Pak J Agri. Sa. l'u!. 39(3), 2002

SILICON NUTRITION AND CROP PRODUCTION: A REVIEW

Tariq Aziz, Maqsood Ahmad Gill and Rahmatullah
Department of Soil Science, University of Agriculture, Faisalabad

In a few plant species essentiality of silicon has been demonstrated so far, but it is beneficial for most of the higher plants, under certain circumstances. The beneficial effects of silicon on crop growth are well documented especially under biotic and a-biotic stress conditions, Several mechanisms have been proposed for these responses, Crop yield responses to silicon may be associated with improved resistance against biotic and a-biotic stresses, such as disease and pest resistance, AI, Mn and Fe toxicity alleviation, increased P availability, reduced lodging, improved leaf and stem erectness, freeze resistance and improvement in plant water economy, This review covers the beneficial effects of silicon on crop growth and yield,

INTRODUCTION

Per acre yield of most of agricultural crops in Pakistan is very low compared to many of the other countries. Among the factors responsible for low yield, biotic stresses (insect pest and disease attack) and a-biotic stresses are very important. Crop species differ greatly for their tolerance and/or resistance against these stresses (Marschner, 1995) because of different genetic characteristics. Environmental factors (may be mineral nutrition) contribute considerably in increasing and or decreasing the plant's resistance and/or tolerance against these stresses.

Integrated nutrient management practices are gaining popularity nowadays and management of 13 physiologically essential nutrients namely six macro nutrients (N, P, K, Ca, Mg, and S) and seven micronutrients (Fe, Zn, Mn, Cu, B, Cl, Mo) is generally considered by the agronomists for sustaining and increasing crop yields (Marchner, 1995; Savant et aI., 1997), However, there are some elements that under certain agro-clirnatic conditions enhance plant growth by promoting several physiological processes but are not essential. Although not considered essential, these elements are said to be beneficial nutrient (Mengel and Kirkby, 1982). Silicon is an example of such elements.

Silicon has not been considered an essential element for the growth of higher plants; however, soluble Si has enhanced the growth, development and yield of several plant species including rice (*Oryzae saliva L.*), sugarcane (*Saccharum officinarum L.*) and most other cereals and several dicotyledons (Belanger et aI., 1995; Elawad and Green, 1979: Jones and Handrech, 1967; Yoshida, 1975; Takahashi et aI., 1990: Savant et ai, 1997; Savant et aI., 1999), especially under biotic and a-biotic stress conditions (Epstien, 1994). Improved growth of cotton plants due to Si application (Aziz et aI., 2002) could be one of the reasons of an increase in number of sympodia/plant, number of boils/plant, boil size and lint yield (Shengyi et aI., 1998). The maintenance of photosynthetic activity due to Si fertilization could be one of the reasons for increased dry matter production in rice crop (Agurie et aI., 1992). Disease severity or incidence tends to be reduced with increasing tissue contents of Si in rice (Datnoff et al., 1990,91; Osuna-Canizales et al., 1991) in cotton (Aziz et al., 2001) and in sugarcane (Savant et aI., 1999: Deren et aI., 1993).

This review intends to summarize the potential agro-economic benefits of Si inclusion in integrated nutrient management.

SILICON NUTRITION OF CROPS

Silicon is the second most abundant element in the earth's crust, with soils containing approximately 32 percent Si by weight (Lindsay, 1979). The essentiality of Si as a nutrient for higher plants is very difficult to prove because of its ubiquitous presence in the biosphere. Even highly purified water contains about 20 nM Si (Werner and Roth, 1983).

Different species and varieties within species utilize greatly different amounts of Si from the growth medium (Deren et aI., 1994; Aziz et al., 2001). The plant absorbs Si from the solution in the form of mono silicic acid (H_4Si0_4) which has no electric charge and is not very much mobile in plant (Yoshida, 1975; Savant et aI., 1997). Movement of Si follows that of water as the uptake of H_4Si0_4 is nonselective and energetically passive and its transport from root to shoot is in the transpiration stream in the xylem (Jones and Handreck, 1965). In rice, however, large amount of Si in leaves cannot be fully explained by the passive uptake (Savant et aI., 1997) and may be active by gaining energy from the anaerobic respiration (van del' Vorrn, 1980), Silicon deposited in the walls of epidermal cells after absorption by plants, contributes considerably to stem strength. Monosilicic acid polymerizes to Si gel when Si concentration increases in the plant water (Yoshida, 1975) or biogenetic opal as amorphous $Si0_2.nH20$ (Lanning, 1963).

