SILICON USE FOR PEST CONTROL IN AGRICULTURE: A REVIEW

LAING M D, GATARAYIHA M C and ADANDONON A

Plant Pathology, University of KwaZulu-Natal, Pietermaritzburg, 3209, South Africa
laing@ukzn.ac.za

Abstract

Silicon (Si) deficiency in crops has been recognised since the 1970s, and a substantial body of research, particularly on rice and sugarcane, now shows that silicon is a 'functional' plant nutrient. In particular, silicon application can significantly enhance insect pest and disease resistance in plants, with consequent yield increases. Responses to silicon application in reducing pest populations and plant damage are usually more obvious in susceptible than resistant varieties. Silicon depositions in monocots may provide a mechanical barrier against insect pests. However, this passive role of silicon is now being contested, and an active role of silicon has been shown in the physiological resistance of crops to diseases. Silicon is now considered to have a catalytic role in the expression of physiological resistance through the production of, among other chemicals, tannic and phenolic compounds. The application of silicon in crops provides a viable component of integrated management of insect pests and diseases because it leaves no pesticide residues in food or the environment, and it can be easily integrated with other pest management practices, including biological control. Given that at least 70% of Africa's soils are deficient to highly deficient in accessible silicon, this has implications for African agriculture.

Keywords: silicon, insect control, pest resistance, disease resistance, physiological resistance, IPM

Introduction

Insect pests are one of the major biological constraints that limit crop production throughout the world (Ukwungwu, 1990; Panda and Kush, 1995). For example, in South Africa sugarcane (*Saccharum offinarum* L.) regularly suffers from stalkborer (*Eldana saccharina* Walker, Lepidoptera: Pyralidae) damage, costing the industry approximately R60 million in the 2003-2004 season (Meyer and Keeping, 2005). Of all insect control methods, the planting of pest resistant varieties is the most effective (Ukwungwu, 1990; Panda and Kush, 1995) because it leaves no insecticide residues in food or the environment and is constantly effective. However, pest damage may also be reduced through careful management of the nutrient requirements of the crop or amendments with mineral nutrients, such as silicon (Si), that reduce crop susceptibility to pests (Meyer and Keeping, 2005). This is because the development of phytophagous insects often depends on the physiological condition of host plants, and particularly their nutrient and stress status (Sétamou *et al*, 1993; Huberty, and Denno, 2004).

For many years, silicon deficiency in crops went unrecognised, and this element was widely regarded as non-essential for plant growth, although often present in the highest concentration in inorganic constituents (Jones and Handreck, 1967). However, there is now a greater consensus amongst scientists in the role of silicon as a 'functional' plant nutrient (Bhavnagary *et al*, 1988; Epstein, 1999). Silica content in the plant is reported to play an important role in strengthening the cell walls of plants (Painter, 1951; Table 1), and enhances resistance to both pests and diseases in the field (Qin and Tian, 2004) and in storage (Korunic, 1997). It has been reported that silicon suppresses insect pests such as stemborers, brown planthopper, green leafhopper, whitebacked planthopper, and non-insect pests such as spider mites (Savant *et al,* 1997, Ma and Takahashi, 2002). The objective of this paper is to review prior research on the application of silicon for insect pest control in crops.

