

SILICON USE FOR PEST CONTROL IN AGRICULTURE: A REVIEW

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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 officinarum* 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 SiO₂ 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 (Na₂SiO₃.5H₂O) 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.

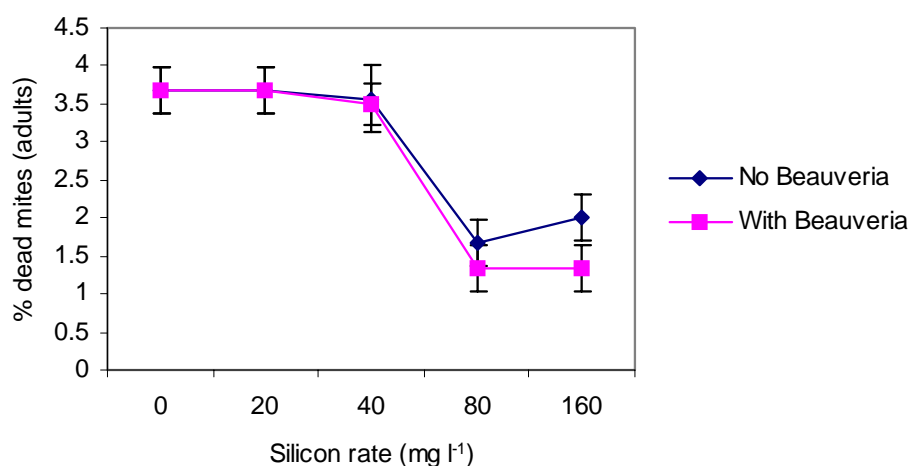


Figure 1. Trial 1: Leaf damage index means of brinjal for four potassium silicate rates plus a control (no Si), with Eco-Bb (*Beauveria bassiana*) (applied or not applied).

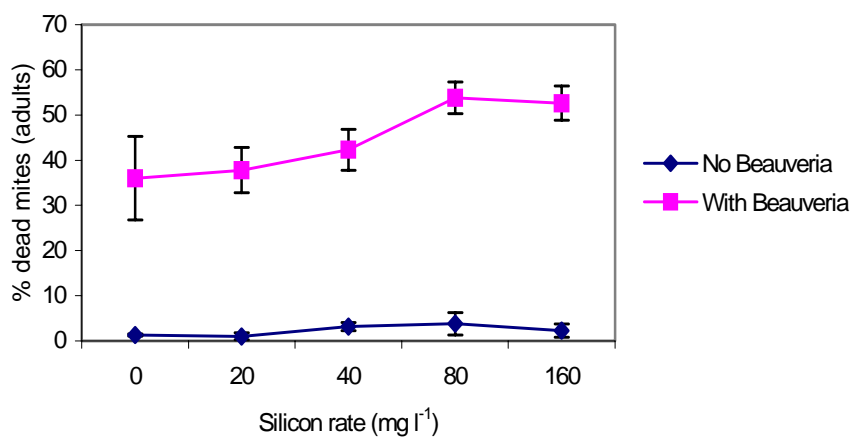


Figure 2. Trial 1: Percentage of dead adult mites associated with four different levels of potassium silicate plus a control (no Si), and Eco-Bb (*Beauveria bassiana*) (applied or not applied) observed on brinjal.

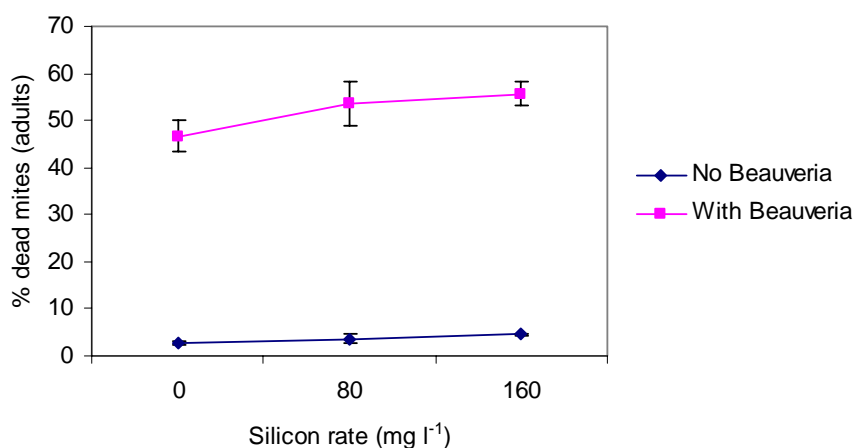


Figure 3. Trial 2: Percentage of dead adult mites associated with two different levels of potassium silicate plus a control (no Si) and Eco-Bb (*Beauveria bassiana*) (applied or not applied) on brinjal.

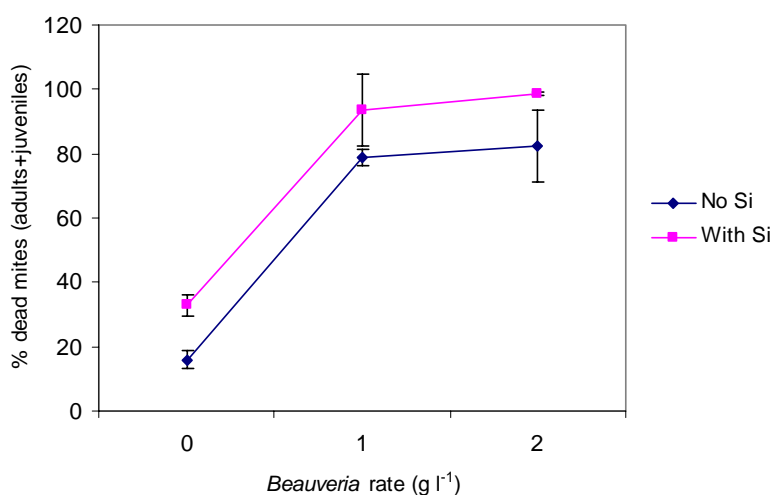


Figure 4. Trial 3: Percentage of dead mites associated with potassium silicate treatment (at 0 or 160 mg/L) and Eco-Bb (*Beauveria bassiana*) at two different rates plus a control (no *B. bassiana*) on brinjal.

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 polyphenoloxylases, 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 *Acyrtosiphon 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.

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