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Drought Stress In Plants And Possible Methods Of Alleviation

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Abstract

Drought stress is one of the most critical abiotic factors limiting plant growth and agricultural productivity worldwide. Water deficit affects plant physiological, biochemical and molecular processes, often leading to stunted growth and reduced yield. To mitigate these effects, sustainable and environmentally friendly strategies are gaining importance. This review focuses on the potential of plant growth-promoting bacteria (PGPB), silicon (Si), and superabsorbent polymers (SAPs) in alleviating drought stress in plants. PGPB enhance drought tolerance by improving root development, increasing nutrient and water uptake and modulating stress-related phytohormones. Silicon contributes to drought resistance by improving structural integrity, reducing water loss and activating antioxidant defense mechanisms. SAPs, due to their high water-retention capacity, improve soil moisture availability and help maintain plant water status during prolonged dry periods. The use of these agents offers a promising integrated approach for improving drought resistance in crops. This review synthesizes recent advancements, highlights underlying mechanisms and discusses future prospects for their application in sustainable agriculture under drought conditions.

Keywords: Drought stress, Plant growth promoting bacteria, Silicon, Superabsorbent polymer.

Introduction

The increase in worldwide population and drastic climatic changes haunt the food security (Lesk et al. 2016). The present scenario shows that plants are continuously getting bare to several stress conditions. Water is essential factor in agriculture field however it is limited resource (Wang et al, 2012). Drought stress is major abiotic stress affecting food security for worldwide increasing population and is predicted to severely affect plant growth by 2050 for more than 50 % of land (Vinocur and Altman 2005; Kasim et al. 2013 Hashem et al., 2017). As per WHO affects around 55 million people worldwide (WHO 2020). Drought stress may be short, moderate, severe and extremely prolonged, affecting overall crop growth and yield (Bottner et al. 1995). The main cause of drought stress is changed pattern of rainfall and decreased precipitation (Lobell et al., 2011). The plant water relationship is affected at whole plant and cellular level thus leads to specific plus nonspecific physiological response (Beck et al. 2007). Drought stress results in reduction in leaf expansion, stem elongation ((Engelbrecht et al., 2007), water potential, photosynthesis (Yang et al. 2010; Alcazar et al. 2011), ionic and nutrient imbalance (Engelbrecht et al., 2007). Drought stress induced elevated level of reactive oxygen species (ROS) affect redox status of plants resulting in damages due to oxidation of proteins, lipids, nucleic acid and photosynthetic pigment (Nahar et al., 2017). Drought stress reduces growth of several important crops such as wheat, maize, barley, potato, pigeon pea and rice (Rampino et al. 2006; Kamara et al. 2003; Samarah 2005; Lafitte et al. 2006; Hijmans, 2003; Nam et al., 2001).

Effect of drought stress on plant growth

Drought stress induces several morphological, physiological and biochemical changes in plants thus affect overall plant growth and productivity (Noman et al. 2015; Ye et al. 2012). Drought stress affects cell membrane hence maintenance of cell membrane integrity and stability is vital for development of drought tolerance in plants (Bajji et al., 2002). Drought stressed plants have altered elasticity of cell wall, excessive toxic metabolites and reduced photosynthesis consequenting in plant death. Drought stressed plants have altered proteomic and biochemical status due to changes in gene expression (Caruso 2009, Alvarez 2008, Li 2008, Carmo 2009).

Presence of sufficient water level is essential for plant survival in drought condition. Drought stressed plants maintains high water level through osmotic adjustment (Osakabe et al. 2014). However reduced water potential and water contents under drought stress have been reported in several plants (Ali et al. 2013b; Noman et al. 2015). Plants requires sufficient amount of essential nutrients for growth and development. Drought condition affects soil nutrients availability and its transport in plant as water carries the nutrients to plant root. Drought stress reduces diffusion and mass flow of nutrients, which are water soluble such as calcium, magnesium, nitrate and sulfate (Selvakumar et al. 2012).

The main response to drought condition is arrest of plant growth. Under drought stress the cell growth is severely impaired due to reduced turgor pressure (Taiz and Zeiger, 2006). Drought stress inhibits cell division and enlargement (Jaleel et al, 2009), reduces plant height (Bunnag and Pongthai, 2013) and tillers number (Bunnag and Pongthai, 2013). Maize plant growing under water limiting condition showed decreased height and leaf size (Khan et al. 2015). Under water limiting conditions fresh and dry weight of plants gets significantly decreased (Zhao et al. 2006).

