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Agro-techniques for moisture stress management in maize – A review

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Abstract

Maize is very sensitive crop to moisture deficit and its growth and development has significantly affected by water stress, with primary impact on plant morphology, cell ultrastructure and physiological process. This article highlights the effect of Pink Pigmented Facultative Methanotrophs, Brassinolides and Silicic acid as a drought mitigating agent. It is a well-known fact that plant physiological processes like stomatal conductivity, photosynthesis and respiration are severely affected by water deficit with further implications on the metabolic activity such as carbohydrate and energy synthesis as well as carbohydrate translocation and utilization. Even though maize possesses mechanisms to anticipate the negative effects of water deficits such as accumulation of silicon in leaf surface, production of antioxidants, osmolytes and heat shock proteins. Their protective capacity depends on the extent of the stress and also on the timing as well as the way stress occurs as either sudden or gradual. Reduction in growth, reproduction and quality parameter are inescapable when water deficit conditions override the plant's protective mechanisms. However, advances are being made at the physiological level entailing identification of exogenous or endogenous substances that can ameliorate the negative effects of drought.

Keywords: Maize, pink pigmented facultative methanotrophs, brassinolides and silicic acid

Introduction

Maize (*Zea mays* L.) is a most important cereal crop and grown in all over the world under a wide range of climates. The current crisis in agricultural production revolves around many issues and ineffective water management is one among them. Irrigation water is becoming a critical scarce resource and expensive due to higher demand by industry and urban consumption and on another side ground water is depleting at an alarming rate (GOR, 2007) [40] and therefore farming strategies to reduce irrigation water losses and enhance crop water productivity (WP) need special attention. Approximately, one third of the cultivated area of the world suffers from chronically inadequate supplies of water (Massacci *et al*., 2008) [90]. Water deficit is the major abiotic factor limiting plant growth and crop productivity around the world (Kramer, 1983) [64] which is responsible for severe yield reduction in maize by 40% on a global scale (Daryanto *et al*., 2015) [27].

Drought stress is considered to be a moderate loss of water, which leads to stomatal closure and limitation of gas exchange. Stomatal closure decreases water loss, and the movement of CO_2 into the plant. Moreover, photosynthetic rate of the leaves decreases as the relative water content and leaf water potential decrease (Lawlor and Cornic, 2002) [67]. Ennahli and Earl (2005) [30] reported that, under moderate stress, the photosynthetic rate remained unaffected with significant decrease in the carboxylation while, under severe water deficit both photosynthetic rate and concentration of CO_2 at the site of carboxylation decreased. Photosynthesis plays a major role in determining crop productivity in all species and is directly affected by water stress.

Pink pigmented facultative methylotrophic bacteria (PPFM) are associated with the roots, leaves and seeds of most terrestrial plants and utilize volatile C1 compounds such as methanol generated by growing plants during cell division (Irvine *et al*., 2012) [50]. Increasing CO_2 concentration inside stomata leading to accelerated rate of photosynthesis and decreased the rate of photorespiration in C3 plants (Wingler *et al*., 2000) [137]. During dry spell PPFM exudates osmoprotectants (sugars and alcohols) on the surface of host plants and this matrix helps to protect the plants from desiccation and high temperature (Xoconostle *et al*., 2010) [138].

Silicon is an important element and plays an important role in tolerance of plants to

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environmental stresses (Savant *et al.*, 1999) [119]. Increased Silicon (Si) supply improves the structural integrity of crops and may also improve plant tolerance to diseases, drought and metal toxicities (Ma, 2004) [77]. Silicon can alleviate water stress by decreasing transpiration as Si is deposited beneath the leaf cuticle forming a Si-cuticle double layer. Hence, transpiration through the cuticle will be decreased. Silicon can reduce the transpiration rate by 30% in rice, which has a thin cuticle (Ma *et al*., 2001). Si-induced growth improvement under water-deficit conditions has been observed in different species such as wheat (Gong and Chen, 2012) [38], rice (Chen *et al*., 2011), and soybean (Shen *et al*., 2010) [125].

Brassinolide has emerged as a new phytohormone with pleiotropic effect (Sasse, 1997) [118], and influences varied physiological processes like germination, growth, flowering, senescence and confers resistance to plant against various abiotic stresses. As the first steroidal plant growth regulator was isolated from the pollens of rape (Brassica napus), a generic name “Brassinosteroids” has been given to this new group of phytohormones. Brassinosteroids improve the resistance of plants against environmental stresses such as water stress, salinity stress, low temperature stress and high temperature stress (Rao *et al*., 2002) [110]. Ryu *et al*. (2007) [114] concluded that brassinolide was critical for signaling in plant growth and development. Applying exogenous PGRs was one way to reduce destructive effects of abiotic stress (Yuan *et al*., 2010) [140]. Zhang *et al*. (2004) [144] reported that the plant growth regulators like benzyladenine and brassinolide significantly increased leaf water potential and improved chlorophyll content in soybean under water deficit condition. Li *et al*. (2009) [69] revealed that, Robinia pseudoacacia seedlings treatment with 0.2 mg l^{-1} brassinolide decreased the transpiration rate, stomatal conductance and malondialdehyde (MDA) content of seedlings growing under moderate or severe water stress compared to untreated seedlings. Exogenous application of substances can ameliorate the negative effects of drought (Bayat and Sepehri, 2012) [15].