Silicon application and sugarcane resistance to pest damage

One of the earliest reports linking silicon nutrient levels with stalkborer damage in cane is credited to Indian research (Rao, 1967). The author found that sugarcane varieties tolerant to the shootborer (*Chilo infuscatelus* Snellen) showed the highest density of silicon per unit area in the leaf sheath. In Florida, Elawad *et al*. (1982), found that after applying 20 t/ha of TVA slag to a muck soil, there was a significant decrease in leaf freckling in sugarcane. Furthermore, with improved silicon nutrition, there was an increase in sugarcane resistance to the stem borer *Diatraea saccharalis* F. (Elawad *et al,* 1985). Subsequent studies have confirmed the positive effect of silicon in increasing the resistance of sugarcane to this stalkborer (Anderson and Sosa, 2001). In Taiwan, Pan *et al.* (1979) conducted an experiment where different forms of silicon including bagasse furnace ash and silica slag were applied. The results showed that the incidence of borer damage in Si-treated sugarcane was less than in untreated control sugarcane. In South Africa, recent studies have focused on the association between silicon assimilation and host-plant resistance to *Eldana saccharina* (Meyer and Keeping, 2001; Keeping and Meyer, 2002; Keeping and Meyer, 2003; Meyer and Keeping, 2005). Greenhouse and field trials have been conducted to compare the efficacy of four silicon sources (Keeping and Meyer, 2003). In the greenhouse, sugarcane varieties were artificially inoculated with *E. saccharina* and treated with three doses (0, 5 and 10 t/ha) of calcium silicate. At 10 t/ha calcium silicate, there was a reduction of 30% in borer damage and 20% in borer mass. The most susceptible varieties showed the highest silicon uptake and the greatest response. Of the four carriers tested, stalkborer incidence declined as follows: South African calcium silicate > imported USA calcium silicate > local Slagment > flyash. In the field experiment, similar results were recorded (Keeping and Meyer, 2003).

Silicon application and wheat resistance to pest damage

Miller *et al.* (1960) found that wheat (*Triticum aestivum* L.) stems that contained high levels of silicon were not injured severely by larvae of Hessian fly (*Phytophaga destructor* Say). They indicated that several susceptible varieties developed marked resistance when they were grown in a solution containing sodium silicate. Moreover, in a greenhouse experiment, they showed that most of the resistant wheat varieties had dark shapes of silicon depositions ranging from round to oblong and a relatively dense and grainy covering of silicon over the entire surface of the leaf sheath. More extensive deposition of silicon was found as the age of the plant increased. In all susceptible varieties, the silicon was deposited in rod-shaped masses arranged in rows with spaces between the rows. Recent reports showed that application of silicon to susceptible wheat increased crop resistance and reduced pest infestation, both in the field (Weryszko-Chmielewska and Soczyński, 1994; Basagli *et al*, 2003; Moraes *et al*, 2004; Kordan *et al*, 2005) and in storage (Korunic, 1997).

Silicon application and rice resistance to pest damage

Ukwungwu and Odebiyi (1985) recorded a negative correlation between percentages of silicon content in different rice (*Oryza sativa* L.) varieties and the percentage of stems bored by the African striped borer *Chilo zacconius* Bleszynski (Lepidoptera: Pyralidae), and the number of living larvae per plant. Panda *et al*. (1975) reported that the larvae of the yellow rice borer, *Scirpophaga incertulas* Walker (Lepidoptera: Pyralidae) were unable to attack resistant rice plants because of the high silica content of their stems. Similarly, Sasamoto (1961) found an increase in the silicon content of rice plants when grown in silicon supplied soils and a parallel decrease in their susceptibility to the stem borer *Chillo suppressalis* Walker. In Petri dish trials using rice stem pieces with various silicon contents, Ma and Takahashi (2002) showed that the number of larvae which bored into the stems, and the amount of faeces, was negatively correlated with the silicon content of the stems (Table 1).

Table 1. Effect of silica supply on the resistance of rice to *Chilo suppressalis*.

Parameters	Amounts of silica gel supplied (g/pot)			
	0	1.5	4.5	6.0
SiO_2% in the stem	1.35	1.71	2.02	2.11
NLB	22	7	4	2
Amounts of faeces* (mg)	139	29	11	9

Forty-fourth instar larvae were incubated in each Petri dish containing 5 cut stems of various SiO_2 contents. Number of larvae which bored into the rice stems (NLB) were counted 24 h after inoculation (Ma and Takahashi, 2002).

Other experiments in Asia showed that, on rice, silicic acid at concentrations as low as 0.01 mg Si/ml was an active sucking inhibitor against the brown planthopper (*Nilaparvata lugens* (Stal) (Yoshihara *et al*, 1979). Furthermore, Salim and Saxena (1992) found that at high levels of silicon, fewer planthopper nymphs became adults and there was a decrease in adult longevity and female fecundity.