Transpiration rate of the specific part determines the distribution of Si within the shoot and shoot parts of plant. The epidermal cell walls become effective barriers against both fungal infections and water loss by cuticular transpiration when impregnated with a firm Si layer (Jones and Handrech, 1967).

Silicon is not much mobile element in plants (Savant et aI., 1999); therefore, a continued supply of this element would be required particularly for healthy and productive development of plant during all growth stages (Yoshida, 1975). In a field study, plant height was quadratically related to the rate of Si application, while it related linearly with crop plant stem diameter (Elawad et al., 1982). In another solution culture experiment shoot dry matter of cotton plants increased three fold with Si application as compared to control (Aziz et aI., 200 I), In a nutrient culture experiment, the application of Si (Fig. 1) decreased the uptake of N, K, Fe and Mn in transplanted rice and increased the uptake of P, Ca, Mg and the formation of carbohydrate (Islam and Saha, 1969).

In short, Si is a beneficial element for most of the crop plants especially for rice and sugarcane. The potential beneficial effects of Si for most of the crops are summarized here.

POTENTIAL BENEFITS OF SILICON NUTRITION

The effective management of Si can offer several potential benefits for crop production including improved plant growth, increased yield, induced resistance to stresses and increased productivity of problem soils.

Improved Plant Growth and Yield

Low per acre yield of most of crops is common in developing countries like Pakistan and imbalanced nutrition is one of the most important causes for this low yield. Research work demonstrating the effects of Si on yield of various crops especially rice and sugarcane is well documented in few areas of world especially USA, Brazil and Japan. The yield responses are great enough that Si fertilization in rice and sugarcane is a common practice in these countries (Datnoff et al., 1999; Osuna-Canizales et al., 1991; Savant et al., 1999; Yoshida, 1975).

Silicon nutrition has several beneficial effects on plant growth largely due to its unique physiological role (Takahashi et al., 1990). Adatia and Besford (1986) reported a number of positive effects of Si on the growth of cucumber plants such as more leaf thickness, more dry matter per unit area of leaf, a small but significant added increment in root fresh and dry weight, and less propensity of leaves to wilt.

In another experiment, Si application to growth medium significantly improved growth of cotton plants infected with root rot (Aziz et al., 200 I). The shoot dry matter increased about three fold and root dry matter about two fold due to Si application (Fig. I & 2). Formation of new roots was also observed in cotton plants as Si was added to the nutrient solution, when earlier roots were rotted due to uncertain causes (Aziz et al., 2002). In dense stand of cereals, low light intensity is likely to limit photosynthesis; the modifying effect of Si on leaf erectness can be beneficial (Yoshida, 1969; Kang, 1985). The maintenance of photosynthetic activity due to Si fertilization could be one of the reasons for the increased dry matter production (Agurie, et al., 1992). They also observed an increase in water use efficiency in Si amended rice plants probably due to prevention of excessive transpiration.

In various field experiments, various slags applied to nursery plants increased the number of leaves and dry matter of rice plants (Lee et al., 1985). After transplanting, Si fertilization increased the number of tillers and panicles.

The function of Si deposition in cell walls is analogous of that of lignin (Epstien, 1994). Silicon prevents the compression of xylem vessel when transpiration is high. In experiments with both in solutions culture and soil grown plants, a recurring observation has been that plants supplied with sufficient Si resist lodging (Epstien, 1994). The mechanical strength of plants resides in cell wall, which enables them to maintain an erect habit (Epstein, 1994). Reviews on the role of Si in plants, therefore. stress the association of Si with cell walls and discuss the increased rigidity of cell walls of plants grown with ample available Si in terms of that association (Jones and Handreck, 1967).

Savant et al. (1997; 1999) reported several levels of yield increases due to Si application in rice and sugarcane. When Si is applied, yield increases of 10 % are common in rice and exceed 30 % when leaf blast is severe (Yoshida. 1981).

The benefits of Si ferti lization are generally observed in rice and sugarcane grown on weathered tropical soils and Histosols, which are Si deficient (Korndorfer et al.. 1999; Takahashi et al, 1990). Gascho and Andreis (1974) concluded that Si is a beneficial and probably essential for sugarcane grown on organic and quartz sand soils. Increases in tonnage of sugarcane amounting to 18 % in cane and 22 % in sugar for plant cane crop after the application of electric furnace slag to Latosols has been reported by Ayers (1966). This beneficial effect of slag on low Si soils lasted for four years.