Pink Pigmented Facultative Methylobacteria (PPFM)

The genus, Methylobacterium, is a group of facultative and aerobic in nature, utilizes single carbon compounds such as methanol, formate, formaldehyde, methylamine, and also uses a wide range of multi-carbon compounds as growth substrates (Green, 2006) [41]. One group of methylotrophs is distinguished as pink pigmented facultative methylotrophic bacteria (PPFM) because of their pink to red colony formation in selective isolation media.

Pink pigmented facultative methylotrophic bacteria (PPFM) are associated with the roots, leaves and seeds of most terrestrial plants and utilize volatile single carbon compounds such as methanol generated by growing plants during cell division (Irvine *et al*., 2012) [50].

1. Effect of Pink pigmented facultative methylobacteria on crop production

The bacteria use single carbon compounds produced by the plants in return they can produce plant growth regulators and positively influences the plant growth and survival. Many researchers found that, PPFM has been positively driven the agricultural systems, by improved seed germination, crop yield, resistance to pathogen and drought stress tolerance. Methylobacterium is a symbiotic-bacteria which consumes waste material produced by the plants and produce useful metabolites to the plant (Holland, 1997) [47]. Several beneficial aspects of methylobacterium have been reported such as the production of vitamin B12 (Basile *et al*., 1985) [14], production of urease (Holland, 1997) [47], stimulation of seed germination and plant growth (Holland, 1997) [47], production of auxins (Abanda *et al*., 2006) [1], cytokinins (Koenig *et al*., 2002) [62], and 1-aminocyclopropane-1-carboxylate (ACC) deaminase (Madhaiyan *et al*., 2005) [81].

Increasing CO_2 concentration inside stomata led to accelerate the rate of photosynthesis and decrease the rate of photorespiration in C3 plants (Xoconostle *et al*., 2010) [138] because the competition between CO_2 and O_2 for rubisco enzyme. Kolb and Stacheter (2013) [63] reported that the generation of CO_2 from methanol can also occur by PPFM.

2. Effect of PPFM on Seed germination and seedling establishment

The pervasive epiphytic species of Methylobacterium genus plays a vital role in promotion of seed germination and establishment (Holland, 1997) [47]. Madhaiyan *et al*. (2004) [84] found zeatin and cytikinin in PPFM treated maize seedling which enhanced the seed germination and plant growth. Furthermore, production of vitamins and growth regulators by the PPFM on phyllosphere region of the plant improved the vigour of the seedling in maize. Similarly, foliar application of PPFM increased the nitrogen use efficiency in rice seedlings, in connection to that the plant metabolic activities have been elicited (Madhaiyan *et al*., 2004) [84]. When the seeds are treated with Methylobacterium sp. germination percentage was increased by 19.5% compared to control. Seedling establishment has promoted by producing plant growth regulators and stimulating germination (Madhaiyan *et al*., 2006) [80].

Lee *et al*. (2006) [68] conducted study on rice seedling and found increased crop growth rate (20.51%) and drymatter accumulation than control. From the result, it could be concluded that treating seedling with PPFM stimulates the seed germination and improves seedling vigor and biomass production by inducing and regulating the plant growth hormone production and also raising the nitrogen fixation.

Methylobacterium induce production of urease enzyme and other growth regulators like IAA and cytokinin which has a direct influence on plant growth and development (Omer *et al*., 2004) [99]. Methylobacterium has a role in reducing the ethylene concentration in leaves by hasten the production of 1-aminocyclopropane-1-carboxylate (ACC) deaminase, furthermore it produces siderophores and induce systemic resistance against pathogens (Idris *et al*., 2006). PPFM produces plant growth hormones which is responsible for plant tolerance to biotic and abiotic stresses by inducing system resistance (Madhaiyan *et al*., 2007) [82], and was found to increase the net photosynthetic rate by regulating the stomatal conductance, increasing chlorophyll content and malic acid concentration in leaves (Cervantes *et al*., 2005) [20]. Increased nitrogen fixation in green gram due the presence of PPFM was studied by Selvakumar *et al*. (2008) [122].

Pink pigmented facultative methylobacteria are well known for their plant growth enhancement and induced systemic resistance in plants, suggesting the possibility of PPFM as a means of biological control of biotic and abiotic stresses.

3. Effect of PPFM on growth hormones

Ivanova *et al*. (2000) [51] revealed that phytohormones synthesized by plants were found to be necessary for phytopathogenic and phytosymbiotic microorganisms and aerobic methylobacteria were able to synthesize cytokinins. They are also of vital importance for invitro manipulations of plant cells and tissues.

