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# Effect of bio-silica on drought tolerance in plants

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**Abstract.** Drought is considered the single most devastating environmental stress, which decreases crop productivity more than any other environmental stresses. The main consequences of drought in crops are reduced rate of cell division, leaf size, stem elongation, root proliferation, disturbed stomatal oscillations, plant water and nutrient relations with diminished crop productivity. Many studies demonstrated that the deposition of silica in plant tissues can reduce drought stress. Silicon (Si) has beneficial effects on many crops, mainly under biotic and abiotic stress. Despite its abundance, silicon is never found in plants in an available form and is always combined with other elements, usually forming oxides or silicates. Monosilicic acid ($H_4SiO_4$) is the form of silicon used by plants, which is found both in liquid and adsorbed phases of silicon in soils. The concentration of the $H_4SiO_4$ in soil solution is influenced by the soil pH, clay, minerals, organic matter and Fe/Al oxides/hydroxides, which are collectively related to the geological age of the soil. Furthermore, to improve plant-available Si in the soil, silicate solubilizing microorganisms (SSM) are potentially useful in solubilizing insoluble forms of silicate. This paper aimed to review an important issue of bio-silica effects on plants under drought stress and water deficiency.

## 1. Introduction

Drought is one of the gravest threats to plants, and due to global warming; its prevalence is increasing worldwide [1]. Approximately one-third of the world land area is prone to drought [2]. Drought induces various changes in morphological, metabolic, or/and physiological functions of plants. At the initial phase of plant growth and establishment, it negatively affects both elongation and expansion growths [3, 4]. Reduced leaf growth and in turn the leaf areas and higher root/shoot ratio in response to drought has also been reported in many species [5]. Severe water stress poses injurious effects on plant water relations, photosynthesis, ion uptake, and nutrient metabolism and assimilates partitioning [5, 6]. Interrupted water supply from the xylem to the surrounding elongating cells under drought stress leads to loss of turgor and stomatal closure [7]. It also disturbs the photosynthetic apparatus through its interaction with UV or/and visible radiation [8]. Both stomatal and nonstomatal limitations are generally considered to be the main determinant of reduced photosynthesis under drought stress [6]. Ma and Yamaji [9] stated that the beneficial effects of Si on plant growth are commonly observed in plants under stress conditions. From a physiological point of view, for the growth and development of plants, silicon has demonstrated beneficial effects on the growth and development of plants in the increased production of various crops. Application of silicon may be a facile means to increase crop yield during drought. Moreover, because silicon can improve drought tolerance of plants, its application may help reduce the need for irrigation.

Silicon (Si) plays an important role in plant health when plants are exposed to multiple stresses. As a physicomechanical barrier, Si is part of the epidermal cell walls and vascular tissues in stems, pods, leaves and bark [10]. According to [11] and [12] indicated that Si might decrease the negative effects of oxidative stress and offer slight resistance to some abiotic and biotic plant stressors. Thus, using Si instead of herbicides and pesticides could reduce harmful environmental effects [13-15]. Some studies indicate that Si application is able to avoid the damage of the plant when grown under drought stress conditions [16-20].

Unfortunately, many soils are considered lack of available silicon that has positive impact on plants by stimulating nutrient uptake and plant photosynthesis, decrease susceptibility to disease and insect damage, alleviate water and various mineral stresses and decrease the toxic effects of aluminum and heavy metals [21-26]. Furthermore, microorganisms play an important role in the weathering of silicate minerals. We found that solubilisation of silica *in situ* in soil by silicate solubilising bacteria to supplement crop would beneficial to improving drought tolerance. This paper aimed to review an important issue of bio-silica effects on plants under drought stress and water deficiency. This may be a promising strategy for improvement of soil and plant productivity.