Increase in yield with Si fertilization of flooded rice has been reported in Sri Lanka (Rodrigo, 1964). Thailand (Takahashi et al., 1980), Indonesia (Burbey et al., 1(88), India (Datta et al., 1962), China (Ho et al., 1980; Liang et al., 1994) and Florida (Snyder et al., 1986; Datnoff, et al., 1991,1992).

INDUCED RESISTANCE TO STRESSES.

Biotic stresses such as pests and plant diseases, and abiotic stresses such as soil water shortage, salinity and mineral toxicities, etc, are very common under field conditions reducing crop yields drastically. Silicon has a unique physiological role in alleviating both biotic and abiotic stresses in most of the crops (Yoshida, 1975; Epstein, 1994; Savant et al., 1999; Takahashi, 1995; Rodrigues et al., 1998, Datnoff et al., 2001; Seebold et al., 200 I; Korndorfer et al., 1999).

Biotic Stresses

Silicon can reduce the severity of several important diseases of rice, including blast, brown spot, sheath blight, leaf scald and grain discoloration and of sugarcane, including leaf freckling and ring spot (Datnoff et al., 200 I; Savant et al., 1997; Korndorfer et al., 1999). Fungal hyphae and parasite hustoria successfully infecting plant cells must break the cell wall, which they do through chemical means. Formation of a physical barrier in epidermal cells by Si deposition contributes to plant resistance against diseases and pests (Miyake and Takahashi, 1983; Epstein, 1994). Rodrigues et al. (1998) reported a significant reduction in sheath blight development in rice with the addition of Si. 1n another experiment, Rodrigues et al., (200 I) reported that Si fertilization increased the host resistant against sheath blight in rice.

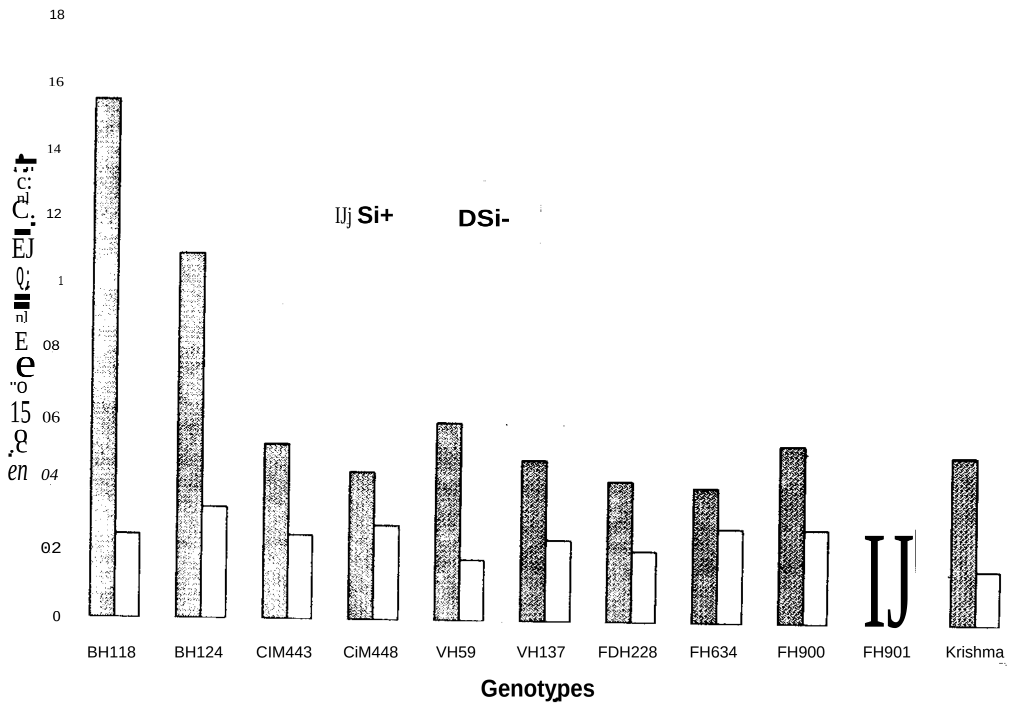

Fig. 1. Effect of Si on growth of cotton genotypes grown with and without Silicon (after Aziz, et al., 2001)