Omer *et al.* (2004) [99] conducted a colorimetric assay on sixteen PPFM cultures and found positive results on the presence of auxin and IAA compounds in three cultures. Then the three cultures are further tested with High Performance Liquid Chromatography in combination with Nuclear Magnetic Resonance. From the result it could be concluded that, the production of IAA stimulated by L-tryptophan.

In water deficit condition plant arouses the ethylene production and reduces the new cell formation which leads to abnormal growth of a plant (Mattoo and Suttle, 1991) [91]. Anu Rajan (2003) [10], for the first time reported the production of gibberellic acid by Methylobacterium sp. which acted as plant growth regulator by modifying plant morphology. (Madhaiyan *et al.*, 2012) [83] conducted a study on canola seedlings and found that, treating the seedlings with deaminase in Methylobacterium fujisawaense and M. Oryzae has been found to lower the ethylene levels and promotion of root elongation and was due to the production of ACC under gnotobiotic conditions. The presence of 1-aminocyclopropane-1-carboxylate deaminase (ACCD) reacts in the phyllosphere region of rice seedlings treated with methylobacteria strain was accessed and its role in regulating the ethylene level was detected (Chinnadurai *et al.*, 2009) [25].

4. Effect of PPFM on moisture deficit management in crops

PPFM affects the plants positively by production of auxin and cytokinins and influences the root growth to make it grow deeper for avoiding the moisture stress in dry condition. It increases the stomatal count, chlorophyll and malic acid concentration in leaves thereby increasing the net photosynthetic rate (Cervantes-Martínez *et al.*, 2004) [21]. Mirakhori *et al.* (2009) [93] concluded that methanol spraying had a positive effect on root area to leaf area ratio of soybean. Research on sugar beet showed that methanol foliar application led to increased root length and root volume under drought stress. (Chandrasekaran and Chun, 2016) [22] noticed that application of 2 per cent PPFM recorded an increased root length, root volume, leaf area and specific leaf weight in tomato.

There are two major mechanisms of PPFM which could help the plant to have normal growth and development even in the dry condition and induce early germination and root extension hence the plants send their roots deeper rapidly and gain competitive advantage than shallow rooted plants. Second, PPFM exudate sugars and alcohols on leaf surface which acts as a osmoprotectants. This matrix helps the plant to protect from desiccation and high temperature (Irvine *et al*., 2012) [50]. Sivakumar *et al.* (2017) [130] revealed that PPFM (2%) was found superior in improving RWC, photosynthetic rate, SPAD value and proline content. The antioxidant enzyme, catalase activity was enhanced by PPFM (2%). PPFM (2%) treatment gave statistically superior relative water content of 64.42 per cent followed by brassinolide (62.66%) and salicylic acid (61.24%) at 60 DAT in tomato.

5. Effect of PPFM on yield

Madhaiyan *et al.* (2012) [83] observed the application of PPFMs as a foliar spray significantly increased plant height and boll numbers of cotton. Increase in growth, yield and juice quality of sugarcane has reported by Madhaiyan *et al.* (2005) [81]. Radhika *et al.* (2008) [107] observed that significantly higher maize grain yield (7941 kg ha^{-1}) was recorded in PPFM @ 5 litres ha^{-1} foliar applied plots. Significantly increased grain yield was due to increase in size and weight of cob and higher number of grains per cob. Similar results were reported in soybean, foliar application of methanol increased the yield up to 38% (Nadali *et al*., 2010) [97].

Keerthi *et al.* (2015) [58] conducted a study on irrigated greengram and found that the foliar spray of TNAU pulse wonder and pink pigmented facultative methylotrophs (PPFM) on one week after flowering and 1% KNO3 at 50 per cent flowering produced significantly higher dry matter production of 2865 kg ha^{-1} and yield attributes viz., number of pod clusters plant^{-1} (10.34), number of pods plant- (53.40), number of seeds pod^{-1} (13.23), pod length (8.77 cm) and seed test weight (3.42 g), grain yield (1775 kg ha^{-1}), haulm yield (2920 kg ha−1), harvest index (0.38), net return (57,806 Rs. ha−1) with B:C ratio (2.43).

Rajasekar *et al.* (2016) [108] also noted that irrigation at IW/CPE of 0.8 with mulching and foliar application of PPFM registered more cotton kapas yield. Similarly, Kannan (2017) stated that foliar application of PPFM @ 500 ml ha^{-1} on 75 and 90 DAS significantly enhanced the number of fruiting points, number of bolls, boll setting percentage, boll weight and seed cotton yield.