Silicon application and maize resistance to pest damage

Sharma and Chatterji (1972) found that a high silicon content contributed to maize (*Zea mays* L.) resistance to stalkborer (*Chilo zonellus* Swinhoe) damage. Similarly, in Benin, Sétamou *et al.* (1993) evaluated the effects of silica application to maize on the borer, *Sesamia calamistis* Hampson (Lepidoptera: Noctuidae). They applied sodium metasilicate ($Na_2SiO_3.5H_2O$) at a rate of 0, 0.56 and 0.84 g Si/plant. They recorded that an increasing silica supply reduced larval survival from 26.0% (control) to 4.0% at 0.56 g Si/plant. Rojanaridpiched *et al.* (1984) showed that maize resistance to the second generation of *Ostrinia nubilalis* Hübner (Lepidoptera: Pyralidae) was significantly correlated with the silica content in the sheath and collar tissue.

Silicon application in other crops for resistance to pest damage

The contribution of silicon content to pest resistance has also been recorded in other crops such as vegetables (Chelliah, 1972; Puzyrkov *et al*, 1996), citrus (Matichenkov *et al*, 2000) and turf (Korndorfer *et al*., 2004). Furthermore, silicon deposits occurring in plant organs were reported in most crops, including both Mono- and Dicotyledonous families (Jones and Handreck, 1967; Nishimura *et al*, 1989). This suggests that silicon plays a role in pest resistance in most, if not all, cultivated crops.

Recent research on red spider mite control

Gatarayiha, Neumann and Laing (unpublished) have conducted a series of trials against twin spotted spider mite or red spider mite (*Tetranychus urticae,* Koch), on dicotyledenous crops, specifically brinjal, tomato, green bean and cucumber, using integrated pest management, with silicon and a biocontrol agent to manage this pest. Brinjal is particularly susceptible to this pest under conditions where the leaves are kept dry. Silicon was applied as potassium silicate (20.9% a.i.), dissolved in hydroponic water, which was applied to the crops on a daily basis. The biocontrol agent was *Beauveria bassiana* formulated into a commercial biocontrol agent, Eco-Bb®, by Plant Health Products (Pty) Ltd, Nottingham Road, South Africa.

The working hypothesis is that soluble silicon absorbed by plants acts as a catalyst in the plant's pest resistance mechanisms. Hence, pests feeding on silicon positive plants will struggle to feed without interference by natural plant resistance compounds. As such, these pests are likely to be stressed, and therefore will be more susceptible to biocontrol agents than pests feeding on silicon negative plants.

Results to date are consistent and fairly conclusive. On dicotyledenous crops, soluble silicon application to the root systems of these plants results in enhanced dissolved silicon in the leaves of these plants. Furthermore, when potassium silicate was applied at above 80 mg/L:

- RSM damage was substantially reduced in silicon-treated plants ($p<0.001$; F= 17.4; df: 4, 18; ANOVA) by 59.1% and 45.5% for 80 mg/L, and 160 mg/L, respectively (Figure 1).
- RSM did not die directly as a result of silicon applications.

However, biological control of RSM was significantly enhanced by silicon treatment of host plants, resulting in synergistic ($p=0.0185$; F= 3.7; df= 4, 18; ANOVA for trial 1 and $p=0.0385$; F= 4.25; df= 2, 10; ANOVA for trial 2) or additive (trial 3) control of RSM.

Results of three trials are shown in Figures 1 to 4.

