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Review
SILICON IN THE CROP RESISTANCE TO AGRICULTURAL PEST

Revisión bibliográfica
El Silicio en la resistencia de los cultivos a las plagas agrícolas

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ABSTRACT. The silicon (Si) is the most abundant element in the terrestrial (crust) after the oxygen. The Si is not considered essential for the higher plants because it doesn't respond to the direct and indirect approaches of the essentiality. In spite of that its absorption can cause beneficent effects for some crops, such as: resistance to pests and diseases. The objective of the present paper was to carry out an up-to-date revision of investigation results related with the resistance to the insect's pests that confers the silicon in some crops. Since more than 40 years investigation results on beneficent effects on the resistance of the insect's pests on different crops have been informed, however the information is even poor in many crops and insect groups. The most encouraging results for the reduction of pests obtained from the literature was concentrated at the beginning in rice, sugar cane, corn and others Gramineae specie, but later were informed in Solanaceae, Cucurbitaceae, Cruciferaceae, forest specie and coffee, being the most successful results on insect species that are located mainly in Lepidoptera, Hemiptera and Thysanoptera orders. Among the sources more widely used of this element are, the scum of calcium silicate and the silicate of potassium.

Key words: insect, pest management, plant nutrition

RESUMEN. El silicio (Si), después del oxígeno, es el segundo elemento más abundante en la corteza terrestre y considerado no esencial para las plantas superiores. Su absorción puede ocasionar efectos benéficos para algunos cultivos, como la resistencia a plagas. El objetivo del trabajo fue realizar una revisión actualizada de los resultados de investigación relacionados con la resistencia que confiere el silicio a algunos cultivos contra los insectos plagas. Desde hace más de 40 años se están informando los efectos benéficos del Si en la resistencia de los cultivos a los insectos plagas, sin embargo la información es aún pobre en muchos cultivos y grupos de insectos. Aunque los resultados más alentadores se concentraron en un inicio en el arroz, la caña de azúcar, el maíz y otras gramíneas, se informan también en solanáceas, cucurbitáceas, crucíferas, forestales y el cafeto, siendo más exitosos sobre las especies de insectos que se ubican principalmente en los órdenes Lepidóptera, Hemíptera y Thysanóptera. Entre las fuentes de silicio más empleadas para el manejo de insectos plagas se encuentran la escoria de silicato de calcio y el silicato de potasio.

Palabras clave: insectos, manejo integrado de plagas, nutrición de las plantas

INTRODUCTION

Plant mineral nutrition has been one of the most studied factors related to plant susceptibility and resistance against pests and diseases. In general, high nitrogen contents and low potassium concentrations increase plant susceptibility to harmful agents (1).

Plant resistance to pests and diseases may decrease or increase by mineral nutrition effect on anatomical structures, as for instance: thinner cuticles and epidermal cells, cell wall with lower degree of salification, suberization and lignification. Besides, nutrition may affect biochemical properties, such as reducing phenolic compounds, which act as pest and disease developing inhibitors or accumulating low-molecular-weight organic compounds (glucose, sucrose and amino acids) as a result from the increased activity of decomposing enzymes, as amylases, cellulases,

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proteases and carbohydrases, that is very common with potassium deficiency (2).

A well-nourished plant has several advantages in terms of its resistance to pests and diseases compared to a nutritionally deficient plant, and among mineral elements, silicon is considered beneficial to plants, since it helps reduce harmful agent intensity in several crops (3).

Silicon (Si), after oxygen, is the second most abundant element on earth; it consists of about 28 % terrestrial crust (4) and is only found in combined forms, such as silica and silicon minerals. Silicates are minerals in which silicon is combined with oxygen or other elements as Al, Mg, Ca, Na, Fe, K, and others in over 95 % terrestrial rocks, meteorites, in all waters and the atmosphere (5). The most common silicone minerals are quartz, alkali feldspar and plagioclases (6).

Silicon is present only as monosilicic acid ($Si(OH)_4$) in soil solution, mostly as non-dissociated form, which is readily available to plants. Due to des-silicatization caused by intense weathering and tropical soil leaching, most silicon forms found in these soils are quartz, opal ($SiO_2.NH_2O$) and other unavailable forms to plants. Chemically active silicon forms in the soil are represented by soluble and frankly adsorbed monosilicic acid, polysilicic acid and organ-silicic compounds (7).

Its beneficial effects have been proved in several plant species and, in the case of plant health, it is able to improve plant resistance against the attack of insects and pathogens (8). Silicon may confer plant resistance by deposition, making up a mechanical barrier (9), or by its action as resistance inducer (10).

The objective of this study was to make an updated review on research results related to resistance conferred by silicon to some crops against insect-pests.

SILICON IN THE PLANT

Silicon is not considered essential to higher plants, because it does not respond to direct and indirect criteria of essentiality (3). However, its absorption may cause beneficial effects to some crops, such as: pest and disease resistance, tolerance to heavy metal toxicity as well as to water and salt stress, lower evapotranspiration, promoted legume growth and nodulation, effect on enzyme activity and mineral composition, improved plant architecture, reduced plant lodging and, thereby, increased photosynthetic rate (8, 11).

Plants absorb silicon as silicic acid and evaluations recorded on dry matter indicate element concentrations of 0,1-10 % in rice and sugarcane crops (8). In general, grasses are considered Si-accumulative plants, although some dicots also seem to show this feature (8).