## 2. Silicon in Soil

Silicon (Si) is the second most abundant element after oxygen in the soil. Silicon dioxide comprises 50–70% of the soil mass. Therefore, all plants rooting in soil contain some Si in their tissues. However, the role of Si in plant growth and development was overlooked until the beginning of the 20th century [27, 28]. In nature, silicon occurs generally in the form of silicates, including ferromagnesian silicates (e.g. olivine, pyroxenes, and amphiboles), aluminosilicates (e.g. feldspar, mica, and clays), and silicon dioxide (e.g. amorphous silica, quartz). In general, the silicon in silicate minerals is surrounded by four oxygen atoms in tetrahedral fashion [29]. Silicon content in soil varies from 50 to 400 g Si per kg of soil [14]. In soil, Si compounds mainly present as $SiO_2$, about 50–70% of the soil mass, and in various aluminosilicate forms [30]. Although Si is abundant in soil, most of its sources are not available for plant uptake due to the low solubility of Si compounds in soil [31, 32, 33]. Bio cycling of silica in the soil also occurs through microbial activities that involve fungi, bacteria, and actinomycetes. Thus, plants and microbes, through their intricate interplay with soil minerals, contribute appreciably to the global silicon cycle.

## 3. The Function of Silicon in Plants

Silicon (Si) is an abundant element which, when supplied to plants, confers increased vigour and resistance to exogenous stresses, as well as enhanced stem mechanical strength. Plant species vary in their ability to take up and to accumulate Si under the form of silicon dioxide ($SiO_2$) in their tissues. Silicon as a macroelement has a vital role in plants cycles. This element is the eighth most common element in nature and the second most common element found in the soil after oxygen. One of the main functions of Si is improving the plant's growth and yield, especially in stress condition. To achieve plant tolerance, Si promotes plant photosynthesis by favourably exposing leaves to light. On the other hand, the role of the macroelement has proven to be in response to different abiotic and biotic stresses [34]. Monocots usually accumulate more Si than dicots; however, the impact of Si on dicots was greater, notably on economically important dicots. This is a subject requiring further study [35]. One major contribution of Si is a reinforcement of cell walls by deposition of solid silica. It is translocated from the roots as silicic acid [$Si(OH)_4$] through the xylem until deposition under the cuticle and in intercellular spaces. These silica bodies are called phytoliths, or plant opal. These structures are very resistant to decomposition. In addition to naturally occurring soluble Si in the soil, many crops respond positively to additions of supplemental Si.

Plants, especially grasses, can take up large amounts of Si contributing to their mechanical strength. Besides a structural role, Si helps to protect plants from insect attack, disease, and environmental stress. For some crops, Si fertilization of soils increases crop yield even in unfavourable growing conditions and in the absence of disease. The mechanism of Si in triggering a range of natural defences is through hydrolytic enzymes and some active compounds as well. The presence of Si stimulates activities of chitinase, peroxidase, polyphenol oxidases, and flavonoid phytoalexins which providing protection against fungal pathogens [22]. Regardless of the mechanism, some observed benefits due to Si nutrition include (i) direct stimulation of plant growth and yield through more growth and plant rigidity, (ii) suppression of plant diseases caused by bacteria and fungi (such as powdery mildew on cucumber, pumpkin, wheat, barley; gray leaf spot on perennial ryegrass; leaf spot on Bermuda grass; rice blast), (iii) improved insect resistance (such as suppression of stem borers, leaf spider mites, and various hoppers), (iv) alleviating various environmental stresses (including lodging, drought, temperature extremes, freezing, UV irradiation), (v) and chemical stresses (including salt, heavy metals, and nutrient imbalances).

## 4. Effect of Bio-Silica on Drought Tolerance

Drought is one of the most limiting environmental stresses for plant production [36]. The growth and development of plants experiencing occasionally periods of drought depend on the ability of stomata to control water loss. Plants respond to drought by closing their stomata, which reduces leaf transpiration and prevents excessive water loss in their tissues. The control of leaf stomata closure is a crucial mechanism for plants since it is essential for both $CO_2$ acquisition and desiccation prevention [37]. Leaf water potential and water content decrease substantially when plants are exposed to drought [6]. Application of silicon can significantly improve water status in non-irrigated crops. Based on our research, the application of silicate solubilizing bacteria (SSB-bio-silica) on oil palm seedling have a significant effect on stomatal opening in the period after drought stress treatment (**Figure 1**).