Seed germination is most important step in the formation of seedling. Drought condition is major stress which delays or prevents process of seed germination (Hubbard et al. 2012; Shi et al. 2014). The acclimatization of germination and establishment of seedling to environmental condition is necessary for plant propagation (Zhang et al. 2005). The drought stress originated reduced germination and seedling growth has been reported in important crops such as *Oryza sativa* L., *Pisum sativum* L. and *Medicago sativa* L. (Okcu et al., 2005; Manikavelu et al., 2006; Zeid and Shedeed, 2006). Plants subjected to drought stress have inhibited shoot growth which decreases plant requirement of metabolites and mobilize them for production of compounds needed for osmotic adjustment (Hsaio and Xu 2000). Okcu et al. (2005) reported impaired germination and seedling growth of pea subjected to drought stress. These results corroborates with Zeid and Shedeed (2006) who reported reduced germination, length and weight of alfalfa (*Medicago sativa*) grown under water deficit conditions.

Drought stress affects photosynthesis, an important process of plant growth and productivity. Drought stress induced decrease in chlorophyll content has been reported in *Carthamus tinctorius* (Siddiqi et al., 2009), *Paulownia imperialis* (Ayala-Astorga and Melendez, 2010), Jatropha curcas (Evandro N. Silva 2010) and bean (Beinsan et al., 2003). The decrease in rate of photosynthesis in drought condition is due to the decrease in photosynthetic enzymes activity, decreased efficiency of photosystem II, stomatal closure (Centritto et al, 2009)., reduced leaf expansion and leaf senescence (Wahid et al., 2007). Drought stress makes the plants more vulnerable to photo damages due to stomatal closure, which decreases availability of CO_2 (Lawlor and Cornic, 2002).

Drought stress results in oxidative stress in plants because of the amassed synthesis of ROS due to disruption in photosynthesis, increased rate of photorespiration which alters cell homeostasis. ROS such as hydroxyl radicals, hydrogen peroxide and super oxide radicals are normally generated in very less amount under non stress conditions in several plant organelles (Apel and Hirt 2004). Accumulated ROS increases lipid peroxidation, resulting in DNA, proteins and lipid damages (Pompelli et al. 2010). Elimination of ROS and prevention of drought stress originated oxidative stress is is effective strategy for development of drought tolerance in plants (Bartels 2001) Plants are equipped with enzymatic (catalase (CAT), glutathione reductase (GR), superoxide dismutase (SOD), ascorbate peroxidase (APX)) and non-enzymatic (ascorbic acid, glutathione and cysteine) defense system which scavenge ROS thus protects them against drought stress induced elevated level of ROS (Miller et al. 2010).

The most common response of plant to drought condition is osmotic stress because of the imbalance in water level (Vinocur and Altman 2005). Osmotic stress results in different effects in drought stressed plants at cellular level. It limits plant growth due to reduced rate of photosynthesis, resulting in increasing production of ROS that damages cell components. Severe drought stress reduces volume of cytosole and vacuole because of the cell dehydration (Bartels and Sunkar 2005). Drought stress stimulated osmotic stress is mediated by osmolytes synthesis thus reestablishes homeostasis (Zhu 2002). Plants adapt to drought stress condition by accumulating osmolytes such as trehalose, glycine betaine and proline (Vendruscolo et al. 2007; Rodriguez et al. 2009). Drought tolerance in plants is indicated by an increased level of amino acids (Zhu 2002) which is reported in drought stressed plants including wheat, sorghum and pepper (Yadav et al. 2005). Increased level of proline gives indication of presence of drought stress in plants (Valentovic et al. 2006).

Plants tolerate drought stress condition by multiple mechanisms such as antioxidant production and osmolytes synthesis (Umezawa et al. 2006). Abscisic acid is hormone, produced by drought stressed plants which coordinates several strategies of plants for protection against drought condition (Hubbard et al. 2010). Plants may increase root growth by improving plant water acquisition (Gowda et al. 2011) or reduce use of water by closing stomatas and slowing growth (Lopes et al. 2011) or may accelerate flowering stage before beginning of stress (Neumann 2008).

Strategies to alleviate drought stress

Plant growth promoting bacteria

Bioinoculants improves quality of soil as compared to chemical based fertilizers (Kumar et al., 2016). PGPB are potential candidates which modulates physiological response to drought hence ensures survival of drought stressed plants (Manjunatha et al. 2022, Marasco et al. 2012).

