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Role of Silicon in Sugarcane: A Review

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ABSTRACT

Silicon (Si), the second most abundant element in earth crust (28.8%) after the oxygen (47%), is usually found as silicates or metasilicates. Most soils contain Si content in the range of 14 to 20 mg Si/l. In spite of its abundance in the biosphere, it is usually sparingly soluble and limited in availability; essentiality of Si as an essential nutrient for higher plants is difficult to prove. Sugarcane, a typical Si accumulating plant is known to absorb a large amount of silica from the soil. The benefits of Si for sugarcane were realized for the first time at Hawaii, where field amended with Si-rich compounds had significantly higher cane yield as compared to untreated control. This review is an attempt to discuss the role of silicon on nutrient uptake, alleviating biotic and abiotic stresses along with reported physio-biochemical attributes in sugarcane.

Key words: Abiotic stress, Biotic stress, Silicon, Sugarcane, Yield attributes.

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Fragmentation of Silicon from soil minerals is a slow process and its adsorption or resorption by the soil particles along with a continuous monoculture of crops may cause its reduction to the level that soil amendment with soluble Si sources is required to achieve high yields. Generally, Si is considered a "quasi-essential" nutrient element for plants that plays an important role in promoting plant growth, improving tissue strength and resisting various biotic and abiotic stresses (Epstein, 1994, 2009; Ma *et al*., 2001, Vasanthi *et al*., 2014). Several reports are available on role of silicon in plant health and ecology (Cooke and Leishman, 2011), specifically in alleviating abiotic and biotic stresses *viz.*, water and salinity stress, metal toxicities, nutrient imbalance, fungal and bacterial pathogens and insect herbivores, *etc*. (Ma, 2004; Datnoff *et al*., 2007; Liang *et al*., 2007; Epstein, 2009; Reynolds *et al*., 2009; Zhu and Gong, 2014; Adrees *et al*., 2015). Plants absorb silicon as monosilicic acid (H_4SiO_4), which is present in small quantities up to 2 mmol, depending upon the soil type (Jones and Handreck 1967; Fox *et al*. 1967). The solubility of silicic acid in soil solution is strongly pH-dependent; highest at low pH and decreases progressively up to a pH of 9.8. At 9.8 pH, silicate anion is maximally adsorbed to soil surfaces, especially Al and Fe hydrous oxides, causing reduction in Si concentration in soil solution. Members of the grass family, such as sugarcane (*Saccharum species hybrids*) and rice (*Oryza sativa* L.), accumulate large amounts of Si (>1.0% shoot Si dry mass) and capable of removing up to 470 and 700 kg Si ha^{-1} $year^{-1}$, respectively (Ma and Takahashi, 2002, Meyer and Keeping, 2000, Ross *et al*., 1974; Savant *et al*., 1997, 1999; Meena *et al*., 2014). Si as biogenic silicon ($SiO_2 \cdot nH_2O$) is localized in and between epidermis and cuticle as well as in phytoliths. Phytoliths are amorphous silicon dioxide (SiO_2) incrustation that occur in and between the cells and tissues of plants (Shakoor and Bhat, 2014). Silicon is accumulated in plants higher than the essential major nutrients. Although it is not considered as an essential element it is accepted as an agronomically beneficial element as it confers rigidity and strength, resistance against pests and diseases, improves water economy by reducing transpiration rate, alleviates the ill effects of abiotic stresses and enhances crop yield (Vasanthi *et al*., 2014). Silicon has been documented to have potential roles in reducing incidence of crop lodging, pest and pathogens, water loss by evapo-transpiration and heavy metal toxicities. As silicic acid, Si catalyzes various biochemical reactions within plants, while the polymerized silicic acid integrates firmly into the structural matter, provides mechanical strength and also acts as a physical barrier for insect, pest and pathogen infestation. Si suppresses brown spot, stem rot, sheath brown rot in rice and *Fusarium* wilt and *Corynespora* leaf spot on cucumber (Datnoff *et al*., 2002) and also increases resistance to the fungal disease in cucumber roots (Cherif *et al*., 1994). Silicon fertilizer has a double effect on the soil–plant system: (i) it improved plant-silicon nutrition reinforces plant-protective properties against diseases, insect attack and unfavorable climatic conditions. (ii) it optimizes soil fertility through improved water, physical and chemical soil properties and maintenance of nutrients in available forms (Meena *et al*., 2014). Depending on their SiO_2 content (as % shoot dry weight), plants can be divided into three major groups: wetland Gramineae, such as rice or horsetails (Equisetum) with 10-15%; dry land Gramineae, such as sugarcane and most of the cereal species and a few dicotyledons with 1-3%; and most dicotyledons, especially legumes, with 0.5% SiO_2 (Takahashi and Miyake, 1977). Plants take up different quantities of silica according to their plant parts in different species. Seed coat of rice, oat, rye and wheat accumulates most of the silica and least in grain. Although Si is not a nutrient, Si fertilization may be necessary in weathered soils where Si is depleted to obtain increased crop yield, especially for Si-accumulating sugarcane plant (Camargo and Keeping, 2021).