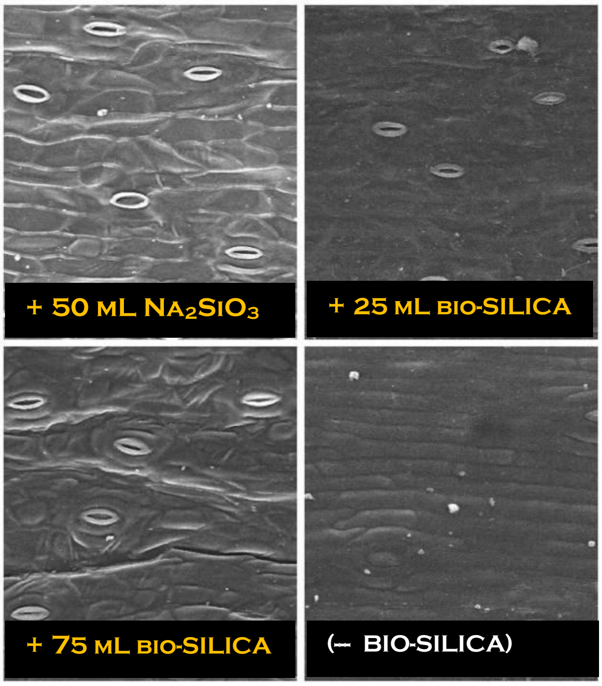
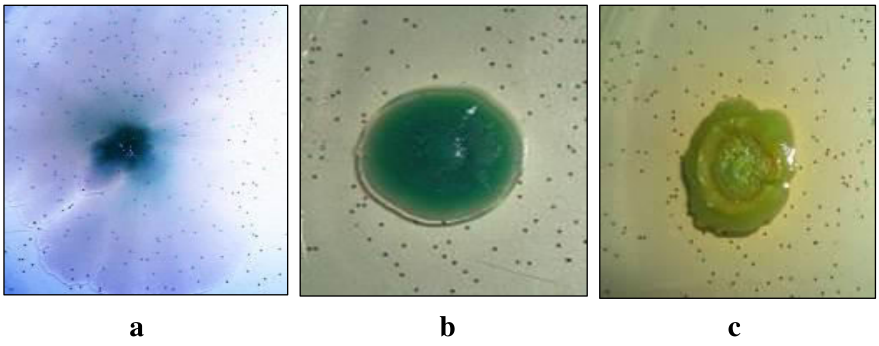


**Figure 1.** Scanning electron microscopy of oil palm leaf surfaces showing open stomata in application $Na_2SiO_3$ and Bio-Silica and closing stomata in treatment without application Bio-Silica in the period after drought stress treatment.

Silicate solubilizing bacteria (SSB) occurring in soil and rhizosphere, solubilize silica and render it available to plants. Inoculation of SSB with organosiliceous rice straw, husk and husk ash (black char/ash) to rice was found enhancing the growth, chlorophyll content, thousand grain weight, matured grains, biomass and yield [38]. The SSB inoculation along with fly ash to rice reduced the incidence of stem borer, leaf folder and gall midge and increased the yield [39]. Our study indicated that application bio-silica on oil palm seedling improved total chlorophyll in leaf up to 20% compared to control.