Ethylene is plant hormone involved in plant growth and development plus defense against several abiotic stress conditions at low level (Kazan 2015). When plants are exposed to stressful condition an elevated level of ethylene is produced (Abdelaal et al. 2021) hence this hormone is widely known as stress ethylene, which hinders overall growth of plant. After the exposure of plants to stress condition, the stress ethylene synthesis occurs in two peaks, small first peak of ethylene is responsible for expression of plant defense genes while the large second peak known as stress ethylene is deleterious to plant growth and development (Glick et al. 2007). PGPB have ability to produce ACC deaminase enzyme which metabolize ACC, an immediate precursor of ethylene into ammonia and α-ketobutyrate hence reduces stress ethylene level in plants (Shaharoona et al. 2006). The inhibitory effects of drought stress on growth and yield of pea are eliminated by ACC deaminase expressing PGPB (Arshad et al., 2008). Mayak et al. (2004) examined reduced ethylene level and improvement in weight of drought stressed tomato and pepper plants bacterized with ACC deaminse producing *Achromobacter piechaudii* ARV8. Similarly inoculation of drought stressed *pisum* with ACC deaminase producing PGPB *Pseudomonas* spp. results in longer root development which increases plant water uptake from soil (Zahir et al. 2008). Similarly, drought stress suffering wheat plants inoculated with ACC deaminase producing PGPB have increased shoot biomass and increased root length (Magnucka and Pietr 2015).

PGPB involves some biochemical and physiological changes in plants hence induce drought resistance such as antioxidants defense, production of plant hormones such as indole-3-acetic acid (IAA), gibberellic acid, abscisic acid (ABA) and cytokinins, synthesis of ACC deaminase enzyme, exopolysaccharides and induced systematic tolerance (IST) (Khalid et al. 2006, Kim et al. 2012;

Timmusk et al. 2014). IST is microorganism originated physicochemical changes in plant, which ensures improved tolerance to abiotic stress conditions (Yang et al., 2009).

Plant hormones such as IAA, gibberellic acid, cytokinins and ABA are essential for plant growth and development (Egamberdieva, 2013) and helps the plants to survive under stress conditions (Fahad et al., 2015). PGPB have an ability to synthesize plant hormones which stimulates growth and division of plant cells to develop tolerance against stress conditions (Glick and Pasternak, 2003). Reduced ethylene level by ACC deaminase and promotion in plant growth by bacterial auxin has been reported by Belimov et al. (2015) when potato plants exposed to drought conditions were inoculated with PGPB. Furthermore, *Azospirillum lipoferum* producing gibberellic acid and ABA, mitigates drought stress in maize plants (Cohen et al., 2009). Furthermore *P. putida* H-2–3 with gibberellic acid producing ability when inoculated to drought stressed soyabean plants improves plant growth (Kang et al., 2014). IAA producing PGPB mediates interaction between producing bacteria and plant plus protects bacteria from stressful environmental conditions. In an experiment carried by Bianco et al. (2006) about 50 % of bacterial cells gets died when exposed to osmotic stress, while treatment of IAA showed 30 % death of bacterial cells. The exopolysaccharides produced by PGPB increases soil aggregation, maintains high water potential around bacterized plant roots which leads to increase plant nutrient uptake hence increases plant growth and helps the drought stressed plants for survival (Selvakumar et al., 2012). Bacterization of drought affected maize plant by exopolysaccharide producing *Pseudomonas aeruginosa, Proteus penneri* and *Alcaligenes faecalis* exhibited increase in proteins, sugar, proline level and decrease in antioxidant enzyme activity (Naseem and Bano, 2014). Exopolysaccharide protects PGPB and plants from desiccation as it holds the water in microenvironment and releases water slowly in surrounding soil hence dries up very slowly (Hepper, 1975). Exopolysaccharide production also increases rhizospheric competence of PGPB which results in direct effect of plant growth promoting properties of organism on plant growth and productivity (Bhise et al. 2017). Some PGPB produces phytase enzyme which solubilize phytate compounds thus make the soluble phosphate available to plants which again help the plants for their growth under stress conditions (Kumar et al. 2016b). Abdelaal et al. (2021) reported improved height and weight in drought stressed soyabean plants added with *Pseudomonas*. Plants suffering from drought condition respond by increasing abscission and senescence of older leaves, the process also called as leaf area adjustment (Gepstein and Glick 2013), however elongation in plant roots occurs to reach ground water for plant need (Brunner et al. 2015). For continuous growth of plant under drought stress, maintenance of water potential is necessary and this can be achieved by accumulation of compatible solute such as proline, organic acids and glycine betaine, which plays a vital role in osmotic adjustment. Osmolytes produced by PGPB maintains osmotic balance of plants thus help the plant to grow in drought stress (Vanderlinde 2010). Inoculation of drought stressed maize plants by *Pseudomonas putida* GAP-P45 showed accumulation of proline which improved relative water content and plant biomass (Sandhya et al., 2010). Furthermore inoculation of drought exposed tomato plant by *Bacillus polymyxa* exhibited increased proline to mitigate stress (Shintu and Jayaram, 2015).