Silicon in sugarcane

Sugarcane (*Saccharum officinarum* L.) is the most adaptable plant under tropical and sub-tropical conditions. Among the C_4 plants, sugarcane is one of the most efficient crops exhibiting higher converting efficiency of solar radiation into photosynthates than any other crops evolved (Suganthi *et al*., 2019). It is one of the major cash crops, used for the production of sugar and bio-ethanol and many by-products like bagasse, molasses and press mud. Sugarcane wax is a value added product obtained by the processing of press mud (Mohan *et al*., 2021). Sugarcane bagasse is a significant renewable energy source for the sugar and bioethanol industries. Bagasse ash, the waste from the combustion process is rich in silica (SiO_2) and it is therefore an alternative source for silica extraction (Chindaprasirt and Rattanasak, 2020). The benefits of Si for sugarcane were realized at Hawaii in 1965, where field amended with Si-rich compounds had significantly higher yields compared to untreated control. It was observed that the leaves of sugarcane and bamboo had highest silica than other plant parts. Under certain conditions sugarcane may absorb more silicon than any other nutrient from the soil. In Puerto Rico, the above ground parts of a 12-month crop contained 379 kg ha^{-1} of Si, compared with 362 kg ha^{-1} of K and 140 kg ha^{-1} of N (Samuels, 1969). Leaf analysis can be a useful indicator of Si status indicating optimal growth and sugar yield with 0.60% Si content in leaf tissue (McCray and Mylavarapu, 2010). A recent survey of Florida sugarcane fields determined 10% production losses due to insufficient leaf Si content (McCray *et al*., 2010).

Nutrient uptake

Silicon plays an important role in inducing resistance to various biotic and abiotic stresses in plants, helps in controlling Al, Mn and Fe toxicities, increases P availability, reduces lodging and improves rate of photosynthesis by effective use of sunlight as well as efficient management of plant water economy. Silicate materials increased the levels of Si, P, Ca and Cu and reduced the levels of N, K, Mg, Fe, Mn and Zn in the leaf tissues. It also increased soil pH, soil Si, P, Ca and Mg contents (Elawad *et al*., 1982b). Several mechanisms have been reported for increase or decrease in the level of nutrient in leaf by silicate application; which include decrease in Fe and Mn uptake by plants due to enhanced oxidizing power of roots (Okuda and Takahashi, 1965), dilution effect due to the increased growth associated with Si addition, increase in Fe and Mn tolerance of plant tissue by Si (Horst and Marschner, 1978) and soil pH alterations (Samuels and Alexander, 1969) as Si is necessary for the normal growth of sugarcane (Elawad *et al*., 1982b). In sugarcane, effect of silicon (Si), applied as calcium silicate (Ca-silicate) (@ 0, 20, 40, 60, 80, 120 and 150 g/pot) was evaluated for leaf nutrient concentrations and soil fertility under greenhouse conditions in two different soil types (Bokhtiar *et al*., 2012). Results obtained indicated decreased iron, copper, zinc and manganese contents in leaf tissues with increasing silicate application. Soil pH, Si contents, available sulfur, exchangeable Ca and magnesium and cation exchange capacity were increased significantly, whereas aluminum contents decreased dramatically in both the soils when amended with Ca-silicate. Si-amended treatments significantly increased maximum dry matter and cane yield by 77% and 66% in soil 1 and 41% and 15% in soil 2, respectively. Results indicated that different soil fertility status and rates of Si application are important factors influencing the yield, growth parameters and nutrient contents of sugarcane leaf as well as soil properties. The decreasing effect of Si on both Mn and Fe content and uptake may be due to the promotion effect of Si on the oxidation power of the roots and thus decreased the solubility of Mn and Fe resulting in a depression of the uptake by rice (Okuda and Takahashi, 1962).