Microorganisms are able to degrade silicates including aluminium silicates. In the course of the metabolism in microbes, numerous organic acids are produced and have a twin position in silicate weathering. They supply $H^+$ ion to the medium and promote hydrolysis. Natural acids like citric, oxalic acid, keto acids, and hydroxy carbolic acids which form complexes with cations, promote their elimination and retention within the medium in a dissolved state. Santi and Goenadi [40] reported that *Burkholderia cenocepacia* KTG, *A. punctata* RJM 3020, and *B. vietnamiensis* ZEO3 have shown to accelerate the solubilization of $SiO_2$ originated from quartz. The amount of Si, Ca, and Mg solubilized from quartz mineral were optimum in 96 hours incubation periods. All isolates were gram-negative, a rod shape, producing exo polysaccharide, organic acid (citric, acetic, and oxalic acid), and have several different of biochemical reactions specific to each. Acetic acid was predominant substances produced by SSB isolates in liquid Bunt and Rovira media.

Several mechanisms of silicate dissolution by SSB involving acidolysis, alkaline hydrolysis, ligand degradation, enzymolysis, capsule adsorption, extracellular polysaccharides and redox play a role in the bacterial dissolution of silicate. Acidolysis is the major mechanism of weathering silicate minerals [41]. In our research, *B. cenocepacia* KTG, *A. punctata* RJM3020, and *B. vietnamiensis* ZEO3 isolates were capable of solubilizing silicates and produced acid as detected by yellow halo formation on solid Luria Bertani media containing 0.2% (v/v) bromophenol blue (**Figure 2**). As an acid-base indicator, bromophenol blue useful range lies between pH 3.0 and 4.6. It changes from yellow at pH 3.0 to blue at pH 4.6. The colour change on solid Luria Bertani medium amended with 0.2% (v/v) bromophenol blue from blue into yellow or greenish-yellow indicating pH drop through the release of organic acid into the medium by SSB inoculant [40].



**a** **b** **c**

**Figure 2.** The growth of *Burkholderia cenocepacia* (a); *Aeromonas punctata* (b); and *Burkholderia vietnamiensis* (c) in solid Luria Bertani medium amended with 0.2% (v/v) Bromophenol Blue. The yellow zone indicates the ability of the isolates to generate organic acids.

According to Vandevivere [42], *Bacillus mucilaginosus* increases the dissolution rate of silicate and alumino-silicate minerals and releases the $K^+$ and $SiO_2$ from the crystal lattice primarily by generating organic acids. However, this hypothesis is controversial and *B. mucilaginosus* is also thought to accelerate the dissolution of a variety of silicates by the production of extracellular polysaccharides (EPS). The action of microorganism and chemical reactions in the soil make the silicon available to the plants. The primary and secondary silicate minerals in rocks are mineralized through microbial metabolism and chemical reactions, where the silica is converted and made available to plants. Bacterial metabolic activity in relation to micronutrient fixation in plants is the predominant role in these PGPR organisms like iron bacteria, sulphur bacteria, silicon mobilizing bacteria [43]. Bacteria when applied to root, cause an alteration in the rhizosphere, where its population persist and has a continuously increases in the ecosystem.

Silicon accumulation in plants is controlled by the ability of roots to take up Si. Deposition of silicon in root tissues, plants absorb Si as silicic acid [$Si(OH)_4$], an uncharged monomeric molecule, when the solution pH is below 9 [27]. Plants differ greatly in their ability to accumulate Si, ranging from 0.1% to 10.0% Si (dry weight) [28]. Factors such as soil pH, temperature, water conditions, the presence of cations, and organic compounds in solution influence the formation of soluble silicic acid and thus affect silicon accumulation in plants [44]. At the pH levels of most agricultural soils, $H_4SiO_4$ concentration in soil solution ranges from 0.1 to 0.6 mM [45]. Absorption of $H_4SiO_4$ takes place at the lateral roots via active, passive, and rejective mechanisms [46]. It is believed that in high Si accumulators, the amount of $H_4SiO_4$ taken up by active mechanism is greater than concentrations taken by mass flow because of the high density of Si transporters in roots and shoots facilitating $H_4SiO_4$ movement across root cell membranes [47]. The $H_4SiO_4$ absorbed by root's cells is deposited into leaf epidermal cells. The amount of literature documenting the benefits of Si on plants is vast and primarily highlights the value of Si fertilization in maintaining plant productivity under stressed conditions [48]. The established Si-induced mechanisms to improve plant resistance to biotic and abiotic stresses take place in the soil, the root system, and inside the plant [49]. Our research has shown that bio-silica application on oil palm seedling can enhance root growth under drought conditions. It has been demonstrated that deposition bio-silica occurs in endodermis part of roots oil palm seedling (**Figure 3**).

