polymyxa and Rhizobium tropici* | Common bean | Drought | Change in hormone balance and stomatal conductance | Figueiredo et al. (2008) |
| *Pseudomonas* sp. | Pea | Drought | Decreased ethylene production | Arshad et al. (2008) |
| *Pseudomonas mendocina* and Glomus intraradices | Lettuce | Drought | Improved antioxidant status | Kohler et al. (2008) |
| *Pseudomonas* sp. AMK-P6 | Sorghum | Heat | Induction of heat shock proteins and improved plant biochemical status | Ali et al. (2009) |
| *Pseudomonas putida* P45 | Sunflower | Drought | Improved soil aggregation due to EPS production | Sandhya et al. (2009a, 2009b) |
| *Bacillus megaterium* and *Glomus* sp. | Trifolium | Drought | IAA and proline production | Marulanda et al. (2007) |

Accumulation of proline buffers cellular redox potential under environmental stresses (Jain et al. 2001; Wahid and Close 2007).

Trehalose metabolism in rhizobia is key for signaling plant growth, yield and adaptation to abiotic stress and its manipulation had a major agronomical impact on

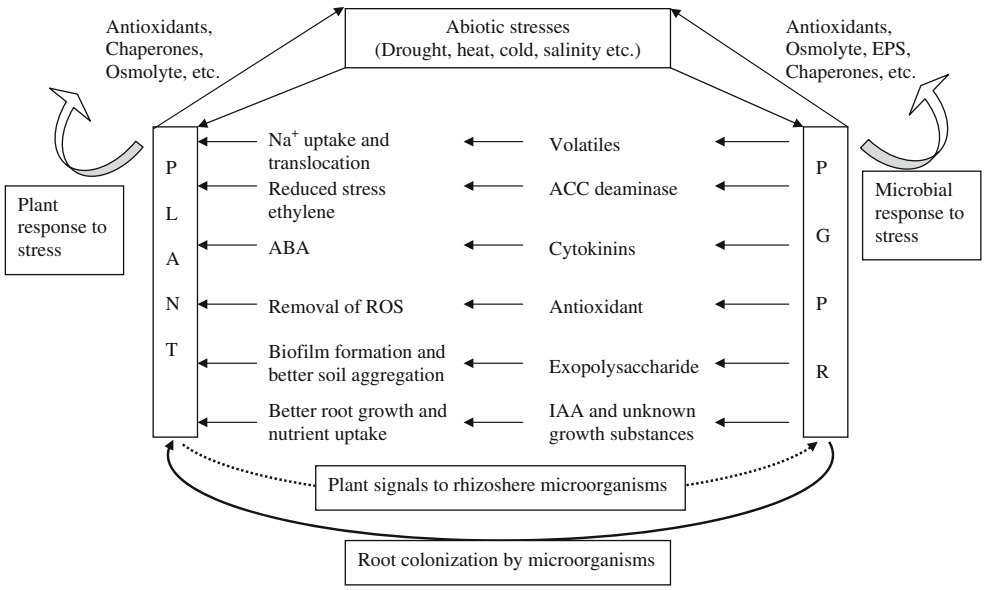


**Fig. 1** Conceptual diagram, on the plant–microbe interactions under abiotic stress

leguminous plants (Suarez et al. 2008). Figueiredo et al. (2008) reported increased plant growth, N content and nodulation of *Phaseolus vulgaris* L. under drought stress due to coinoculation of *Rhizobium tropici* and *P. polymyxa*. *Phaseolus vulgaris* (common bean) plants inoculated with *Rhizobium etli* overexpressing trehalose-6-phosphate synthase gene had more nodules with increased nitrogenase activity and high biomass compared with plants inoculated with wild type *R. etli*. Three weeks old plants subjected to drought stress fully recovered whereas plants inoculated with a wild type *Rhizobium etli* died. Microarray analysis of 7,200 expressed sequence tags from nodules of plants inoculated with strain over expressing trehalose-6-phosphate synthase gene revealed upregulation of genes involved in stress tolerance, suggesting a signaling mechanism for trehalose.

Some of the volatiles organic compounds (VOCs) emitted from *Bacillus* (Ryu 2004) are bacterial determinants involved in IST. The volatiles emitted by PGPR down regulate *hkt1 (HIGH AFFINITY* $K^+$ TRANSPORTER 1) expression in roots but upregulates it in shoots, orchestring lower $Na^+$ levels and recirculation of $Na^+$ in the whole plant under salt conditions (Zhang et al. 2008). Root colonization of *Arabidopsis thaliana* by *Pseudomonas chlororaphis* O6 induced tolerance in the plants against biotic and abiotic stresses due to the production of a volatile metabolite, 2R, 3R-butanediol. Studies with *Arabidopsis* mutant lines indicated that induced drought tolerance requires salicylic acid (SA), ethylene and jasmonic acid-signalling pathways (Cho et al. 2008).