Effect of Si on abiotic and biotic stresses

Silicon (Si) is effective in alleviating both biotic and abiotic stresses in various crop plants (Yoshida, 1975). Sugarcane is strongly influenced by water deficit, especially when it occurs during critical growth phases (Boaretto *et al*., 2014) and Si application could be an alternative method to minimize the effects of this abiotic stress (Ming *et al*., 2012; Ma *et al*., 2016). Si enhanced protection against oxidative damage caused by the water deficit during the tillering phase (Verma *et al*., 2021). In Brazil, experiments were carried out by Bezerra *et al.* (2019) with sugarcane grown in polyethylene pots filled with soil under greenhouse condition using drought-tolerant (RB86-7515) and drought-sensitive (RB85-5536) cultivars with and without silicon fertilization and subjected to water deficit for 30 and 60 days during the tillering and grand growth phases. Silicon was applied @ 600 kg ha^{-1} Si as calcium magnesium silicate (108.4 g kg^{-1} Si; 274 g kg^{-1} Ca; 481 g kg^{-1} Mg), in furrows 11 weeks before planting. Silicon fertilization increased the Si levels in the leaves and improved physiological responses by increasing the water potential and relative water content in leaves during the tillering and grand growth phases. Additionally, Si increased proline concentrations and activity of superoxide dismutase (SOD) and ascorbate peroxidase (APX) in drought tolerant and sensitive cultivars under water deficit. These results suggested that Si could play a role in the detoxification of excessive reactive oxygen species (ROS) production by increasing proline levels or APX activities in sugarcane grown under water deficit.

To study the effect of silicon fertilizer on brown rust incidence, Camargo *et al*. (2013) have conducted several experiments for three years with pot grown sugarcane receiving four levels of silicon fertilizer (0, 185, 370, 555 kg ha^{-1} Si), with three different soil types (Quartzipsamment-RQ; RhodicHapludox-LV; Rhodic Acrudox-LVdf). There was a significant reduction in *brown rust incidence* due to increasing leaf Si concentrations in all soil types suggesting important role of Si fertilization in the management of brown rust for sugarcane. In year 2014, Camargo *et al.* have examined the effects of silicate fertilization on soluble Si concentration in soils, plant uptake and damage caused by the *stalk borer (Diatraea saccharalis)* in sugarcane under field conditions. Silicate placement at low rates (<200 kg ha^{-1} Si) in the furrow at the time of planting increased soluble Si in the soil, its uptake and sugarcane yield and reduced the stalk borer damage of *D. saccharalis*. Silicon concentration in the range of 0.1%-3.2% in sugarcane leaves resulted in increase in cane yield to the tune of 17-30% by reduced incidence of pest and diseases and increased frost resistance (Matichenkov and Calvert, 2002).

Impact of Si on physio-biochemical attributes

Besides its role in improving the resistant of sugarcane against pest and disease, Si is also known to act as an important enzyme regulator in sugar synthesis, storage and retention in the sugarcane (Meyer and Keeping, 2000, Wang *et al*., 2019). Silicon (Si), application as calcium silicate (Ca-silicate) @ 0, 20, 40, 60, 80, 120 and 150 g/pot) along with traditional fertilizers showed higher rate of Gas exchange characteristics such as photosynthesis, transpiration and stomatal conductance over unamended control (Bokhtiar *et al*., 2012). Results showed that as compared to unamended control, Si-amended treatments significantly increased maximum dry matter and cane yield by 77% and 66% in soil 1 and 41% and 15% in soil 2 with Si content up to 2.64% and 1.86% per dry mass in TVD leaf tissues (Bokhtiar *et al*., 2012). Sugarcane leaf freckling has been reported in soils having low amounts of soluble Si (Wong You Cheong *et al*., 1971; Clements *et al*., 1974; Gascho and Andreis, 1974; Gascho, 1979, 1978). Effect of silicate sources and rates on the incidence of leaf freckling and chemical composition of sugarcane variety 'C.P. 63-588 was examined by Elawad *et al*.(1982a). Application of 15 metric tons/ha of silicates increased leaf chlorophyll by 78 and 65% and decreased leaf freckling by 46 and 41% in plant and ratoon crops, respectively (Elawad *et al*., 1982b). Realizing potential role of Si in different crops, field experiments were conducted at ICAR-IISR experimental Farm, Lucknow to study the effect of silica on physio-biochemical attributes of sugarcane. Silica was applied as silica granules in the form of ortho silicic acid (OSA) provided by Privi Life Sciences Pvt. Ltd., Navi, Mumbai, India (Jain *et al*., 2017). The treatments comprised of control (T1), silica granules @ 20 (T2), 40 (T3) and 80 kg /ha (T4) and calcium silicate @ 2 t/ha (T5). Results obtained indicated higher shoot population, specific leaf weight (SLW) and total dry matter accumulation due to silica application. This may be due to the maintenance of high photosynthetic activity and efficient utilization of light and translocation of assimilated products to sink due to Si application as reported earlier by Rani *et al*. (1997) and Rohanipoor *et al*. (2013) in rice and maize plants. Jawahar and Vaiyapuri (2010) also reported higher dry matter accumulation in rice in presence of Si in the growing medium. Cane girth, height, weight and yield were increased due to silica application; highest increase in these traits was obtained in T3 (Si @ 40 kg/ha) treatment. Beneficial effect of Si in improving the growth and yield has been reported earlier in rice (Jawahar *et al*., 2015), sugarcane (Elawad *et al*., 1982a) and several dicots (Jones and Handreck, 1967). Juice quality attributes *viz.,* °Brix, sucrose % juice, juice purity, juice extraction, CCS per cent juice, S/R ratio and SPS activity were higher in silica treated plants relative to control.Silica application showed higher activity of sucrose phosphate synthase (SPS) enzyme at ripening phase as compared to control, highest was in T2 treatment. In contrast to SPS activity, soluble acid invertase (SAI) activity decreased due to silica application. Silica in the form of sodium metasilicate (SMS) is known to be strong inhibitor of acid invertase (Rosario and Santisopasri, 1977; Alexander, 1973; Batta *et al*., 1991) helps in improving sucrose content in cane stalk and controlling juice quality attributes. Compared to control, soluble silica content was significantly higher in leaf and root tissues of treated plants and it ranged between 1.28 and 4.28% in leaf and 0.36-1.5% in roots (Fig 1). Higher content of silica in leaf tissues of OSA treated plants (T2, T3 and T4) as compared to calcium silicate (T5) indicated that orthosilicic form of silica is highly soluble and readily transported to leaf lamina, while calcium silicate (T5) is relatively less soluble showing highest accumulation in root tissues. Findings suggested beneficial effect of silica granules in improving cane yield and juice quality of sugar cane (Jain *et al*., 2017).