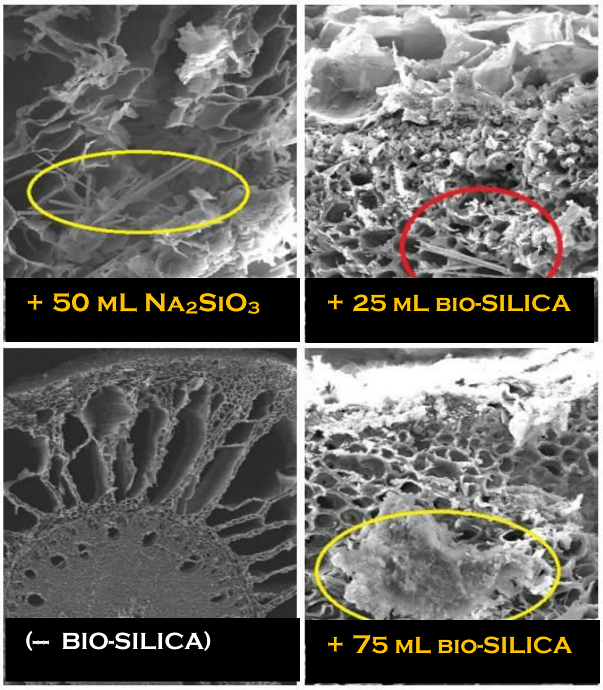


**Figure 3.** Scanning electron microscopy deposition of Si in root tissue of oil palm seedling by application bio-silica.

In drought-stressed sorghum [50] observed a significantly lower shoot/root ratio and higher root dry mass accumulation in silicon-applied plants compared with plants not treated with silicon, indicating that silicon facilitates root growth during drought. Ahmed *et al* [51] suggested that silicon application is mainly beneficial to the growth of sorghum root, allocating more matter to the plant root system grown hydroponically. The simulative effect of silicon on root growth may be due to enhanced root elongation as a consequence of enhanced cell wall extensibility in the growth zone, as observed in sorghum [52]. However, the beneficial effects of silicon on root growth under drought were not observed in some plants such as wheat, cucumber, and sunflower [12]. These observed differences may be related to culture conditions and plant species/cultivars. Nutrient uptake is related to root surface area and length. An increase in the surface area provides more exposed sites for uptake of diffusible ions. Silicon-mediated enhancement of root growth may, therefore, stimulate nutrient absorption and increase drought tolerance. In some studies, although silicon did not stimulate root growth under drought, silicon application, in fact, increased water uptake [53], thereby contributing to stimulation of nutrient uptake. The increased water uptake upon silicon addition under drought was due to the improved hydraulic conductance of roots [54] and root activity [55]. These studies suggest that silicon application may improve plant growth under drought by balancing nutrient uptake. Further investigations will be needed to determine how silicon regulates water uptake by roots and affects root anatomical characteristics to better understand the mechanisms of silicon promoted plant growth. Nutrient uptake is related to root surface area and length. An increase in the surface area provides more exposed sites for uptake of diffusible ions.

## 5. Conclusions

Due to several positive effects on the alleviation of different forms of biotic as well as abiotic stresses, silicon (Si) has been a focus of plant biology and agronomy research in recent decades. Silicon has numerous functions on plant physiology, and its most significant effects are focused on the cell wall. The presence of silicon in the cell wall increases their strength, resistance to salinity, drought tolerance, and photosynthetic activity. The beneficial effects of silicon are mostly on abiotic stresses such as drought. Oil palm seedlings treated with bio-silica grown in drought conditions displayed higher stomatal conductance than drought-stressed plants without bio-silica application. Silicon, especially refer to bio-silica can enhance root resistance to drought and promotes root growth. The other important role of bio-silica in reducing the adverse effects of stress may be by improving soil conditions. Therefore, bio-silica could be used as a growth regulator to improve plant growth and resistance to stress conditions. There is a need for applied research to evaluate water use efficiency and drought tolerance on more crops and areas.