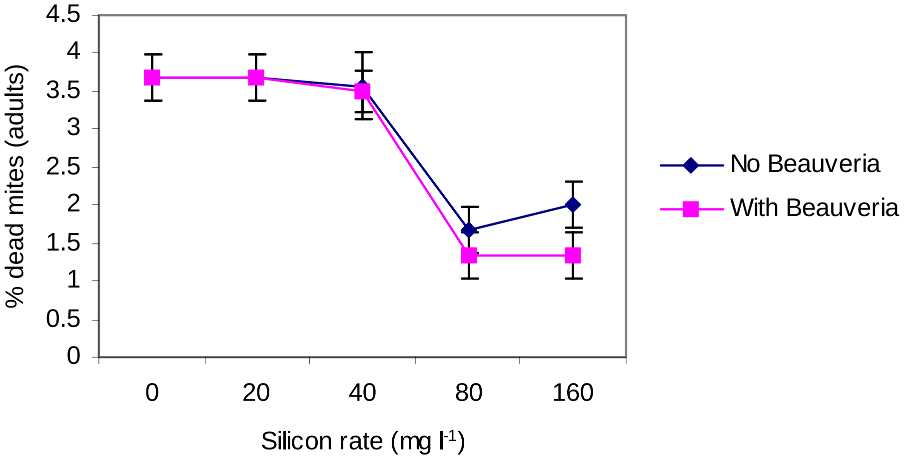

Figure1. Trial 1: Leaf damage index means of brinjal for four potassium silicate rates plus a control (no Si), with Eco-Bb (*Beauveria bassiana*) (applied or not applied).

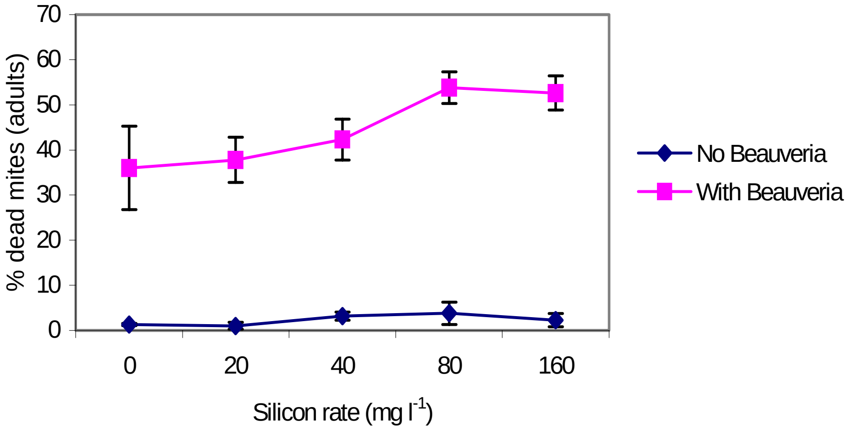

Figure 2. Trial 1: Percentage of dead adult mites associated with four different levels of potassium silicate plus a control (no Si), and Eco-Bb (*Beauveria bassiana*) (applied or not applied) observed on brinjal.

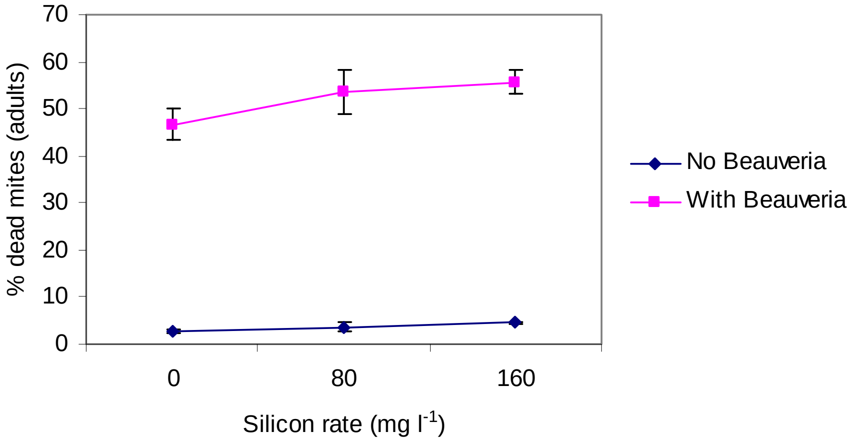

Figure 3. Trial 2: Percentage of dead adult mites associated with two different levels of potassium silicate plus a control (no Si) and Eco-Bb (*Beauveria bassiana*) (applied or not applied) on brinjal.