Further, an impact of Si in the form of Silixol sugarcane was examined on growth and juice quality of sugarcane planpted during spring season at IISR farm, Lucknow (Jain *et al*., 2018). Treatments comprised two sets with three doses of Silixol @ 2 ml, 4 ml and 8 ml/l of water: Set I-application was done at five critical stages of growth and in Set II, Silixol was applied in every month till crop maturity. Silixol Sugarcane is a unique propriety formulation of orthosilicic acid obtained from Privi Life Sciences Pvt. Ltd., Navi, Mumbai, India. Silixol Sugarcane has a stimulatory impact on vegetative growth parameters (Fig 2). Silixol Sugarcane when used at 4 ml/l dose had exhibited positive effect. Increase in plant height could be due to deposition of silicon in the plant tissues causing erectness of leaves and stem (Yavarzadeh *et al*., 2008; Jain *et al*., 2017). Leaf area (ranged between 266.2 and 362.8 cm^2) increased in all the treatments as compared to untreated control. Application of orthosilicic acid formulation showed increase in specific leaf weight (Jain *et al*., 2017). Similar results were reported earlier in maize (Rohanipoor *et al*. 2013) following Si application.

Silixol sugarcane application showed improvement in fresh and dry weight of different plant parts at grand growth phase. Silicon accumulation in shoot epidermal tissues provides mechanical hardening to crop, which results in increase in dry matter of different plant parts (Ma *et al*., 2001). Application of Si in growing medium results in higher dry matter accumulation in rice (Jawahar and Vaiyapuri, 2010). Specific leaf weight (SLW) was relatively higher in Si treated plants as compared to untreated control. Activity of nitrate reductase, an indispensible enzyme for nitrogen metabolism, was improved by Silixol application. Silicon content determined in leaf tissues ranged from 1.98 to 3.42 per cent; highest was obtained with 8 ml/l Silixol and lowest in control plants. Silixol Sugarcane application had a positive influence on cane yield attributes *viz.*, cane length and girth, which contributed to more cane yield. Juice quality attributes *viz*., Brix, sucrose % juice, S/R ratio, were relatively higher in Silixol treated canes (Table 1) which might be due to role of silicon in cane ripening (Jain *et al*., 2017; Batta *et al*., 1991).