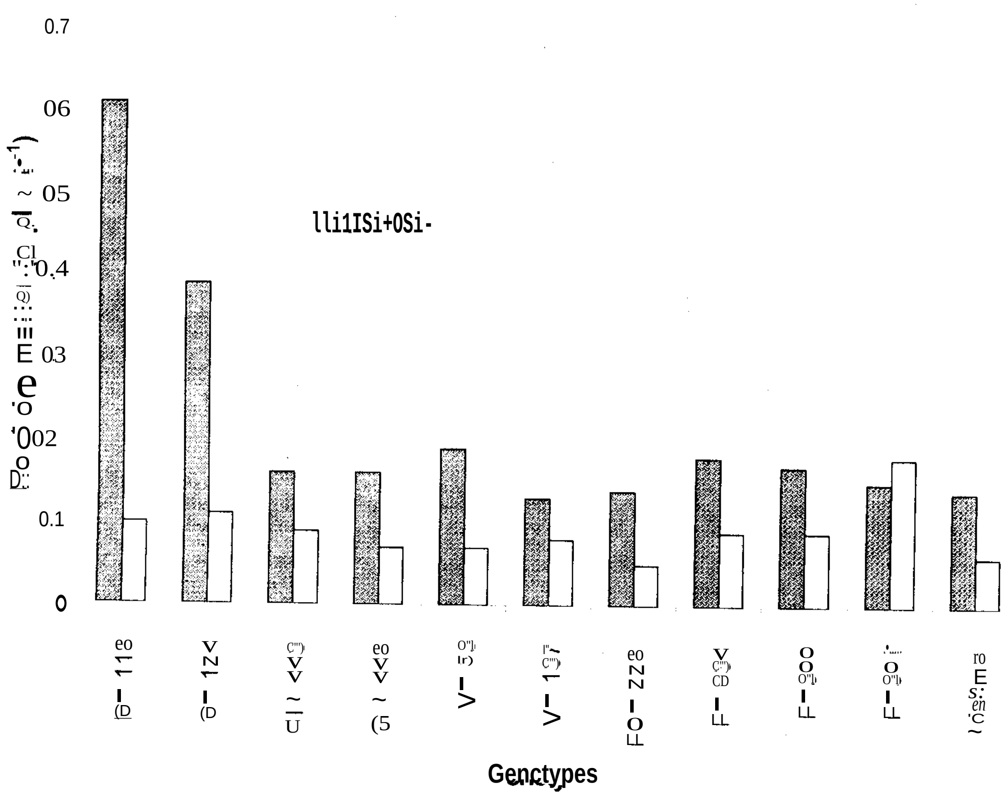

Fig. 2 Fb::t ay r.TBtterd eatoo gen1yJEs goN1 Vlitharx: VlithU SiliCal (Mer Aziz et a., 2(01)

In most disease control programmes fungicides and/or resistant cultivars are being used. However, host resistance may not always be practical and when available can breakdown due to shifts in pathogen races. Fungicides are currently perceived to be potentially harmful to the environment, particularly to the soil and water (Korndorfer et al., *1999).* Therefore, an encouraging alternative to fungicide use is Si fertilization offering an enhancement in resistance of host plant against these stresses (Datnoff et al., 1997). Deren et al. (1994) concluded that the increase in rice yield with added Si was attributable to increased resistance against diseases such as brown spot, being negatively correlated with Si concentration in the plant tissue. In Brazil, Korndorfer et al. (1999) found that an increase in Si application rate reduced grain discoloration from 46% in the control to 29% at the highest Si rate (960 kg Si ha"), [t was also found that this difference corresponds to a 64% reduction in grain discoloration.

In other field experiment at Florida, Seebold et al. (2001) reported that the number of sporolating lesions, lesion size, rate of lesion expansion, diseased leaf area, and number of spores per lesions reduced with increasing rate of Si applicaiton. Silicon deposited in the epidermal tissue mechanically deters hyphae invasion (Takahashi, 1996). Furthermore, Si physiologically promotes ammonium assimilation and restrains the increase in soluble N compounds, including amino acids and amide, which are instrumental for the propagation of hyphae (Takahashi, 1996).

The presence of Si crystals in epidermal tissues hinder the feeding of the insect, which in their phase has rather fragile mandibles (Savant et aI., 1997). Plants like sugarcane and rice, with high Si content, seem to interfere in the feeding of larvae, damaging their mandibles. It is possible that plants with higher Si contents in their tissue would have a higher level of resistance to the infections by such pests (Savant et al., 1999).

Several economically important insect pests, such as stem borer (Ota et al., 1957; Yoshida, 1975; IRR[, 1965; Sawant et aI., 1994), brown plant hopper (Sujatha et al., 1987), green leaf hopper (Maxwell et aI., 1972), leaf spider (Yoshida, 1975), sugarcane stalk borer (Coulibaly, 1990), and mites (Tanaka and Park, 1966) have been suppressed by improving Si concentration in plants.