PGPB activates antioxidant defense which improves cell membrane stability hence increases drought resistance in plants (Gusain et al. 2015). Reduced activity of antioxidant enzymes such as GPX and APX in *Bacillus* species inoculated maize plants has been observed by Vardharajula et al. (2011), developing protection against drought condition. In soil environment plant and bacteria communicates with each other by producing volatile organic compounds (VOC). These VOC activates plant gene synthesis encoding ROS scavenging enzymes such as CAT, SOD and GR, which in turn protects the plants against drought stress (Timmusk et al. 2014). Significantly reduced melondialdehyde (MDA) contents has been observed by (Chandra et al. 2018) in drought stressed finger millet (*Eleusine coracana* (L.) when supplemented with ACC deaminase producing PGPB *pseudomonas* sp. Furthermore author has also reported increased fresh and dry weight of shoot and root and photosynthetic pigment content in finger millet exposed to drought stress applied with *pseudomonas* sp. inoculum. Batool et al. (2020) also reported improved chlorophyll, total soluble sugar and protein contents in drought stressed potato plants inoculated with *B. subtilis* HAS31

Silicon

Silicon (Si) is second mainly abundant element of earth crust accounting for 28 % of total earth crust (Sommer et al. 2006). Si considered as nonessential for plant growth and development (Luyckx et al., 2017). However Si plays a key role in plant growth, enzyme functioning, gene expression (Vatansever et al., 2017), activates many processes of physiologically and metabolically important (Parveen and Ashraf, 2010).

Plants growing in soil have Si in their tissue (Ma and Yamaji, 2008) which gets varied based on plant genotype and species (Ma and Yamaji, 2008). The uptake and transport of Si in plants is classified as active, passive or rejective. It has been reported that Si mitigates dangerous effects of abiotic stresses such as drought, salinity and metal toxicity (Ali et al. 2012a, 2013a; Ahmed et al. 2014a; Keller et al. 2015).

Inoculation of Si mitigates adverse effects of drought stress on sorghum (Yin et al. 2014), potato (Crusciol et al. 2009) and wheat (Gong et al. 2005).

Si inoculation to drought stress suffering plants increases plant water contents and decreases loss of water by stimulating synthesis of silica cuticles double layer under leaf epidermis (Luyckx et al., 2017). Increase in water uptake by plant root inoculated with Si is because of the activation in amino acids and sugar accumulation (Sonobe et al. 2011). Under drought stress Si increases hydraulic conductance of plant root which increases plant water uptake and transport thus results in up regulation of transcription of several aquaporin genes (Liu et al. (2014). Si plays a vital role in maintenance of plant mineral balance under stress condition due to increased water conservation and nutrient absorption in plants (Zhu and Gong, 2014). In addition, Si increases membrane stability and reduces cell membrane permeability and inorganic leakage of stressed plant cell (Merwad et al., 2018). Si application to stressed plants maintains plant function and integrity of cell membrane and, improves plant growth hence mitigates stress condition (Merwad et al., 2018).

Plant uptake of essential nutrients is reduced in drought condition (Emam et al. 2014). Si addition in drought stressed wheat increases P level (Gong and Chen 2012). Furthermore Emam et al. (2014) reported improved P and K in drought stressed rice straw when provided with Si over non provided Si plants.

Application of calcium silicate to drought stressed maize improved seed germination (Zargar and Agnihotri 2013). Si application under drought stress increases plant growth. Ahmed et al. (2011b) reported improved dry weight of root and shoot of drought stressed *Sorghum bicolor* L. inoculated with Si. Furthermore Hamayun et al. (2010) examined increased fresh plus dry weight and shoot length of *Glycine max* L. when applied with Si. Similarly Si inoculated drought affected rice showed increased rice grain yield over control (Nolla et al. 2012) and increased level of phenolics and flavonoids (Emam et al. 2014) over uninoculated plant. Si application increases chlorophyll contents of drought stressed plants such as soybean (Shen et al. 2010), wheat (Pei et al. 2010) and sorghum (Yin et al. 2014). Si induced increase in photosynthetic pigment contents in drought stress suffering plants might be due to the Si originated reduced oxidative stress and increased water potential and gas exchange. Drought affected wheat plants added with Si showed increased rate of photosynthesis, relative water contents and stability of cell membrane (Maghsoudi et al., 2016).