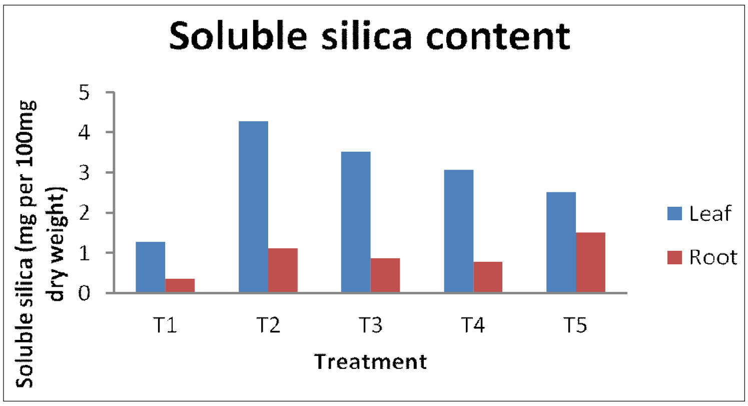

Fig 1: Soluble silica content in leaf and root tissues of sugarcane.
Control (T1), silica granules @ 20 (T2), 40 (T3) and 80 kg /ha (T4) and calcium silicate @ 2 t/ha (T5). Source: modified from Jain *et al.* (2017).

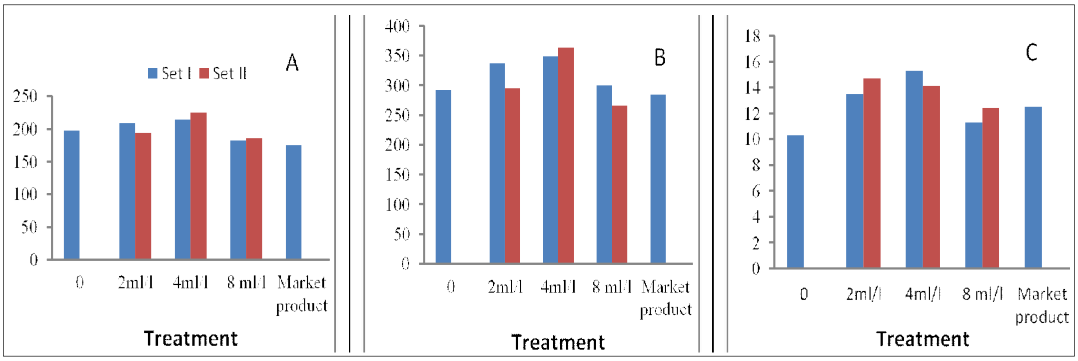

Fig 2: Effect of Silixol Sugarcane on vegetative growth parameters of sugarcane at grand growth stage. Treatments comprised of two sets with three doses of Silixol @ 2 ml, 4 ml and 8 ml/l of water: Set I-application was done at five critical stages of growth and in Set II, Silixol was applied in every month till crop maturity. A-Plant height (cm), B-Leaf area (cm^2), C-SLW (g dry weight/cm^2) (Source: Jain *et al*., 2018).

Table 1: Effect of Silixol Sugarcane on juice quality parameters at harvest (Source: Jain *et al*., 2018).

Treatments	°Brix		Sucrose % juice		S/R ratio	
	Set I	Set II	Set I	Set II	Set I	Set II
0	17.99±0.58		14.13±0.16		36.14±1.34	
2ml Silixol/l water	17.71±0.57	19.04±0.37	15.25±0.29	16.59±0.14	51.52±1.26	58.42±1.09
4ml Silixol/l water	18.18±0.49	18.87±0.15	15.37±0.22	16.72±0.44	60.73±1.19	65.31±0.98
8 ml Silixol/l water	18.27±0.45	19.31±0.08	16.01±0.12	16.84±0.04	51.98±1.23	54.13±1.74
Market product	18.24±0.44		16.13±0.49		43.13±2.04	

Mean value with±SE (n=3). Treatments comprised of two sets with three doses of Silixol @ 2 ml, 4 ml and 8 ml/l of water: Set I-application was done at five critical stages of growth and in Set II, Silixol was applied in every month till crop maturity.(Source: Jain *et al*., 2018).

Monthly application of silixol even at higher dose has shown positive response on plant growth and yield, indicating that the Silixol Sugarcane formulation is completely safe. Findings indicated that applications of silixol sugarcane @ 4 ml/l at five critical growth stages could lead to a yield increment up to 20 per cent.

CONCLUSION

This paper provides an overview of role of Si on sugarcane growth and highlights recent hypotheses and research findings on impact of silicon fertilizer improving nutrient availability, resistance to biotic and abiotic stresses and yield of sugarcane and several other crop species. Although Si, being a beneficial nutrient and required in very small amount, it is involved in regulating various plant metabolic processes, modulation of ROS species and antioxidant defense system and maintaining plant-water/ nutrient status, thereby providing tolerance to plants against biotic and abiotic stresses. Based on findings of experiments conducted at IISR, farm, using silica formulation in the form of silica granule and Silixol sugarcane, we found positive effect of Si on chlorophyll content, plant height, leaf area, dry matter accumulation, cane yield and juice quality attributes which confirmed that Si application is beneficial for sugarcane cropping system. However, it needs further exploration on forms and rates of silicon application for controlling pest and diseases, increasing resistance to water stress and improving sugarcane productivity and to develop economically viable and farmers friendly silicon technology for commercial application.