Chandrasekaran *et al.* (2017) [23] reported that the exogenous application of PPFM significantly increased the fruits, fruit weight and fruit yield in tomato under water stress condition. Application of PPFM isolates significantly increased growth, biomass production and yield of paddy. PPFM treated paddy plants recorded the highest grain yield of 46.30 g hill^{-1} whereas the control recorded a grain yield of 33.65 g hill^{-1} (Nysanth *et al.*, 2019) [98].

Brassinolide (BR)

Brassinosteroids are the naturally occurring growth promoting steroidal lactone acting as PGRs in crop plants. Brassinosteroid is a compound (C28 H48O6) with a molecular weight of 480.69. Brassinosteroids are a class of polyhydroxysteroids that is considered as a sixth class of plant hormones. 'Brassinolide' is the first isolated brassinosteroid from the pollen of Brassica napus in 1979, which caused stem elongation and cell division. Several studies showed that exogenously applied brassinosteroids are effective in controlling plant growth under stressful conditions.

Several steroidal compounds related to brassinolide have been discovered from a wild range of micro and macro flora and they are collectively called as brassinosteroids (BRs) (Takatsuto, 1994; Fujioka and Sakurai, 1997) [132, 36]. Brassinosteroid is plant growth hormone which positively affects the plants by increasing stem elongation, pollen tube formation, modulating leaf orientation in the joints, controls leaf rolling, activates proton pumps, reorienting the cellulose microtubules, and xylogenesis as well as elevated ethylene production when it is applied exogenously (Sasse, 1997; Yokota, 1997) [118, 139].

BRs is a natural hormone with non-toxic, non-mutagenic and environmentally friendly in nature, it is more effective at low concentrations (0.1 to 1 ppm), ease of application due to the fact they are destined to agriculture use (Kang and Guo, 2011; Zhang *et al.*, 2014) [55, 144].

1. Effect of brasinolide on plant growth and development

Brassinosteroids is found in all plant species with low concentrations and it is considered to be essential for normal growth and development of plants (Sasse, 1997) [118]. Vardhini *et al.* (2006) [135] conducted a study on groundnut and found that, seed treatment with 24-epibrassinolide and 28-homobrassinolide promoted the germination and seedling growth of groundnut.

Pre-treatment with brassinolide stimulated germination and seedling emergence of aged rice grains. Seeds soaked in brassinolide exhibited an increase in α-amylase activity (Hayat *et al*., 2003) [46]. Ryu *et al.* (2007) [114] concluded that brassinolide was critical for signaling in plant growth and development. Applying brassinosteroids cause an increase in plant biomass (Li *et al*., 2009) [69], PGRs was one way to reduce destructive effects of abiotic stress (Yuan *et al*., 2015) [141].

Foliar spray of eBR at 0.5 µM to 2.0 µM concentrations significantly enhanced the rate of shoot length, root length, photosynthetic, non-photosynthetic pigments and biochemical constitutions. Among the concentrations, only 1.0 µM was found to be useful in triggering the growth responses. Thus, the exogenous application of BR proved to be physiologically and biochemically efficient in improving the vegetative growth of cowpea (Asha and Lingakumar, 2015) [12].

Essential oil content in the peppermint plants sprayed with 0.5 ppm of 24-epibrassinolide was significantly higher than that in control plants. BR also modified essential oil composition. Especially important is that, 24-epibrassinolide had positive effects on menthol content; the highest menthol content was found in plants treated with 0.5 ppm 24-eBL (Çoban and Baydar, 2017) [26].

BRs promote the activation as well as synthesis of enzymes responsible for the formation of chlorophyll. BRs regulate different components of photosynthetic machinery like photochemistry, stomatal conductance and enzymes of calvin cycle. BRs promote photosynthetic carbon fixation by altering the functioning of stomata (Siddiqui *et al*., 2019) [128].

2. Effect of brasinolide on abiotic stress management

Brassinolide caused increased NR activity in maize and rice (Mai *et al*., 1989; Shen *et al*., 1990) [86, 126], chlorophyll in maize (Shen *et al*., 1990) [126], membrane integrity in maize and wheat (Shen *et al*., 1990; Kulaeva *et al*., 1991) [126, 65]. Anuradha and Rao (2001) [136] observed that, treatment with 24-epibrassinolide or 28-homobrassionolide enhanced the germination percentage, shoot length, fresh weight, dry matter accumulation and soluble protein content in rice seedlings under salt stress. Exogenous application of brassinolide enhances the nucleic acids and soluble protein content which promotes plant growth under salt stress condition. It had a pleiotropic effect and influences plant physiological processes such as growth, seed germination, rhizogenesis, senescence and leaf abscission.

Foliar application of brassinolide @ 0.5 ppm increased the activity of rubisco by improved efficiency of photochemical reaction and with ultimately enhanced the rice yield (Maibangsa *et al*., 2000) [87]. Farahat (2002) [33] observed increased crude protein content, carbohydrates and oil contents in fenugreek seeds treated with foliar application of brassinolide 0.5 ppm. Rice seedling treated with brassinolide had a significant influence on CAT, SOD, GR activities and APX activity under saline condition (Muradi *et al*., 2003) [96]. Senthil *et al.* (2003) [123] found that foliar treatment with 0.5 ppm brassinolide on soybean showed a significant increase in chlorophyll content. Ali *et al.* (2008) reported that brassinolide treatment improved the germination percentage, root length, root dry weight and dry matter production under high salinity doses in mungbean.