Higher temperatures influence photosynthetic rate, plant water relations, flowering and fruit set in tropical and temperate crops. Similarly low temperature is a major factor limiting the productivity and geographical distribution of many species, including important agricultural crops. Srivastava et al. (2008) isolated a thermotolerant *Psseudomonas putida* NBRI0987 from drought affected rhizosphere of chickpea. Over production of stress sigma (S) (RpoS) was observed by this microorganism when grown under high temperature stress at 40°C compared with 30°C. A thermotolerant *Pseudomonas* sp. strain AMK-P6 induced thermotolerance in sorghum seedlings due to synthesis of high molecular weight protein in leaves and improved plant biomass as well as biochemical status in terms of proline, sugar, amino acid and chlorophyll content (Ali et al. 2009). A plant growth promoting bacterium *Burkholderia phytofirmans* PsJN, capable of epiphytic and endophytic colonization of grapevine tissue and organs (Compant et al. 2005) could protect the plants against heat as well as chilling stress (Bensalim et al. 1998; Ait Bakra et al. 2006). The bacterized plantlets showed significantly increased levels of starch, proline and phenolics. These increases correlated with the enhancement of cold tolerance of the grapevine plantlets. Cold tolerant *Serratia marscescens* strain SRM and *Pantoea dispersa* strain 1A exhibited PGP characteristics like IAA production, P-solubilization, HCN and siderophores production at 15 and 4°C. Seed bacterization with the strains significantly enhanced biomass and nutrient uptake of wheat seedlings grown in cold temperature (Selvakumar et al. 2007a, b).

In bacteria, cold shock proteins (CSP) proteins are 7 to 10 kD in size and contain the nucleic acid binding activity, sufficient for their function as RNA chaperones. The chaperone function of CSP is thought to be important for

stimulating growth following stress acclimation and during periods of high metabolic activity The expression of bacterial CSPs (Csp A and Csp B) was shown to improve tolerance of transgenic rice, maize and arabidopsis plants to a number of abiotic stresses including cold, heat and water deficit resulting in improved yields under field conditions (Castiglioni et al. 2008). These studies confirmed that the family of proteins is capable of delivering broad stress tolerance, which also translates to improved grain yields under both managed stress and natural environment.

Rhizobacteria inhabiting the sites exposed to frequent stress conditions, are likely to be more adaptive or tolerant and may serve as better plant growth promoters under stressful conditions (Lifshitz et al. 1986). It has been reported that *P. polymyxa* inoculation is more effective in relatively harsh and poor quality conditions (Chanway and Holl 1994). Drought-exposed barley plants when inoculated with *P. polymyxa* could tolerate stress, 2 weeks longer than uninoculated control plants (Timmusk 2003). The isolation of indigenous microorganisms from the stress affected soils and screening on the basis of their stress tolerance and PGP traits may be useful in the rapid selection of efficient strains that could be used as bioinoculants for stressed crops.

## Symbiotic fungi for alleviation of abiotic stress in plants

Arbuscular mycorrhizal (AM) symbiosis is often alleged to improve plant resistance to water deficit and drought stress through the alteration of plant physiology and the expression of plant genes (Subramanian and Charest 1998; Ruiz-Lozano and Azcon 2000). There are reports of AM-induced increases in drought tolerance, involving both increased dehydration and dehydration tolerance (Allen and Boosalis 1983). AM fungi inoculation could decrease the leaf content of malondialdehyde and soluble protein and enhance activities of superoxide dismutases (SOD), peroxidasse (POD) and catalase (CAT) resulting in improved osmotic adjustment and drought tolerance of mycorrhizal citrus grafting seedlings (Wu and Xia 2005). Inoculation of *Glomus versiforme* in citrus plants improved the osmotic adjustment of the plant under drought stress through enhanced levels of non-structural carbohydrates, K(+), Ca(+) and Mg(2+) resulting in the enhancement of drought tolerance (Wu and Xia. 2006).

The role of abscisic acid (ABA) had been suggested behind AM mediated stress response of plants (Aroca et al. 2008). The addition of exogenous ABA considerably enhanced the ABA content in shoots of non-AM plants, concomitant with the expression of the stress marker genes *Lsp5cs* and *Ls1ea* and the gene *Lsnced*. By contrast, the addition of exogenous ABA decreased the content of ABA in shoots of AM plants and did not produce any further enhancement of the expression. Co-inoculation of lettuce with PGPR *Pseudomonas mendocina* and *G. intraradices* or *G. mosseae* augmented an antioxidative catalase under severe drought conditions, suggesting that they could be used in inoculants to alleviate the oxidative damage (Kohler et al. 2008). A 14-3-3 protein encoding gene from *Glomus intraradices* growing in vitro and subjected to drought stress was identified (Porcel et al. 2006). Role of these proteins that regulate both signaling pathways and also effector proteins was suggested in imparting protection to the host plants against drought stress. Glutathione and ascorbate have an important role in confering protection and maintain metabolic function of plants under water deficit conditions. Low accumulation of these compounds in the lavender plants colonized by autochthonous drought tolerant *Glomus intraradices* and *Glomus* sp. strain indicated high drought tolerance in plants (Marulanda et al. 2007). Mycorrhized lavender plants showed improved water content, root biomas and N and K content.