Conflict of interst: None.

REFERENCES

Adrees, M., Ali, S., Rizwan, M., Zia-ur-Rehman, M., Ibrahim, M., Abbas, F., Farid, M., Qayyum, F.M., Irshad, M.K. (2015). Mechanisms of silicon-mediated alleviation of heavy metal toxicity in plants: A review. Ecotoxicology and Environmental Safety. 119: 186-197.

Alexander, AG. (1973). A Comprehensive Study of *Saccharum* Source to Sink System. In: Sugarcane Physiology, Amsterdam: Elsevier Scientific Pub Comp, pp. 472.

Batta, S.K., Singh, J. Sharma, K.P. and Singh, R. (1991). Kinetic properties and inhibition of soluble acid invertase from sugarcane juice. Plant Physiology and Biochemistry. 29: 415-419.

Bezerra, B.K.L., Lima, G.P.P., Reis, A.R.D., Silva, M.D.A. and Camargo, M.S.D. (2019). Physiological and biochemical impacts of silicon against water deficit in sugarcane. Acta Physiologiae Plantarum. 41: 189. DOI: 10.1007/s11738-019-2980-0.

Boaretto, L.F., Carvalho, G., Borgo, L., Creste, L., Landell, M.G.A., Mazzafera, P. and Azevedo, R.A. (2014). Water stress reveals differential antioxidant responses of tolerant and non-tolerant sugarcane genotypes. Plant Physiology and Biochemistry. 74: 165-175.

Bokhtiar, S.M., Huang, H.R. and Li, Y.R. (2012). Response of sugarcane to calcium silicate on yield, gas exchange characteristics, leaf nutrient concentrations and soil properties in two different soils. Communications in Soil Science and Plant Analysis. 43: 1363-1381.

Camargo, M.S., Amorim, L., Gomes Júnior, A.R. (2013). Silicon fertilisation decreases brown rust incidence in sugarcane. Crop Protection. 53: 72-79.

Camargo, M.S., Korndörfer, G.H. and Wyler, P. (2014). Silicate fertilization of sugarcane cultivated in tropical soils. Field Crops Research. 167: 64-75.

Camargo, M.S. and Keeping, M.G. (2021). Silicon in Sugarcane: Availability in soil, fertilization and uptake. Silicon. 13: 3691-3701.

Cherif, M., Asselin, A. and Belanger, R.R. (1994). Defense responses induced by soluble silicon in cucumber roots infected by Pythium spp. Phytopathology. 84: 236-242.

Chindaprasirt, P. and Rattanasak, U. (2020). Eco-production of silica from sugarcane bagasse ash for use as a photochromic pigment filler. Scientific Reports. 10: 9890. https://doi.org/10.1038/s41598-020-66885-y.

Clements, H.F., Putman, E.W., Suehisa, R.H., Yee, G.I.N. and Wehling, M.L. (1974). Soil toxicities as causes of sugarcane leaf freckle, Macadamea leaf chlorosis (Keaau) and Maui sugarcane growth failure. Hawaii Agricultural Experiment Station,University, Technical Bulletin. No. 88 Honolulu, HI.

Cooke, J. and Leishman, M.R. (2011). Silicon concentration and leaf longevity: Is silicon a player in the leaf dry mass spectrum?. Functional Ecology. 25: 1181-1188.

Datnoff, L.E., Elmer, W.H. and Huber, D.M. (2007). Mineral Nutrition and Plant Disease. APS Press-The American Phytopathological Society. St. Paul, Minnesota, U.S.A. pp.278.

Datnoff, L.E., Brecht, M.O., Kucharek, T.A. and Nagata, R.T.(2002). The role of silicon in turfgrass disease management. Abstract of Second Silicon in Agriculture Conference. 105-110.

Elawad, S.H., Street, J.J. and Gascho, G.J. (1982a). Response of sugarcane to silicate source and rate. I. Growth and yield. Agronomy Journal. 74: 481-484.

Elawad, S.H., Street, J.J. and Gascho, G.J. (1982b). Response of sugarcane to silicate source and rate. II. Leaf freckling and nutrient content. Agronomy Journal. 74: 484-487.

Epstein, E. (1994). The anomaly of silicon in plant biology. Proceedings of National Academy of Sciences. U.S.A. 91: 11-17.