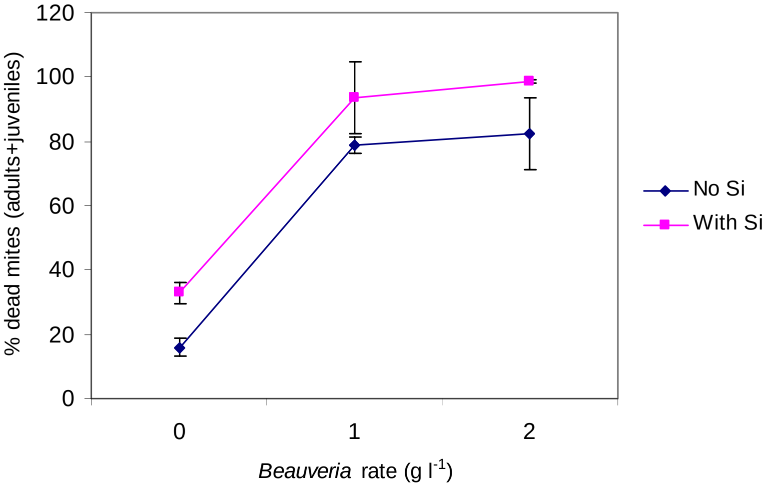

Figure 4. Trial 3: Percentage of dead mites associated with potassium silicate treatment (at 0 or 160 mg/L) and Eco-Bb (*Beauveria bassiana*) at two different rates plus a control (no *B. bassiana*) on brinjal.

The consistent result on brinjal is that a combination of biocontrol and silicon enhanced the control of RSM. These results have been surpassed by results on less susceptible crops such as green beans, tomatoes and cucumbers, suggesting that this may be a general finding of application to many crops. Others (as reported by Savant *et al*, 1997) obtained similar results.

Discussion

Many experiments have been conducted since 1942 on the potential agronomic benefits of silicon in agriculture. The use of silicon (replacing carbon), with its high natural abundance and non-toxic nature, has received most attention. Examples of silicon-for-carbon exchange can be found for all major classes of insecticides, including carbamates, organophosphates, pyrethroids, as well as di-ethyl di-chloroethane (DDT) and juvenile hormone analogues, and generally the silicon analogues retain insecticidal activity (Sieburth *et al*, 1990a).

Recent research has focused on the beneficial effects of silicon in increasing crop resistance to pests and diseases (Sétamou *et al*, 1993; Keeping and Meyer, 2002; 2003; Kordan *et al*, 2005). According to Bernays and Barbehenn (1987) several features of Poaceae (=Gramineae) make them relatively difficult to chew, and silicon content in the plant is one of these factors. The authors reported that most of the plant silicon occurs in the epidermis, which might dislodge young borer larvae before they can establish in the stem. Various studies have shown that silicon increases the hardness of plant tissue, which interferes with insect larval boring and feeding activity. An example of this is the enhanced resistance to rice striped borer of silicon supplemented rice plants (Djamin and Pathak, 1967; Ukwungwu and Odebiyi, 1985; Savant *et al,* 1997). Painter (1951), Takahashi (1996) and Epstein (1999) suggested that silicon deposited in the epidermal tissue may have several functions including support and protection as a mechanical barrier against pathogen and herbivore invasions. It has been demonstrated that the mandibles of larvae of the rice stem borer are damaged when the silicon content of rice plants is high (Djamin and Pathak, 1967) However, in some varieties of wheat, resistance to Hessian fly was not found to be related to high silica content in the plant, and Miller *et al.* (1960) suggested that the physical arrangement of silica along the abaxial portion of the leaf sheath might be another important factor in the resistance of the varieties to the insect.