Abiotic Stresses

The climate of Pakistan is arid and semi arid and water stress in fields is common effecting crop yields significantly. Silicon significantly improves water economy of plants largely by reducing cuticular transpiration (Yoshida, 1975; Wang You Cheong et aI., 1972). Excessive rate of transpiration is one of the symptoms associated with Si deficiency. In nutrient culture experiment, the wilted cotton plants became erect when Si was added, (Aziz et aI., 2002). This erectness may be attributed to improved water economy and hinders the root xylem to rupture due to excessive transpiration (Savant et al., 1997). The rate of transpiration is presumably influenced by the amount of Si gel associated with the cellulose in the cell walls of epidermal cells. Hence, a well-thickened layer of Si gel should help to retard water loss, while epidermal cell wall with less Si gel will allow water to escape at an accelerated rate (Savant et al., 1999)

Salinity restricts the growth of crops hence holds back the development of sustainable agriculture. By increasing Si content of plants, it may be possible to reduce plant's internal water stress and thereby enable them to withstand salt stress (Ahmad et al., 1992). A less decrease in shoot dry matter accumulation of salt stressed barley plants when Si was added to growth medium (Liang et al., 1996) can be attributed to increased CO_2 assimilation and decreased electrolyte leakage and Na concentration in shoot. Promotion in dry biomass of wheat under saline conditions can also be described as a function of increased water influx. which apart from preventing physiological drought may help to maintain a balanced and efficient absorption and translocation of mineral elements required for energy generations (Ahmad et aI., 1992). There may be a possibility of an interaction between freely available Na and Si ions, forming a complex, which reduce their transportation to the aerial parts of plants (Ahmad et al., 1992). They observed low amounts of Si on the flag leaves at 0.6% NaCI with Si treatment, which may be attributed to the binding of soluble Si with Na in root and retarding its upward translocation. In solution culture experiment, Liang et al., (1996) found that Si could enhance the uptake of K and inhibit the uptake of Na by salt stressed barley, thus mitigating the toxicity of salt to barley and increasing salt tolerance of the plants.

Lodging can be defined as bending and/or breaking over of a plant before its harvest resulting in economic loss to farmers by lowering the quantity and quality of yield. Increased plant Si content has been reported to increase mechanical strength of plant tissue, which resultd in reduced lodging (Takahashi et al., 1990; Liang et aI., 1994). Lee et al. (1990) also noticed an increase in resistance to lodging due to application of Si fertilizer to rice. Liang et al. (1994) reported less than 10 % or practically no lodging in rice fields fertilized with a new silicate material and more than 60 % lodging in control fields. Evidently, thickening of cell walls of the sclerenchyma tissue in the clum and/or shortening and thickening of internodes or increase in Si content of lower internodes provides mechanical strength to enable plant to resist lodging (Lee et al., 1990; Liang et al., 1994; Takahashi, 1995).

Under field conditions, particularly in dense stands of cereals, Si can stimulate growth and yield by decreasing mutual shading through improved leaf erectness. Leaf erectness is an important factor affecting light interception in dense plant population and, hence, photosynthesis (Savant et al., 1999). This effect of Si on leaf erectness is mainly a function of the Si deposition in the epidermal layer of the leaf panicle (Takahashi et. al. 1982).

Thakahashi (1995) has reviewed that Si increased the oxidizing power of rice roots. The roots of rice supplied with Si shows a higher oxidation power of ferrous' iron than of non-supplied one. Due to a decrease in the solubility of iron caused by iron oxidation, the Si supplied rice absorbs less Iron.

Silicon is also reported to alleviate Mn toxicity (Epstien, 1994). Adding Si to the solution did not diminish to Mn content of the leaves. Rather. in the absence of Si, Mn was concentrated in necrotic spots, whereas in the presence of Si, the Mn was distributed more evenly in leaves and thus preventing it from collecting into localized areas which became necrotic (Jones and Handreck, 1967). Aluminum toxicity is also reported to be alleviated by Si application (Takahashi et al., 1994).

Future Outlook

Most of the previous research on Si has concentrated on highly weathered temperate region soils, mostly acidic in nature (Datnoff et al., 1999; Osuna-Canizales, 19: Savant et al., 1999: Yoshida. 1975). Soils of Pakistan are relatively young (less weathered) and are alkaline calcareous in nature. Agricultural crops produced on these soils experience aridity (water shortage) and excess soluble salts (salinity/sodicity) in addition to several biotic stresses like pests and diseases. Preliminary work in our lab. (Aziz et al., 2001) has demonstrated favorable effects of Si addition on growth of cotton genotypes infected with root rot. Hence. future research on Si nutrition of plants in our crop production system should focus on quantitative improvement in resistance against several pest and diseases of historical importance in the region in addition to improvement against salinity and water shortage.