Epstein, E. (2009). Silicon: Its manifold roles in plants. Annals of Applied Biology. 155: 155-160.

Fox, R.L., Leva, J.A., Young, O.P., Pluncknett, U.L. and Hermaw, G.D. (1967). Soil and plant silicon and silicate response by sugarcane. Soil Science Society of America Proceedings. 31: 775-779.

Gascho, G.J. andreis, H.J. (1974). Sugar cane response to calcium silicate slag applied to organic and sand soils. Proceedings of International Society of Sugar Cane Technologists Congress. 15: 543-551

Gascho, G.J. (1979). Calcium Silicate Slag for Sugarcane in Florida. Part I. Agronomic response. Sugar y Azucar. 74: 28-32.

Gascho, G.J. (1978). Response of Sugarcane to Calcium Silicate Slag. I. Mechanism of response in Florida. Proceedings of the Soil and Crop Science Society of Florida. 37: 55-58.

Horst, W.J. and Marschner, H. (1978). Effect of silicon on manganese tolerance of bean plants (*Phaseolus vulgaris* L.). Plant Soil. 50: 287-303.

Jain, R., Singh, S.P., Singh, A., Singh, S., Tripathi, P., Ram, K., Gaur, A., Jain, N., Shukla, S.K. Chandra, A. and Solomon, S. (2017). Changes in growth, yield, juice quality and biochemical attributes of sugarcane in response to orthosilicic acid granules. Sugar Tech. 19: 300-304.

Jain, R., Singh, A., Jain, N., Tripathi, P., Chandra, A., Shukla, S.K., Berghe, D.V. and Solomon, S. (2018). Response of Silixol Sugarcane to growth and physio-biochemical characteristics of sugarcane. Sugar Tech. 20: 439-444.

Jawahar, S. and Vaiyapuri. V. (2010). Effect of sulphur and silicon fertilization on growth and yield of rice. International Journal of Current Research. 9: 36-38.

Jawahar, S., Vijayakumar, D., Bommera, R., Jain, N. and Jeevanandham. (2015). Effect of Silixol granules on growth and yield of rice. International Journal of Current Research Academic Review. 3: 168-174.

Jones, J.H. and Handreck, K.A. (1967). Silica in soils, plants and animals. Advances in Agronomy. 19: 107-149.

Liang, Y., Sun, W., Zhu, Y. and Christie, P. (2007). Mechanisms of silicon-mediated alleviation of abiotic stresses in higher plants: A review. Environment Pollution. 147: 422-428.

Ma, D., Sun, D., Wang, C., Qin, H., Ding, H., Li, Y. and Guo, T. (2016). Silicon application alleviates drought stress in wheat through transcriptional regulation of multiple antioxidant defense pathways. Journal of Plant Growth Regulation. 35: 1-10.

Ma, J.F. (2004). Role of silicon in enhancing the resistance of plants to biotic and abiotic stresses. Soil Science and Plant Nutrition. 50: 11-18.

Ma, J.F. and Takahashi, E. (2002). Soil, Fertilizer and Plant Silicon Research in Japan. 1st ed. Elsevier, Dordrecht, Amsterdam. Pp.1-294.

Ma, J.F., Miyake, Y. Takahashi, E. (2001). Chapter 2: Silicon as a beneficial element for crop plants. Studies in Plant Science. 8, DOI: 10.1016/S0928-3420(01)80006-9.

Matichenkov, V.V. and Calvert, D.V. (2002). Silicon as a beneficial element for sugarcane. J. American Society of Sugarcane Technologists. 22: 21-30.

McCray, J.M. and Mylavarapu, R. (2010). Sugarcane Nutrient Management using Leaf Analysis. Florida Cooperative Extension Service Fact Sheet SS-AGR-335. UF/IFAS Electronic Data Information Source (EDIS) Database. University of Florida, Gainesville. FL. http://edis.ifas.ufl.edu/ag345. Accessed 22 July 2011.

McCray, J.M., Ji, S., Powell, G., Montes, G., Perdomo, R. and Luo, Y. (2010). Boundary lines used to determine sugarcane production limits at leaf nutrient concentrations less than optimum. Communications in Soil Science and Plant Analysis. 41: 606-622.

Meena, V.D., Dotaniya, M.L., Vassanda, C., Rajendiran, S., Kundu, A.S. and Rao, A.S. (2014). A case for silicon fertilization to improve crop yields in tropical soils. Proceedings of National Academy of Sciences. India. B. 84: 505-518.

Meyer, J.H. and Keeping, M.G. (2000). Review of research into the role of silicon for sugarcane production. Proceedings of South African Sugar Technologists Association. 74: 29-40.