Maize crop was adversely affected the relative water content and protein content by water logged condition during seedling stage than other stages, while foliar application of brassinolide increased the plant protein content, dry matter production and yield under water logged condition (Otie *et al*., 2019) [100].

3. Effect of brassinolide on water deficit management

Several researches have investigated the effect of brassinolids on plants exposed to drought. Schilling *et al.* (1991) [121] conducted a study on drought imposed on sugar beet crop and found that, application of homobrassinolide significantly increased tap-root length and diameter, which in turn to raise the yield of sugar beets furthermore it enhanced the sucrose content and quality. Foliar application of homobrassinolide found to increase the relative leaf water content and chlorophyll content led to increased net photosynthetic rate and biomass production of wheat under water deficit condition (Sairam, 1994) [117].

Brassinosteroids are found to induce drought tolerance through altering the metabolic processes. Sairam *et al*. (1996) [116] found that, treating the seeds with 0.5 ppm brassinolide will improve the seed germination and seedling growth under water stressed situation by inducing α-amylase activity. Exogenously applied brassinolide alleviated the detrimental effect of water stress in maize and remarkably improved the leaf water potential, chlorophyll & proline content, and enzymatic antioxidants (Anjum *et al*., 2011) [9].

Sairam (1994) [117] conducted a study on two wheat cultivars (C306 – drought tolerant; HD 2329 – drought susceptible) under water deficit condition and found that, foliar application of brassinolide 0.05 ppm increased the water uptake and membrane integrity. Between the two tested genotypes of wheat crop brassinolide has more influence on drought-tolerant genotype C306 than HD 2329 under drought condition. Homobrassinolide application at 0.05 ppm in wheat significantly reduced the membrane damage by 63% and 45% in C306 and HD 2329 respectively than control due to increased membrane integrity.

In greengram by foliar application of brassinolide up to 1.0 ppm registered to increase photosynthetic rate by 15.22, 16.30 and 17.66 µmol m-2 sec^{-1} at 0.1, 0.5 and 1.0 ppm respectively whereas control recorded lower photosynthetic rate of 14.62 µmol m-2 sec^{-1} on vegetative stage and the same trend followed in flowering stage (Lal *et al*., 2013) [66]. Ananthi and Vanangamudi (2013) [8] conducted a study on green gram and found that transpiration rate and stomatal conductance were 3.38 and 33.18 at 0.1 ppm of brassinolide applied plot (7.98% and 5.5% more than control); 3.52 and 34.98 at 0.5 ppm (12.46 and 11.22% more than control) and 3.7 and 36.10 at 1.0 ppm(18.21 and 14.78% more than control) on vegetative stage but on flowering stage it recorded 4.39 and 38.06 at 0.1 ppm concentration (5.02 and 4.33% more than control), 4.56 and 8.48 at 0.5 ppm concentration (9.09 and 8.48% more than control) and 5.46 and 41.05 at 1.0 ppm concentration(30.6 and 12.31% more than control). The transpiration rate and stomatal conductance were also recorded more at flowering stage.

Zhang *et al.* (2004) [144] reported that plant growth regulators like benzyladenine and brassinolide increased the leaf water content and improved chlorophyll content in soybean under water deficit condition. Enhanced activity of anti-oxidative enzymes in 24- epibrassinolide applied plants reduced the effect of oxidative stress. It could be concluded that, the decrease in malondialdehyde (MDA) content along with increased antioxidant enzyme activity mitigated damage caused by water stress (Zhang *et al*., 2008) [145].

Li *et al*. (2009) [69] conducted a study on the growth and survival of Robinia pseudoacacia seedlings under drought condition and found decreased the transpiration rate, stomatal conductance and malondialdehyde (MDA) content in brassinolide at 0.2 mg per liter of water foliar applied seedlings in water stressed plants compared to control. While, relative leaf water content, soluble sugar content, proline content increased in brassinolide treated plants. Similarly, the activity of superoxide dismutase (SOD), peroxidase (POD) and catalase (CAT) were greater. From the study it could be concluded that, foliar application of 0.2 mg L^{-1} of brassinolide can ameliorate the effects of water stress and enhance drought resistance of Robinia seedlings.

BRs were found to reduce the impact of PEG – induced osmotic stress on seed germination and seedling growth of sorghum cultivars under water stress wherein BRs increased the soluble proteins, free proline, catalase (CAT) activity and lowered peroxidase (POD) and ascorbic acid activities (Vardhini *et al.,* 2006) [135]. Similarly, 28-homoBL also mitigated the oxidative stress in salt treated maize plants by enhancing the SOD activity (Bhardwaj *et al*., 2007) [17].