## 6. References

[1] Yang S, Vanderbeld B, Wan J and Huang Y 2010 *Mol. Plant* **3** 469
[2] Wei L, Jia L, Hu X and Zhao F 1997 *Agric. Res. in the Arid Areas* **15** 66
[3] Kusaka M, Ohta M and Fujimura T 2005 *Physiol. Plant.* **125** 474
[4] Shao H B, Chu L Y, Shao M A, Jaleel C A and Hongmei M 2008 *Comptes Rendus—Biologies* **331** 433
[5] Jaleel C A, Manivannan P and Wahid A 2009 *Int. J. Agric. Biol.* **11** 100
[6] Farooq M, Wahid A, Kobayashi N, Fujita D and Basra S M A 2009 *Agric. Sust. Dev.* **29** 185
[7] Taiz L and Zeiger E 2006 *Plant Physiol.* (Sinauer, Sunderland, Mass, USA, 4th ed.)
[8] Garc´ıa-Plazaola J I and Becerril J M 2000 *Trees* **14** 485
[9] Ma J F and Yamaji N 2008 *Cell. Molecular Life Sci.* **65** 3049
[10] Siddiqui M H and Al-Whaibi M H 2014 *Saudi J. Biol. Sci.* **21** 13
[11] Liang Y, Sun W, Zhu Y G and Christie P 2007 *Environ. Pollution* **147** 422
[12] Pei Z F, Ming D F, Liu D, Wan G L, Geng X X, Gong H J and Zhou W J 2010 *J. Plant Growth Regulation* **29** 106
[13] Vasanthi N, Saleena L M and Raj S A 2012 *World Appl. Sci. J.* **17** 1425
[14] Balakhnina T and Borkowska A 2013 *Int. Agrophys.* **27** 225
[15] Karmollachaab A, Bakhshandeh A, Gharineh MH, Moradi Telavat MR and Fathi G 2013 *Internat. J. Agron. Plant Prod.* **4** 30