In plant diseases, the hypothesis of cell wall reinforcement by silicon to explain enhanced resistance of plants against pathogenic fungi has been strongly contested in recent years in dicots, particularly in cucumber plants (Samuels *et al*, 1991; Chérif *et al*, 1994). These authors proposed that soluble silicon activated defense mechanisms in cucumber against *Pythium* by showing enhanced activity of chitinases, peroxidases and polyphenoloxydases, and increased accumulation of phenolic compounds. This is supported by recent evidence suggesting that silicon may reinforce plant disease resistance by stimulating the expression of natural defense reactions through the production of flavonoid phytoalexins (Belanger *et al*, 1995). In the expression of pest resistance, a parallel mechanism is also possible, such as the resistance to *E. saccharina* in sugarcane (Keeping and Meyer, 2002; Meyer and Keeping, 2005), and in other pest resistant crops (Schoonhoven *et al*., 1998). Significant positive correlations were found between the concentration of silicon dioxide in the needles and total phenols in *Thaumetopoea pityocampa*-infected *Pinus* species plants (Schopf and Avtzis, 1987). Furthermore, the mode of action of silicon compounds against insects, such as the noctuid *Trichoplusia ni*, the coccinellid *Epilachna varivestis*, the aphid *Acyrthosiphon pisum*, and the cockroach *Periplaneta americana* was reported to be repetitive firing in the cercal sensory nerves (Sieburth *et al*, 1990b). This could lead to a lower incidence of insect pests observed in crops with high silicon levels.

Conclusion and future research

Research has shown clearly that silicon applications can contribute significantly to reducing damage due to pests and diseases (Belanger *et al*, 1995; Ma and Takahashi, 2002; Meyer and Keeping, 2005). Furthermore, they may alleviate aluminum (Al) and manganese (Mn) toxicity (Ma, 2003) reduce excess nitrogen (N) uptake leading to enhanced insect damage (Sétamou *et al*, 1993, Savant *et al*, 1999), and enhance biological control (Qin and Tian, 2004). Silicon supplementation leaves no insecticide residues in food or the environment, is relatively cheap, and could easily be integrated with other pest management practices including biological, chemical, and cultural practices (Ukwungwu, 1990).

Future research into pest management with silicon applications could include:

- Validation of silicon application for pest control
- Identification of good silicon sources, and their optimal dosages for effective pest control in different crops
- Clarification of the mode of action of silicon in plant resistance to pests
- Integration of silicon applications with biological control for ecologically sustainable pest (and disease) management.

Acknowledgements

Thanks are expressed to the National Research Foundation, South Africa, and Ineos Silicas for funding this research.

REFERENCES

Anderson DL and Sosa O Jr (2001). Effect of silicon on expression of resistance to sugarcane borer (*Diatraea saccharalis*). *Proc J Am Soc Sug Cane Technol* 21: 43-50.

Basagli MAB, Moraes JC, Carvalho GA, Ecole CC and Gonçalves-Gervásio R de CR (2003). Effects of sodium silicate application on the resistance of wheat plants to the green-aphid *Schizaphis graminum* (Rond.) (Hemiptera: Aphididae). *Neotropical Entomology* 32(4): 659-663.

Belanger RB, Bowen PA, Ehret DL and Menzies JG (1995). Soluble silicon: Its role in crop and disease management of greenhouse crops. *Plant Disease* 79: 329-336.

Bernays EA and Barbehenn R (1987). Nutritional ecology of grass foliage chewing insects, pp 147-175 In: Slansky F and Rodriguez JG (Eds), *Nutritional Ecology of Insects, Mites, Spiders and Related Invertebrates*. John Wiley and Sons, New York, USA.

Bhavnagary HM, Singh K and Majumder SK (1988). Silicophosphates as new seed protectants: Studies on the damage by *Trogoderma granarium* Everts and its effect on the germination of wheat seeds treated with silicophosphates. *Seed Science and Technology* 16(2): 507-513.

Chelliah S (1972). Some investigations in muskmelons *Cucunis melo* L. on resistance to the fruit fly, *Dacus cucurbitae* Coquillet (Diptera: Tephritidae). PhD Thesis, Annamalainagar University, Tamil Nadu, India.

Chérif M, Asselin A and Bélanger RR (1994). Defense responses induced by soluble silicon in cucumber roots infected by *Pythium* spp. *Phytopathology* 84: 236–242.

Djamin A and Pathak MD (1967). Role of silica in resistance to Asiatic rice borer, *Chilo suppressalis* (Walker) in rice varieties. *J Econ Ent* 60: 347-351.

Elawad SH, Allen JR and Gascho GJ (1985). Influence of UV-B radiation and soluble silicates on the growth and nutrient concentration of sugarcane. *Proc Soil Crop Sci Soc Florida* 44:134-141.