Sivakumar *et al.* (2017) [130] conducted a study on tomato and found that the foliar application of brassinolide improved the photosynthetic rate up to 30.57 per cent under drought stress conditions than control. Significantly higher photosynthetic rate was observed in brassinolide (36.43 µmol CO2 m-2s^{-1}) followed by PPFM (2%) treatment (35.80 µmol CO2 m-2s^{-1})

4. Effect of brasinolide on yield and yield components

Fujii *et al.* (1991) ascertained that brassinolide improved the translocation of nutrients resulting in higher number of grains per panicle which contributed towards the increased grain yield of rice. The promoting effect was also observed on yield and yield components such as number of grains panicle, test weight, number of panicles per plant and harvest index (Sairam, 1994) [117].

Bhatia and Kaur (1997) [18] observed increased greengram yield in brassinolide applied plot which was due to the enhanced photosynthetic efficiency and translocation of metabolites to the reproductive sinks. Similarly, Ramraj *et al.* (1997) [109] reported that application homobrassinolide through foliar application was most effective on improving yield of various crops. In hybrid rice seed production foliar application of homobrassinolide 0.1 ppm combine with gibberellic acid 60 ppm increased seed production capacity by increased number of productive tillers, number of seeds per panicle, per cent of seedset and test weight (Thirthalingappa *et al*., 1999) [133].

Jin and Chen (1999) [53] observed that foliar application of natural brassinolide during tillering and booting stage increased rice grain yield of rice. Maibangsa *et al.* (2000) [87] noticed that foliar application of 0.5 ppm brassinolide at booting and ear emergence stage increased the tillering capacity, number of seeds per panicle, seed setting percentage, test weight, grain yield and harvest index compared to control. Foliar application of brassinolide at 0.1 ppm improved the rice grain and straw yield under lower solar radiation condition (Kanojia, 2006) [57]. Bera *et al.* (2014) [16] observed that, foliar application of 0.1 ppm epibrassinolide twice at 45 and 60 days after sowing increased the productivity of seed yield in sunflower by 32.9 percent than control.

Joseph (2000) [54] found increased groundnut pod yield in brassinolide applied plants. Brassinosteroids improved the growth and yield of tomato under field conditions were reported by Varduini and Rao (2001) [136]. Brassinolides were recognized as a crop growth regulator thereby improving the translocation of sugars and metabolites led to increased level of soluble proteins, enzymes, rate of nitrogen fixation and seed yield during the harvest time in rape seed (Fariduddin *et al*., 2003) [34]. Brassinolide application at 0.1 ppm resulted in higher dry matter production and grain seed yield in blackgram. While the total protein content of seeds was also found improved due to brassinoliode treatment (Jeyakumar *et al*., 2008) [52].

Silicon

Earth crust consists of 27.7% of silicon which is the next most abundant element after oxygen (46.6%) a mineral substrate for most of the plant life. Generous researches indicate that, silicon plays a major role in plant growth and mineralization. Furthermore, it improves the plant cell integrity and resistance to most of the biotic and abiotic stresses (Epstein, 1999; Savant *et al*., 1999) [31, 119]. Silicon remains in the soil with high concentration while not readily uptaken by the plants. Plants absorb silicon in the form of mono-silicon acid (H_4SiO^4) (Martin *et al*., 2017) [89].

Among the silicon formulations oligomeric silicic acid is the only stable compound with high concentration even at pH above 9. Most of the soils and natural water bodies consist of undissociated monomeric silicic acid (Dietzel, 2000) [28] as only sources of silicon. Knight and Kinrade (2001) [61] described that monomeric silicic acid (H_4SiO_4) disassociates into H^{++} and $H_3SiO_4^-$ when the pH ranges between 9 to 11 while at pH above 11 it furthermore disassociates into $2H^{++}$ and $H_2SiO_4^{2-}$.

Mitani *et al*. (2009) [95] found a transporter (ZmLsi1) for silicon present in plant roots which was responsible for the transport of Silicon from external solution and one more transporter gene (ZmLsi6) found in the root xylem which functions as a silicon transporter in xylem unloading.

Silicon uptake has been studied in most of the plant species including both silicon accumulating as well as non-accumulating plants, and found that there are three modes of silicon uptake in plants as observed. Silicon have been actively observed in monocots especially in paddy and sorghum, some plants accumulate passively such as cucumber and bottle gourd while some plants exclude silicon absorption (tomato and other vegetable) hence called as non-accumulators. The silicon accumulation has been categorized based on the ratio of silicon to calcium in the plants (Savant *et al*., 1996) [120].

Generally, most of the monocots accumulate more silicon and dicots are moderate in nature while some plants are rarely excluded because of having lower tendency towards the silicon accumulation. Many plant species accumulate silicon adequately with a level of 0.1% in their cell tissue. Most of the monocots and some dicots become stunted in growth and weaker in plant structure under silicon deficit condition which led the plants to become more susceptible to biotic and abiotic stresses (Epstein, 1999) [31].