AM symbiosis has frequently increased resilience of host plants to salinity stress, perhaps with greater consistency than to drought stress. Growth in saline soils was increased by inoculation with *Glomus* spp., with AM plants having increased phosphate and decreased $Na^+$ concentrations in shoots compared to uninoculated controls (Pfeiffer and Bloss 1987; Giri and Mukerji 2004). Salt resistance was improved by AM colonization in maize (Feng et al. 2002), mung bean (Jindal et al. 1993) and clover (Ben Khaled et al. 2003) with AM effect correlated with improved osmoregulation or proline accumulation. AM inoculation also improved NaCl resistance in tomato, with extent of improvement related to salt sensitivity of the cultivar (Al-Karaki et al. 2001). AM improvement of salt resistance has usually been associated with AM-induced increases in P acquisition and plant growth in cucumber (Rosendahl and Rosendahl 1991). *Gigaspora margarita* colonization promoted stomatal conductance in sorghum on exposure to drought stress in salinized soils and also improved the survival dual stress.

Occurance of AM fungi in wetlands is well documented (Saint-Etienne et al. 2006). Accumulation of acetaldehyde, a highly toxic intermediate in ethanol formation, in roots has been suggested as the main factor responsible for flooding injury in sensitive species (Osundina 1998). AM colonization by *Glomus intraradices* contributed substantially to the flood tolerance of *Pterocarpus officinalis* seedlings by improving plant growth and P acquisition in leaves. Flooding induced nodules both on adventitious roots and submerged parts of the stem (Fougnies et al. 2007). Mycorrhizal *Casuarina equisetifolia* seedlings could better adapt to flooding than noninoculated seedlings. This

could be due to increased $O_2$ diffusion and removal of ethanol through greater development of adventitious roots, aerenchymatous tissue and hypertrophies lenticels on the root zone and submerged part of the stem (Rutto et al. 2002). The better tolerance of AM inoculated *A. trifolium* plants to flooding was mediated through an improvement of osmotic adjustment and proline in plant tissue (Neto et al. 2006).

Besides AMF, Endophytic symbiont dark septate fungi (DSF) found in plants growing under stressed environments such as alpine habitats and arid grasslands have been reported to increase their resistance to drought and heat and facilitate the acquisition of nutrients (Porras-Alfaro et al. 2008). *Piriformaspora indica* an endophytic fungus confers drought tolerance in *Arabidopsis thaliana* through priming of the expression of a quite diverse set of stress related genes in the leaves, resulting in stronger upregulation of the message levels for phospholipase Ddelta, calcineurin B-like proteins (CBL 1) and histone acetyltransferase (HAT) in *P. indica* colonized seedlings (Sheramati et al. 2008). Rhizosphere fungus *Paraphaeosphaeria quadriseptata* enhanced plant heat stress tolerance of *Arabidopsis thaliana* through induction of HSP101 and HSP70 the conserved components of the stress response (McLellan et al. 2007).

## Dual symbiotic systems for alleviation of abiotic stress in plants

Besides rhizosphere and endophytic bacteria and symbotic fungi, role of virus in conferring tolerance to host plant against abiotic stress has also been reported. An endophytic fungi *Cuvularia* sp. isolated from the *Dichanthelium lanuginosum* grown under geothermal soils could impart thermo-tolerance (constant 50°C soil temperature for 3 days and intermittent soil temperature as high as 65°C for 10 days) (Redman et al. 2002). Neither the fungus nor the plant could grow at temperature above 38°C, when grown separately. The ability of *Curvularia protuberata* to confer heat tolerance to the host plant was related to the presence of a virus named as *Curvularia* thermotolerance virus (CatahTV). Plants inoculated with the virus-infected wild type isolate of fungus tolerated intermittent soil temperatures as high as 65°C for 2 weeks (10 h of heat per day) whereas both non-symbiotic plants and plants inoculated with the virus free isolate of the fungus became shriveled, chlorotic and died. The ability of *C. protuberata* isolated from a monocot, to confer heat tolerance to tomato (a dicot) was tested and similar results to those obtained with *D. lanuginosum* were observed (Marquez et al. 1996). Several possible mechanisms could confer thermotolerance. In plants, the fungal endophytes produce cell wall melanin that may dissipate heat along the hyphae and/or complex with oxygen radicals generated during heat stress (Davidson et al. 1996). Alternatively, the endophyte may act as a biological "trigger" allowing symbiotic plants to activate stress response systems more rapidly and strongly than non-symbiotic plants (Redman et al. 1999).

## Conclusion

Plant-associated microorganisms can play an important role in conferring resistance to abiotic stresses. These organisms could include rhizoplane and endophytic bacteria and symbiotic fungi and operate through a variety of mechanisms like triggering osmotic response and induction of novel genes in plants. The development of stress tolerant crop varieties through genetic engineering and plant breeding is essential but a long drawn process, whereas microbial inoculation to alleviate stresses in plants could be a more cost effective environmental friendly option which could be available in a shorter time frame. Taking the current leads available, concerted future research is needed in this area, particularly on field evaluation and application of potential organisms.

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