LITERATURE CITED

Adatia, M.H. and R.T. Besford. 1986. The effect of silicon in cucumber plants grown in recirculating nutrient solution. Ann. Bot. 58:343-351.

Agurie, S., W. Agara, F. Kubota and p.B. Kaufman. 1992. Physiological role of Silicon in photosynthesis and dry matter production in rice plants. Jpn. J. Crop Sci. 61: 200-206.

Ahmad, R., S. 11. Zaheer and S. Ismail.. 1992. Role of silicon in salt tolerance of wheat (Triticum aestivum L.). Plant Sci. 85: 43-50.

Ayres, AS 1966. Calcium silicate slag as a growth stimulant for sugarcane on low-silicon soils. Soil Sci. 101(3): 216-227.

Aziz, T., M.A. O.U and I, Ahmed. 200\.. Differential growth response of cotton genotypes infected with root-rot to silicon nutrition. *Pak J Soil Sci.* 20: 101-108.

Aziz, T., M. i\. Gill., I, Ahmed, Rahrnatullah and M.S. Akhtar. 2002. Differential growth response of cotton genotypes to silicon nutrition infected with root rot. (Abst. p.7). 9th lntl.. Cong. Soil Sci., Soc. PaL March 18-20.2002. N lAB, Faisalabad.

Belanger. R.R.. P.A. Bowen. D.L.. Ehret and J.G. Menzies. 1995. Soluble silicon: Its role in crop and disease ?~anagement of greenhouse crops. Plant Dis. 79: 329-.).)6.

Burbey, A.. B. Rizaldi and Z. Yulizar. 1988. Response of upland rice to potassium and silicate application on Ultisol.. Pemberitaan Penelition Sukarami 15: 26-31.

Coulibaly, K. 1990. Influence of nitrogen and silicon fertilization on the attack on sugarcane by the stalk borer (Eldana Saccharina Walker). Sugarcane Spring Supplement 18.

Datnoff. L.E. 1992. Influence of silicon fertilization on rice diseases in Florida. Newslett. Florida Ph) topathol. Soc. 3: 10-1 \..

Datnoff, L.E., C.W. Deren and G. H. Snyder. 1997. Silicon fertilization for disease manazement of rice in Florida Crop Prot.. 16:525-53 I.

Datnoff, L.E., G.H. Snyder and C.W. Deren, 1992. Influence of silicon fertilizer grades on blast and brown spot development and on rice yields. Plnat Dis. 76(10): 1011-1013.

Datnoff, L.E.,. G.H. Snyder and D.B. Jones, 1990. Influence of calcium silicate slag and fungicides on brown spot and neck rot development and yields of rice. In: 1.J. Coale (Ed.), 1999 Rice Growers Seminar. pp. 26-33. Belle Glade EREC, Research Report EV-1990-2. University of Florida, Belle Glade, Florida.

Datnoff, L.E., K.W. Seebold and F.J.. Correa-V. 200\. The use of silicon for integrated disease management: Reducing fungicide applications and enhancing host plant resistance. In: Datnoff, et.. al.. (Ed.) Silicon in Agriculture. The Elsevier Sci.. USA.

Datnoff, L.E., R.N. Raid, G.H. Snyder and D.B. Jones 1990a. Evaluation of calcium silicate slaa and nitrozen on brown spot, neck rot and sheath bligh~ developn~nt in rice. Biol.. Cultural Tests Control Plant Dis. 5: 65.

Datnoff, L.E., R.N. Raid, G.H. Snyder and D.B. Jones. 1991. Effect of calcium silicate on blast and brown spot intensities and yields of rice. Plant Dis. 75:729-732

Datta, N.P., J.E. Shinde, M.D. Karnath and S.K. Datta 1962. Effect of sodium si licate on the uptake of soi I and fertilizer phosphorus by wheat rice and berseem. Indian J. Agric. Sci. 32: 219-227.

Deren, C.W., B. Glaz and G.H. Snvder. 1993. Leaf-tissue silicon content of sugarcane - genotypes grown on Everglades Histosols. J. Plant Nutr. 16(11): 2273-2280.

Deren, C.W., L.E. Datnoff, G.H. Snyder and F.G. Martin 1994. Silicon concentration, disease response and yield components of rice genotypes grown on flooded organic Histosols. Crop Sci. 34:733-737.

Elawad, S. H., J.J. Street and G.J.. Gascho. 1982. Response of sugarcane to silicate source and rate. I. Growth and yield. Agron. J. 74(3): 481-484.