Si regulates overproduction of ROS in plants suffering from abiotic stress conditions. Kim et al. (2017) elucidated that the Si supplementation to stressed plants induces stress resistance in plants by decreasing ROS overproduction by improving antioxidant enzymes activity mainly ascorbate peroxidase and catalase. Reduced lipid peroxidation and H_2O_2 has been reported in wheat (Pei et al. 2010), sunflower (Gunes et al. 2008), chickpea (Gunes et al. 2007) and *G. uralensis* (Zhang et al. 2017) when added with Si.

Si application may increase drought tolerance in plants by adjusting osmotic status of plants and increasing osmolyte level (Zhang et al. (2017). Inoculation of drought stressed *Cucumis sativus* L. by Si has improved tolerance in plant by improving water content and regulating proline level (Ouzounidou et al., 2016).

Superabsorbent polymer

Soil is dynamic material of great importance, playing an important role in ecosystem hence need to restore for sustainable agriculture (Smith et al. 2015). A soil management practice plays a vital role in maintaining soil quality and crop productivity (Diacono and Montemurro 2011). In order to ameliorate drought stress and maintain agriculture productivity, use of water absorbing soil amendments such as superabsorbent polymers is effective strategy (Yazdanpanah et al. 2016).

Superabsorbent polymers (SAPs) are cross-linked macromolecules capable of absorbing and retaining high amount of water compared to its own weight, with difficulty to remove absorbed water even under pressure (Devine and Higginbotham 2005; Zohuriaan-Mehr et al. 2008). Due to high water retention ability SAP reduces time requirement of plant watering hence acts as energy saving soil conditioner (Bai et al., 2010). In addition, SAPs might retain organic nutrients present in soil and has property to acclimatize to drought condition (Arbona et al., 2005; Bai et al., 2010). Inoculation of SAPs in drought stressed soil improved water use efficiency of crops and decreased amount of water needed for irrigation (Bettoni et al. 2014). SAPs are used in agriculture field in the form of seed coating, additives and root dips (Zohuriaan-Mehr and Kabiri, 2008). Supplementation of SAPs can improves properties of soil such as water holding capacity (Akhter et al. 2004; Yu et al. 2012; Yang et al. 2014) thus increases soil water content, water potential (Bhardwaj et al. 2007) and nutrients retention thus helps the plants to mitigate drought stress (Abedi-Koupai and Asadkazemi, 2006; Orikiriza et al., 2009).

Yang et al. (2017) showed enhanced water consumption in maize exposed to water deficit condition when provided with SAPs. Authors has explained this with two mechanisms, first is increased water holding capacity of soil (Yu et al. 2011) and second is absorption of water from rhizosphere which is then translocated to shoot and transpired via stomata, resulting in growth of maize. Similarly Chehab et al. (2017) reported highest total yield of olive fruits and oil in arid region of Tunisia, when olive plants were inoculated with SAPs (Stockosorb®660) under field condition. The author has correlated these observations with improved water status of soil due to addition of SAPs.

Plant growth is directly related to water contents, when water is added to soil, it transferred to plant for its growth. When water supply to plant is limited it results in restricted plant metabolism (Lee et al. 2001). Supplementation of SAPs to drought stress promotes efficiency in the use of rainwater hence confirms drought resistance in crops (Heschel et al., 2002). Supplementation of SAP to maize plants exposed to water deficit conditions showed improved photosynthesis, transpiration rate and stomatal conductance (Islam et al. 2011b). Furthermore Hou et al. (2018) confirmed improvement in soil properties, water use efficiency and increased yield of potato tuber when inoculated with SAPs.

Conclusion:

Drought stress continues to be a major constraint on agricultural productivity, especially in the face of climate change and increasing water scarcity. Addressing this challenge requires innovative and sustainable approaches that enhance plant tolerance to water deficit. The use of PGPB, Si and SAP offers a promising strategy to mitigate the adverse effects of drought stress. Each of these components contributes uniquely to promote plant growth in drought prone soil, PGPB through physiological and biochemical modulation, Si by reinforcing plant defense systems, and SAPs by improving soil water retention. Their application has shown potential to improve plant health, boost stress resilience and sustain yields under limited water conditions. Continued research into their mechanisms, synergistic effects and field-level implementation will be vital to fully harness their benefits. Ultimately, these eco-friendly tools can play a key role in developing resistant cropping systems and promoting sustainable agriculture in drought-prone regions.

Conflict of interest

The authors declare that they have no conflict of interest.

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