Ming, D.F., Pei, Z.F., Naeem, M.S., Gong, H.J. and Zhou, W.J. (2012). Silicon alleviates peg-induced water-deficit stress in upland rice seedlings by enhancing osmotic adjustment. Journal of Agronomy and Crop Science. 198: 14-26.

Mohan, S., Chithra, L., Nageswari, R., Manimozhi, V., Mathialagan, S.M. (2021). Sugarcane wax-A par excellent by-product of sugar industry - A review. Agricultural Reviews. 42: 315-321.

Okuda, A. and Takahashi, E. (1965). The Role of Silicon. In: The Mineral Nutrition of the Rice Plant. John Hopkins Press. pp. 126-146. Baltimore, MD.

Rani, Y.A., Narayanan, A., Devi, V.S. and Subbaramamma, P. (1997). The effect of silicon application on growth and yield of rice plants. Annals of Plant Physiology. 11: 125-128.

Reynolds, O.L., Keeping, M.G. and Meyer, M.H. (2009). Silicon-augmented resistance of plants to herbivorous insects: A review. Annals of Applied Biology. 155: 171-186.

Rohanipoor, A., Norouzi, M., Moezzi, A. and Hassibi, P. (2013). Effect of silicon on some physiological properties of maize (*Zea mays*) under salt stress. Journal of Biological and Environmental Sciences. 7: 71-79.

Rosario, E.J.D. and Santisopasri, V. (1977). Characterization and inhibition of invertases in sugarcane juice. Phytochemistry. 16: 443-445.

Ross, L., Nababsing, P. and Cheong, Y.W.Y. (1974). Residual effect of calcium silicate applied to sugarcane soils. Proceedings of the International Society of Sugar Cane Technologists. 15: 539-542.

Samuels, G. (1969). Silicon and sugar. Sugar y Azucar. 66: 25-29.

Samuels, G. and Alexander, A.G. (1969). Influence of variable manganese and silicon on the nutrition, sugar production and enzyme activity of immature sugarcane. Proceedings of International Society of Sugar cane Technologists Congress. 13: 544-555.

Savant, N.K., Korndorfer, G.H., Datnoff, L.E. and Snyder, G.H. (1999). Silicon nutrition and sugarcane production: A review. Journal of Plant Nutrition. 22: 1853-1903.

Savant, N.K., Snyder, G.H. and Datnoff, L.E. (1997). Silicon management and sustainable rice production. Advances in Agronomy. 58: 151-199.

Shakoor, S.A. and Bhat, M.A. (2014). Morphological diversity of phytolith types in some chloridoid grasses of Punjab. International Journal of Botany and Research. 4(1): 1-10.

Suganthi, M., Muthukrishnan, P. and Chinnusamy, C. (2019). Crop weed competition in sugarcane-A review. Agricultural Reviews. 40(3): 239-242.

Takahashi, E. and Miyake, Y. (1977). Silica and plant growth. Proceedings of the International Seminar on Soil Environment and Fertility Management in Intensive Agriculture. 603-611.

Vasanthi, N., Saleena, L.M. and Raj, S.A. (2014). Silicon in crop production and crop protection-A review. Agricultural Reviews. 35(1): 14-23.

Verma, K.K., Song, X.P., Tian, D.D., Singh, M., Verma, C.L., Rajput, V.D., Singh, R.K., Sharma, A., Singh, P., Malviya, M.K. and Li, Y.R. (2021). Investigation of defensive role of silicon during drought stress induced by irrigation capacity in sugarcane: Physiological and Biochemical Characteristics. ACS Omega. 6: 19811-19821.

Wang, Y., Zhang, B., Jiang, D. and Chen, G. (2019). Silicon improves photosynthetic performance by optimizing thylakoid membrane protein components in rice under drought stress. Environmental and Experimental Botany. 158: 117-124.

Wong, Y.C.Y., Heits, A. and Ville, J.D. (1971). Foliar symptoms of silicon deficiency in the sugarcane plant. Proceedings of the International Society of Sugar Cane Technologists. 14: 766-776.

Yavarzadeh, M.R., Gavali, R.S. and Dhumal, K.N. (2008). Impact of soil application of fly ash on growth and yield of wheat. Journal of Maharashtra Agricultural University. 33(2): 158-160.

Yoshida, S. (1975). The Physiology of Silicon in Rice. In: Technical bulletin no. 25. Food Fertilization Technology Center, Taipei, Taiwan.

Zhu, Y.X. and Gong, H.J. (2014). Beneficial effects of silicon on salt and drought tolerance in plants. Agronomy for Sustainable Development. 34: 455-472.