Elawad, S.H. and V.E. Jr.. Green. 1979. Silicon and the rice plant environment: A review of recent research. 1\ Riso 28: 235-253.

Epstein, E. 1994. The anomaly of silicon in plant biology. Proc. Natl.. Acad. Sci. USA 91:: I 1-17.

Gascho, G J. and HJ. Andreis. 1974. Sugar cane response to calcium silicate slag applied to organic and sand soils. Proc. Int.. Congr.. Soc. Sugar Cane Technol... 15(2): 543-55\.

Ho, D.Y., H.L.. Zang and X.P. Zhang. 1980. On the silicon supplying ability of some important paddy soils in South China. In: Proceedings of tlie Symposium on Paddy Soils, 19-24 October 1980. p. 95. Nanjing, China. {Abstracts}

Horiguchi, T. 1988. Mechanism of Mn toxicity and tolerance of plants. IV. Effects of Si on alleviation of Mn toxicity of rice plants.']. Soil Sci. Plant Nutr.. 34: 65-73.

International Rice Research Institute (lRRI) 1964. Annual Report 1994. Los Banos, Laguna, Philippines.

Islam, A. and R. Saha. 1969. Effects of silicon on the chemical composition of rice plants. Plant Soil 30: 446-458.

Jones, L.H.P. and K.A. Handreck. 1967. Silica in soils, plants and animals. Adv. Agron. 19: 107-149.

Kang, Y.S. 1985. The influence of silicon on growth of rice plants. Res. Rep. Rural Dev. Adrnin., Plant Environ., Mycol., Farm Product Utilization, Korean Republic 27(1): 57-77..·lln Korean: Rice Abstr. 10: 2504, J987]

Korndorfer, G.H .. L.E. Datnoff and G.F. Correa. 1999. Influence of silicon on grain discoloration and upland rice grown on four Savanna soils of Brazil.. J. Plant Nutr. 22: 93-102.

Lanning, F.e. 1963. Silicon in Rice. 1. Agric. Food Chem. 11: 435-437.

Lee. D.B., T.O. Kwon and K.II.. Park. 1985. Influence of nitrogen and silica on the yield and the lodging related traits of paddy rice. Res. Rep. Rural Dev. Adrnin., Soil Fert. 32(2): 15-23.. [In Koren: Soils Fert.. 55: 2428, 19921

Lee, K.S., S.13. Aim, G.S. Rhee. 8.Y. Yeon and 1.K. Park. 1985. Studies of silica application to nursery beds on rice seedling growth. Res. Rep. Rural Dev. Admin., Plant Environ .. Mycol., Farm Product Utilization, Korea Republic 27(I): 23-27. IIn Koren: Rice Abst.. 10: 2502, 1987J

Lee, T.S .. I'.O. Kwon and K.H. Park. 1990. Influence of nitrogen and silicon on the yield and the lodging related traits of paddy rice. Soil Fert.. 32: 15-23.

l.iang, Y.e., IS. Ma, F.J. Li and Y.J. Feng. 1994. Silicon availability and response of rice and wheat to silicon in calcareous soils. Commun. Soil Sci. Plant Anal.. 25: 2285-2297.

Liang, Y.e., S. Qirong, S. Zhenguo and M. Tongsheng. 1996. Effects of silicon on salinity tolerance of two barley genotypes. J. Plant Nutr.. 19(1): 173-183.

l.indsay, W. I. 1979. Chemical Equilibrium in Soi!.. John Wiley & Sons. New York.

Ma, T.S .. DP. Wang, Y.T.. Liung, S.H. Chen, F.S. Zhang, S.F. Wang. 7.z. Chien and L.Z. Liu. 1992. Effect of high efficiency silicate fertilizer on rice. Turang 24(2): 168-169. [In Chenses]

Marschner, H.. H. Cbrie, 1 Cakmak and V. Romheld. 1990. Silicon deficiency and its effects on availability of P and Zn. Plant Soil 124: 211-219.

Marschner, H. 1995. Beneficial mineral elements. In: Mineral Nutrition of Higher Plants. Academic Press Inc.. Sandiego. USA.

Maxwel!.. F. G., 1. N. Jenkins and W.L. Parrott. 1977. Resistance of plants to insects. Adv. Agron. 24: 187-265.

Mengel, K.8. and E. A. Kirkby. 1982. Principles of Plant Nutrition. Potash Institute, Bern, Switzerland.

Miyake, U. and E. Takahashi. 1983. Effect of silicon on the growth of solution cultured cucumber plants. Soil Sci. Plant Nutr.. (Tokyo) 29: 71-83.