Elawad SH, Gascho GJ and Street JJ (1982). Response of sugarcane to silicate source and rate. I: Growth and yield. *Agronomy Journal* 74: 481-484.

Epstein E (1999). Silicon. *Annual Review of Plant Physiology and Plant Molecular Biology* 50: 641-664.

Huberty AF and Denno RF (2004). Plant water stress and it consequences for herbivorous insects: A new synthesis. *Ecology* 85:1383-1398.

Jones, LHP and Handreck, KA (1967). Silica in soils, plants and animals. *Advances in Agronomy* 19: 107-149.

Keeping MG and Meyer JH (2002). Calcium silicate enhances resistance of sugarcane to the African stalkborer, *E. saccharina* Walker (Lepidoptera: Pyralidae). *Agriculture and Forestry Entomology* 4: 265-274.

Keeping MG and Meyer JH (2003). Effect of four sources of silicon on resistance of sugarcane varieties to *Eldana saccharina* Walker (Lepidoptera: Pyralidae). *Proc S Afr Sug Technol Ass* 77: 99-103.

Kordan B, Teodorczyk J, Nietupski M and Ciepielewska D (2005). Can sulphur compounds have an effect on the numbers of offspring beetles of *Sitophilus granarius* L.? *Journal of Elementology* 10: 51-55.

Korndorfer AP, Cherry R and Nagata R (2004). Effect of calcium silicate on feeding and development of tropical sod webworms (Lepidoptera: Pyralidae). *Florida Entomologist* 87: 393-395.

Korunic Z (1997). Rapid assessment of the insecticidal value of diatomaceous earths without conducting bioassays. *Journal of Stored Products Research* 33(3): 219-229.

Ma JF (2003). Functions of silicon in higher plants. *Progress in Molecular and Subcell Biology* 33: 127-147.

Ma JF and Takahashi E (2002). *Soil, Fertilizer, and Plant Silicon Research in Japan*. Elsevier Science, Amsterdam, The Netherlands.

Matichenkov VV, Calvert DV and Snyder GH (2000). Prospective of Silicon fertilization for citrus in Florida. *Proc Soil Crop Sci Soc Florida* 59: 137-141.

Meyer JH and Keeping MG (2001). Past, present and future research of the role of silicon for sugarcane in Southern Africa. pp 257-276 In: LEDatnoff, GH Snyder and GH Korndorfer (Eds), *Silicon in Agriculture*. 1st Edition, Elsevier.

Meyer JH and Keeping MG (2005). Impact of silicon in alleviating biotic stress in sugarcane in South Africa. *Sugarcane International* 23: 14-18.

Miller BS, Robinson RJ, Johnson JA, Jones ET and Ponnaiya BWX (1960). Studies on the relation between silica in wheat plants and resistance to Hessian fly attack. *J Econ Ent* 53: 995-999.

Moraes JC, Goussain MM, Basagli MAB, Carvalho GA, Ecole CC and Sampaio MV (2004). Silicon influence on the tritrophic interaction: Wheat plants, the greenbug *Schizaphis graminum* (Rondani) (Hemiptera: Aphididae), and its natural enemies, *Chrysoperla externa* (Hagen) (Neuroptera: Chrysopidae) and *Aphidius colemani* Viereck (Hymenoptera: Aphidiidae). *Neotropical Entomology* 33: 619-624.

Nishimura K, Miyaki Y and Takahashi E (1989). On silicon, aluminium, and zinc accumulators discriminated from 147 species of *Angiospermae*, *Mem. Coll. Agric. Kyoto Univ.* 133: 23–43.

Painter RH (1951). *Insect Resistance in Crop Plants*. Macmillan, New York, USA.

Pan YC, Kuroshio K and Hokama Y (1979). The effect of bagasse furnace ash on the growth of plant cane. *Sugar Journal* 42: 14-16.

Panda N and Kush GS (1995). *Host Plant Resistance to Insects.* Wallingford, Oxon, CAB International.

Panda N, Pradhan B, Samalo AP and Rao PSP (1975). Note on the relationship of some biochemical factors with the resistance in rice varieties to yellow rice borer. *Indian Journal of Agricultural Scienes* 45: 499-501.