[16] Sacala E 2009 *J. Elementol.* **1** 619
[17] Bocharnikova E A and Benes S 2011 *Proc. Int. Conf. on Silicon in Agriculture* (Beijing: China)
[18] Son MS, Song JY, Lim MY, Sivanesan I and Jeong BR 2011 *Proc. Int. Conf. on Silicon in Agriculture* (Beijing: China) p1
[19] Mauad M, Crusciol C A C, Nascente A S, Filho H G and Lima G P P 2016 *Rev. Ciênc. Agron.* **47** 532
[20] Hajiboland R, Cherghvareh L and Dashtebani F 2017 *J. Plant Process Function* **5** 1
[21] Currie HA and Perry CC 2007 *Ann. Bot.* **100** 1383
[22] Heckman J 2013 *Better Crops* **97** 14
[23] Adrees M, Ali S, Rizwan M, Zia-Ur-Rehman M, Ibrahim M, Abbas F, Farid M, Qayyum MF and Irshad M K 2015 *Ecotoxicol. Environ. Saf.* **119** 186
[24] Ng L C, Anuar S N A, Jong J W and Elham M S H 2016 *Asian J. Plant Sci.* **15** 92
[25] Sakr N 2016 *J. Plant Protec. Res.* **56** 331
[26] Khalifa M M A, Nashwa A H, Fetyan, Magid M S A and El-Sheery N I 2017 *J. Agric. Res.* **6** 376
[27] Epstein E 1999 *Ann. Rev. Plant Physiol. Plant Mol. Biol.* **50** 641
[28] Richmond K E and Sussman M 2003 *Curr. Opin. Plant Biol.* **6** 268
[29] Gauger T, Byrne J M, Konhauser K O, Obst M, Crowe S and Kappler A 2016 *Earth and Planetary Sci. Lett.* **443** 81
[30] Sommer M, Kaczorek D, Kuzyakov Y and Breuer T 2006 *J. Plant Nutr. Soil Sci.* **169** 310
[31] Guntzer F, Keller C, Poulton P R, McGrath S P and Meunier J D 2012 *Plant Soil* **352** 173
[32] Rizwan M, Ali S, Ibrahim M, Farid M, Adrees M, Bharwana SA, Rehman M Z, Qayyum M F and Abbas F 2015 *Environ Sci. Pollut. Res.* **22** 15416
[33] Peera S K P G, Balasubramaniam P and Mahendran P P 2016 *J. Appl. Nat. Sci.* **8** 55
[34] Sahebi M, Hanafi M M, Nor Akmar A S, Rafii M Y, Azizi P, Tengoua F F, Azwa J N M and Shabanimofrad M 2015 *BioMed. Res. Int.* 1
[35] Luyckx M, Hausman J F, Lutts S and Guerriero G 2017 *Plants* **37** 1
[36] Kramer P J and Boyer J S 1995 *Water relations of plants and soils* (San Diego: Academic Press)
[37] Dodd I C 2003 *J. Plant Growth Regulation* **22** 32
[38] Muralikannan N 1996 *Thesis* (Coimbatore: Tamilnadu Agricultural University) p 125
[39] Chandramani P, Rajendran R, Muthiah C and Chinnaiah C 2010 *J. Biopesticides* **3** 423
[40] Santi L P and Goenadi D H 2017 *Menara Perkebunan* **85** 1
[41] Sheng X F, Zhao F, He LY, Qiu G and Chen L 2008 *Can J. Microbiol.* **54** 1064
[42] Vandevivere P, Welch S A, Ullman W J and Kirchman D L 1994. *Microb. Ecol.* **27** 241
[43] Gholami A, Shahsavani S and Nezarat S 2009 *World Acad of Sci Enginer and Tech* **49** 19
[44] Liu WG, Wang LQ and Bai YH 2003 *Acta Bot Boreali Occidentalia Sin* **23** 2248
[45] Knight CTG and Kinrade SD 2001 *Silicon in Agriculture* (Studies in Plant Science vol 8) ed Datnoff LE, Snyder GH, and Korndörfer GH (Amsterdam: The Netherlands Elsevier) p 57
[46] Cornelis JT, Delvauz B, Georg RB, Lucas Y, Ranger J and Opfergelt S 2011 *Biogeosciences* **8** 89
[47] Mitani N and Ma JF 2005 *J. Exp. Bot* **56** 1255
[48] Li QF, Ma CC and Shang QL 2007 *The journal of applied ecology* **18** 531
[49] Brenda ST, Babu T and Datnoff LE 2016 *Soil Science* **181** 1
[50] Hattori T, Inanaga S, Araki H, An P, Morita S, Luxová M and Lux A. 2005 *Physiol Plant* **123** 459
[51] Ahmed M, Hassen FU, Qadeer U and Aslam MA 2011 *Afr J Agric Res* **6** 594
[52] Hattori T, Inanaga S, Tanimoto E, Lux A, Luxova M and Sugimoto Y 2003 *Plant Cell Physiol* **44** 743
[53] Sonobe K, Hattori T, An P, Tsuji W, Eneji AE, Kobayashi S, Kawamura Y, Tanaka K and Inanaga S 2011 *J Plant Nutr* **34** 71

[54] Hattori T, Sonobe K, Inanaga S, An P and Morita S 2008 *J Plant Nutr* **31** 1046
[55] Chen W, Yao XQ, Cai KZ and Chen J 2011 *Biol Trace Elem Res* **142** 67