In general plants belonging to Graminae family accumulate more silicon than that of other plants species. Within the Graminae family maize, wheat and sorghum accumulate higher amount of silicon in their shoots but the magnitude of accumulation is lower than that of rice and sugarcane (Ma *et al*., 2004; Mitani and Ma, 2005; Liang *et al*., 2006) [77, 94, 70]. Mali *et al.* (2008) [88] found that, most of the dicot plants absorb silicon by passive absorption while legumes can efficiently exclude Si from their roots. Plants divested of Si absorption often shows a relatively low development and reproduction, which depends on the type of plant species.

Saeed *et al.* (2005) [115] found that, application of silicic acid as a fertilizer with 0.25 to 0.50 per cent increased the germination per cent of wheat. But when its concentration exceeds the limits it was found to be harmful and affected the germination rate as well as the total crop stand and yield.

1. Effect of Silicon on Water Stress management

Water deficit reduces the relative leaf water content leading to stomatal closure and subsequent reduction in photosynthesis. Silicon application alleviates the moisture stress and maintains good relative water content in the plant by decreasing transpiration. Transpiration mainly occurs through stomata and partly by the cuticle. Foliar application of silicon gets deposited beneath the leaf cuticle and forming a Si-cuticle double layer preventing cuticular transpiration (Ma *et al*., 2004) [79].

In normal growing condition plant did not shows silicon deficiency although silicon containing fertilizers are continuously applied to many crops including sugarcane (Savant *et al*., 1999) [119] and rice (Pereira *et al*., 2004) [103] for increasing yield and quality. Silicon fortification improves the plant physical strength and gives tolerance to pest, diseases infestation and also alleviates moisture stress and metal toxicity (Epstein, 1999; Richmond and Sussman, 2003; Ma, 2004) [31, 111, 77]. In water deficit condition the ameliorative role of silicon was more profound than in plant grown under well moisture condition (Ma *et al*., 2001) [78].

Yield components are significantly influenced by silicon application in both rice and barley plants. Even under water deficit condition silicon application maintains higher moisture content in spikelet which helps in increased level of grain filling (Seo and Ota, 1982) [124]. Ma and Takahashi (2002) [75] conducted a study on rice and found that, plants with higher silicon content had more amounts of polysaccharides present in the cell wall compared to plants with low silicon content. From the study it suggests that silicon has a role in cell wall mechanical properties and water permeability. Silicon application reduced the transpiration rate by 30% in rice, which has a thin cuticle was reported by Ma *et al*. (2004) [79]. Exogenous application of inorganic nutrients like silicon is a viable strategy for overcoming moisture stress in plant (Ashraf and Foolad, 2007) [13].

Water transport in root was mainly through silicification endodermal tissue which plays a major role in water transport across the root of rice (Lux *et al*., 1999) [73] and sorghum (Lux *et al*., 2002) [74]. The level of silicon consumption and deposition in leaf surface by sorghum plants (Lux *et al*., 2003) [72], indicates the important role of silicon in water transportation and maintenance of water potential under drought condition. Gong *et al*. (2008) [39] reported that, silicon treatment produced drought tolerance in wheat plants through increase in antioxidant defense, thereby oxidative stress on functional molecules of cells has been reduced. With presence of silicon, sorghum plant recorded higher water potential and dry matter production compared to control (Hattori *et al*., 2007) [45]. Silicon applied wheat plants maintained higher water content and dry matter accumulation under water deficit condition compared to no silicon applied plants (Gong *et al*., 2008) [39]. Exogenous application of silicon increased the root-shoot ratio due to the facilitation of better root growth, therefore photosynthetic rate and stomatal conductance were enhanced in cucumber under water deficit condition (Hattori *et al*., 2008) [44].

Silicon triggered growth increase under water deficit condition has been studied in different crops such as soybean (Shen *et al*., 2010) [125] rice (Chen *et al*., 2011) [24] and wheat (Gong and Chen, 2012) [38]. Moisture stress amelioration effect of silicon was studied in many crops viz., wheat (Tahir *et al*., 2006) [131], tomato (Romero-Aranda *et al*., 2006) [113], soybean (Shen *et al*., 2010) [125], sorghum (Ahmed *et al*., 2011) [4], rice (Kim *et al*., 2012) [60] and sugarcane (Bokhtiar *et al*., 2012) [19].