Puzyrkov PE, Dorozhkina LA and Dolgushkin VA (1996). Application of tetraetoxisilane for increasing potato yield and for ecological safety of pesticides. *Izvestiya Timiryazevskoĭ Sel'skokhozyaĭstvennoĭ Akademii* 2: 135-144.

Qin Z and Tian SP (2004). Enhancement of biocontrol activity of *Cryptococcus laurentii* by silicon and the possible mechanisms involved. *Phytopathology* 95: 69-75.

Rao SDV (1967). Hardness of sugarcane varieties in relation to shoot borer infestation. *Andhra Agric J* 14: 99-105.

Rojanaridpiched C, Gracen VE, Everett HL, Coors JG, Pugh BF and Bouthyette T (1984). Multiple factor resistance in maize to European corn borer. *Maydica* 29: 305-315.

Salim M and Saxena RC (1992). Iron, silica and aluminum stresses and varietal resistance in rice: Effects on whitebacked planthopper. *Crop Sciences* 32: 212-219.

Samuels AL, Glass ADM, Ehret DL and Menzies JG (1991). Mobility and deposition of silicon in cucumber plants. *Plant Cell Environment* 14: 485–492.

Sasamoto K (1961). Resistance of the rice plant applied with silicate and nitrogenous fertilizers to the rice stem borer, *Chilo suppressalis* Walker. *Proceedings of the Faculty of Liberal Arts and Education* Vol. 3. Yamanasaki University, Japan.

Savant NK, Snyder GH and Datnoff LE (1997). Silicon management and sustainable rice production. *Advances in Agronomy* 58: 151-199.

Savant NK, Korndorfer GH, Datnoff LE and Snyder GH (1999). Silicon nutrition and sugarcane production: A review. *Journal of Plant Nutrition* 22: 1853-1903.

Schoonhven LM, Jermy T and van Loon JJA (1998). Insect plant biology. *From Physiology to Evolution.* Chapman & Hall, London, UK.

Schopf R and Avtzis N (1987). The importance of needle compounds in the predisposition of five pine species to *Thaumetopoea pityocampa* (Schiff.). *J Appl Ent* 103: 340-350.

Sétamou MF, Schulthess F, Bosque-Perez NA and Thomas-Odjo A (1993). Effect of plant N and Si on the bionomics of *Sesamia calamistis* Hampson (Lepidoptera: Noctuidae). *Bull Ent Res* 83: 405-411.

Sieburth SMcN, Lin SY and Cullen TG (1990a). New insecticides by replacement of carbon by other group IV elements. *Pesticide Science* 29: 215-225.

Sieburth SMcN, Manly CJ and Gammon DW (1990b). Organosilane insecticides. Part I: Biological and physical effects of isosteric replacement of silicon for carbon in etofenprox and MTI-800. *Pesticide Science* 28: 289-307.

Takahashi E (1996). Uptake mode and physiological functions of silica. *Science of the Rice Plant: Physiology, Food and Agriculture Policy Resources* 2: 420-433.

Ukwungwu MN (1990). Host plant resistance in rice to the African striped borer, *Chilo zacconius* Bles. (Lepidoptera: Pyralidae). *Insect Sci Appl* 11: 639-647.

Ukwungwu MN and Odebiyi JA (1985). Resistance of some rice varieties to the African striped borer, *Chilo zacconius* Bleszynski. *Insect Sci Appl* 6: 163-166.

Weryszko-Chmielewska E and Soczyński G (1994). Anatomical features of leaves of three cultivars of winter wheat (*Triticum aestivum* L.) and colonization of the plants by cereal leaf beetles, *Oulema* spp. (Coleoptera, Chrysomelidae). *Acta Agrobotanica* 47: 53-62.

Yoshihara TK, Sogawa MD, Pathak BO and Sakamura S (1979). Soluble silicic acid as a sucking inhibitory substance in rice against the rice brown planthopper (Delphacidae: Homoptera). *Entomologia Experimentalis et Applicata* 26: 314-322.