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

Osuna-Canizales, F.J., S.K. Datta and 1.M. Bonman. 1991. Nitrogen form and silicon effects on resistance to blast disease of rice. Plant Soil 135: 223-231.

Ota, M., H. Kobayshi and Y. Kawaguchi. 1975. Effect of slag on paddy rice. 2. Influence of different nitrogen and slag levels on growth and composition of rice plant. Soil Plant Food 3: 104-107.

Rodrigues, F.A., L.E. Datnoff, G.H. Korndorfer, K. W. Seebold and M.e. Rush. 200 I. Effect of silicon and host resistance on sheath blight development in rice. Plant Dis. 85(8): 827-832.

Rodrigues, F.A., L.E. Datnoff, G.H. Korndorfer. M.e. Rush, K. W. Seebold and S. Linscombe. 1998. Effects of calcium silicate and resistance on the development of sheath blight in Rice I. 24th Rice Tech. Working .Meeting, 1998 02 doc., Reno, Nevada.

Savant. N.K., G.H. Korndorfer. L.E. Datnoff and GII. Snyder. 1999. Si licon nutrition and sugarcane production: A review. 1. Plant Nutr.. 22: 1853-1903.

Savant, N.K., G.H. Snyder and L.E. Datnoff 1997. Silicon management and sustainable rice production. Adv, Agron. 58: 151-199.

Sawant, A.S., V.H. Patil and N.K. Savant. 1994. Rice hull ash applied to seebold reduces dead hearts in transplanted rice. Int. Rice Res. Notes 19(4): 21-22.

Seebold, K. W., T.A. Kucharek, L.E. Datnoff, F.J. Correa-Victoria and M.A. Marchetti. 200 I. Phytopathology 91(1): 63-69.

Shengyi, X., W. Qishan, S. Xia and QS. Wang. 1998. Studies on the effect of Si fertilizer on cotton. China Cotton 25(8): 6-7.

Snyder, G.H., D.B. Jones and G.J. Gascho. 1986. Silicon fertilization of rice on Everglades Histosols. Soil Sci. Soc. Am . .I. 50: 1259-1263.

Sujatha. G., G.P.V. Reddy and M.M.K. Murthy 1987. Effect of certain biochemical factors on expression of resistance of rice varieties to brown planthopper (Nilaparvata lugens Stal) . .I. Res. APAU (Andhra Pradesh Agric. Univ.) 15(2): 124-128.

Takahashi, E. 1995. Uptake mode and physiological functions of silica. Tokyo Sci. Rice Plant 2: 99-122.

Takahashi, E. 1996. Uptake mode and physiological fuctions of silica. In: Sciece of the Rice Plant: Physiology. Food Agric. Policy Res. Center, Tokyo, Japan 2: 420-433.

Takahashi, E., 1.F. Ma and Y. Miyake. 1982. The effect of silicon on the growth of cucumber plant. pp. 664-669. In: Proceedings of the 9th Int!. Plant Nutr. Colloquium, Warqick University, England.

Takahashi, E., 1.F. Ma and Y. Miyake. 1990. The Possibility of silicon as an essential element for higher plants. Comments Agric. Food Chem. 2: 99-122.

Takahashi. 1., C. Kanareugsa, J. Somboondumrongkul and J. Prasittikhet. 1980. The effect of silicon, magnesium and zinc on the yield of rice. In: Proceedings of the Symposium on Paddy Soil, 19-24 October, 1980, pp. 82-83. Nanjing, China. [Abstracts]

Tanaka, A. and Y.D. Park. 1966. Significance of the absorption and distribution of silica in the rice plant. Soil Sci. Plant Nutr. 12: 191-195.

Van del' Vorm. P.D.J. 1980. Uptake of silicon by five plant species, as influenced by variation in Si supply. Plant Soil-56: 153-156.

Werner, D. and R. Roth. 1983. Silica metabolism. pp. 682-694. In: A. l.auch and R.L. Bielsky (Ed.), Inorganic Plant Nutrition. New Series. Spring-Verlag, New York.

Wong You Cheong, Y., A. Heits and 1. De Ville. 1972. Foliar symptoms of silicon deficiency in the sugarcane plant. 1971 Proc. Congo Intl. Soc. Sugarcane Technol. 14: 766-776.

Yoshida, S. 1975. The physiology of silicon in rice. Tech. Bull. No. 25, Food Fert. Tech. Center Taipei, Taiwan.

Yoshida, S., S.A. Navasero and E.A. Ramires 1969. Effects of silica and nitrogen supply on some characters of the rice plant. Plant Soil 31: 48-56.