Gong *et al*. (2008) [39] conducted a study on wheat and found that, the effect of silicon application on plant physiological and biochemical parameters were pronounced when the plants are exposed to water stress. Under drought situation silicon applied plants explicated higher antioxidant defense mechanism to relief functional molecules form oxidative damage and maintained increased plant photosynthetic rate (Liu *et al*., 2015) [71]. Under drought stress condition plant root growth and root dry weight have been significantly reduced which tend to reduce the nutrient uptake, dry matter production and water use efficiency of wheat cultivars. Root plays a vital role in nutrient and water uptake hence reduction in root growth directly affects the synthesis and translocation of assimilates While, under moisture stress condition silicon application has increased all the parameters in wheat (Maghsoudi *et al*., 2015) [85].

In barley the spikelets without silicon content recorded higher transpiration loss (20.2%) than spikelets containing silicon (7.6%) during development and ripening stage (Ma *et al*., 2003). The result suggests that, silicon plays a vital role in maintaining higher moisture content in the spikelet through controlling transpiration from cuticle under water deficit condition. Gao *et al.* (2006) [37] observed lower stomatal transpiration rate in silicon applied plants, suggesting that silicon have been involved in stomatal movement. Under water deficit condition silicon content was increased in the hull up to 7.2 per cent in rice grain while it was 1.6 per cent in barley. Silicon deposition occurs between the cell wall and cuticle and forms a cuticular silicon double layer. Hull consist no stomata and the transpiration occurs only through cuticle hence silicon is more effective on controlling transpiration in the cuticle (Pandey and Shukla, 2015) [101].

The regulation of gas exchange attributes of plants by Si under drought stress has also been revealed in many studies (Gao *et al*., 2006; Zhang *et al*., 2013; Putra *et al*., 2015) [37, 143, 106]. Si pretreatment was demonstrated to up-regulated the expression of both ring domain containing protein OsRDCP1 gene and drought-specific genes, OsCMO coding rice choline monooxygenase and dehydrin OsRAB16b, in drought-stressed rice plants as compared to control (Khattab *et al*., 2014) [59]. However, in some plants such as rice, soybean and pepper (*Capsicum annuum* L.) silicon application increased transpiration rate as well as photosynthetic rate under moisture stress (Rizwan *et al*., 2015) [112].

Si supply has been widely reported to decrease oxidative damage through enhancing the antioxidant enzyme (SOD, APX, CAT and POD) activities under drought stress in chickpea (Gunes *et al.*, 2007) [42], sunflower (Gunes *et al.*, 2008) [43], wheat (Ahmed *et al*., 2011) [4] and tomato (Shi *et al*., 2016) [127].

Silicon fortification reduces the yield loss due to water stress by conserving water potential through reduced transpiration rate and membrane permeability under water-deficit conditions in different crop species viz., rice (Agarie *et al.*, 1998; Ming *et al*., 2012) [2, 92], wheat (Gong and Chen, 2012; Maghsoudi *et al*., 2015) [38, 85], maize (Amin *et al*., 2014) [6].

2. Effect of Silicon on Yield

Proper silicon fertilization maintains leaf erectness become more important for higher photosynthetic rate in low land rice (Elliott and Snyder, 1991) [29]. Ahmad *et al*. (2013) conducted a study on rice and found silicon application increased photosynthetic rate of 10 per cent than control by improving the leaf erectness and consequently increased the productivity.

Prakash *et al*. (2011) [104] conducted a study on wetland rice and found that, foliar spray of silicic acid at 2, 4 ml l^{-1} increased the grain and straw yield and application of 8 ml l^{-1} decreased the yield. Foliar spray of silicic acid at 4 ml l^{-1} effectively increased the yields than all other treatments. The content and uptake of silicon in grain and straw was recorded higher with the foliar spray of silicic acid than control.

Pati *et al.* (2016) [102] conducted a study on alluvial zone of West Bengal and found that foliar application of silicon significantly increased grain and straw yield as well as yield-attributing parameters such as plant height (cm), number of tillers m^{-2}, number of panicle m^{-2}, and 1000 grain weight (g) of rice.

Application of oligochitosan and oligochitosan nanosilica increased the soybean seed yield by 10.5 and 17.0% respectively than control. From the results, it could be suggested that radiation degraded oligochitosan and its mixture with nanosilica can be potentially used for cultivation of soybean with enhanced seed yield (Van Phu *et al*., 2017) [134].

The yield components like number of primary and secondary branches per panicle, panicle length, spikelet length, test weight, harvest index and grain yield; quality parameters like starch content and protein content in grains were positively influenced with foliar application of silicon and this influence was more in reproductive stage of silicon application in paddy (Anand *et al*., 2018) [7].

Conclusion

At present, water stress management studies in maize were very few with irrigation system, mulching, foliar application of nutrients are the major areas focused. In this chapter moisture stress management studies in maize have been reviewed. Timely implication of moisture stress management practice through exogenous application of substances can ameliorate the negative effects of drought. Foliar application of PPFM @ 1%, brassinolide @ 0.1 ppm and Silicic acid @ 0.2% are used for enhancing growth and yield for various crops but information on their combined effects are limited in moisture stress management and especially in maize. Hence, the present investigation was carried out for effective management of water deficit in maize.

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