Soils contain significant amounts of Si; however, the use of continuous crop systems, some unavailable forms or biologically-unbalanced soils make its supply necessary. For instance, sugarcane can extract up to 380 kg ha^{-1} $year^{-1}$ from the soil (12). Silicon levels in the tissues of each plant species vary in relation to its availability in the soil (13).

Most species absorbs silicon by passive diffusion, so that it reaches the xylem up to the aerial part along with transpiration rate. Moreover, species of *Poaceae*, *Equisetaceae* and *Cyperaceae* families having high Si accumulation (>4 % Si in dry weight) actively absorb it (14). In this case, silicon is absorbed via specific membrane proteins, ensuring its plant accumulation regardless of the concentration gradient (15).

Silicon absorbed by roots is transported to the aerial part and intra- or extra-cellularly deposited in plant tissues as hydrated amorphous silica ($SiO_2.NH_2O$). In grasses such as corn, rice and sorghum, silica is deposited in the form of siliceous bodies mainly in epidermal cells, leaf stomata and trichomes (14).

In many species, a thick layer can be found under the cuticle formed by silica deposition. Such layer formation has been essential under abiotic stress conditions, in order to help reduce water loss through transpiration and increase its efficiency (16) or biotic stress, it being a mechanical barrier against pathogen and chewing herbivore penetration (8, 12).

Concerning grasses, silicon accumulates higher quantities than any other inorganic element. It is not considered a nutrient except in certain algae, diatoms and Equisetaceae (*Equisetum bogotense* Kunth, horsetail). As a result, silicon is omitted when formulating routine culture solutions and conventional fertilization.

However, evidence shows that plant structures growing without Si are often weaker and more susceptible to abiotic stress, as metal toxicity, also easily attacked by organisms, phytophagous insects and herbivorous mammals (8).

Silicon plays an important role in the structural integrity of plant cells by contributing to its mechanical properties besides including rigidity and elasticity (17). It is present in plants mainly as silica gel in cell walls and as monosilicic acid in xylem sap. Its role in cell walls appears to be analogous to lignin as a resistant element with higher rigidity to replace water between micro-fibrils and other carbohydrate components from non-lignified cell walls[A].

Silicon consists of 0,1 to 10 % dry weight of higher plants, compared with calcium, whose values range from 0,1 to 0,6 % and sulphur from 0,1 to 1,5 %. Rice accumulates up to 10 % Si and monocots generally accumulate more than dicots, although differences may be even at varietal level (3, 8). Nevertheless, tests performed indicate that Si concentration is more influenced by phylogenetic position (genus, species) than by environmental factors, such as water and silicon availability or temperature.

[A]Husby, C. *The role of Silicon in Plant Susceptibility to Disease*. 1998, pp. 1-6.

SILICON ROLE IN PLANT RESISTANCE TO AGRICULTURAL PESTS

In order to improve plant resistance to insect attack, silicon role has been partly attributed to its accumulation and polymerization in cell walls, which constitutes a mechanical barrier against the attack; however, silicon treatment has shown to promote biochemical changes as the accumulation of phytoalexins, lignin and phenolic compounds (11). In plants such as squash (*Cucurbita* spp.), oat (*Avena sativa* L.) and sorghum (*Sorghum bicolor* L. Moench), it has been observed that silicon fertilization increases the synthesis of peroxidase, polyphenol-oxidase, glucanase and chitinase enzymes, which are related to a higher production of quinones with antibiotic properties, favoring a greater tissue lignification, reducing nutritional quality and digestibility, all of which consequently decreasing insect preference for plants (18).

According to Arruda[B], although there is a great natural silicon availability in most soils with maize crop (*Zea mays* L.), which has been verified, its effects on plants and consequently on the biological agents attacking them are not enough to significantly interfere in pest occurrence and damage prevention, so that more research studies should be performed.

[B]Arruda, A. C. *Efeito do silício aplicado no solo e em pulverização foliar na incidência da lagarta do cartucho na cultura do milho dissertação apresentada à Faculdade de Ciências Agronômicas da Unesp*. Mestre em Agronomia, Campus de Botucatu, Brasil, 2009.

SILICON EFFECTS ON PLANT RESISTANCE TO AGRICULTURAL PESTS IN DIFFERENT CROPS

The oldest studies about silicon effect upon agricultural pests have focused on rice crop (*Oryza sativa* L.). Plant resistance to stem borer, *Chilo suppressalis* (Walker) (Lepidoptera: Pyralidae), was positively correlated with silicon content and determined in 20 rice varieties. It was concluded that fewer larvae were found in varieties with high Si content, thereby decreasing insect damage percentage. A high negative linear correlation was also verified between larval survival and silicon percentage recorded in plants (19). For rice pests such as delphacids, thrips and gall midge, one silicon application helped reduce insect populations (20, 21).

The effect of different silicon sources on *Stenchaetothrips biformis* (Bagnall.) (Thysanoptera: Thripidae) in rice crop was studied by Subramanian and Gopalaswamy (20), who concluded that thrips number per leaf was significantly lower in treatments with silicon compared to that without it.

In a study conducted to evaluate the effect of nymphs *Sogatella furcifera* (Horváth) (Hemiptera: Delphacidae) in rice seedlings at Si concentrations (0-150 ppm $Si0_2$), last-instar nymph number decreased whereas male individuals increased in the population (24).

For the species *Chilo supremain* (Walker) (= supressalis), it may be considered a pest in rice crop; Tayabi and Azizi (23) proved that applying 500 kg ha^{-1} potassium silicate reduced over half the number of larvae m^{-2}. Similar responses were observed by Sawant *et al*. (24) for *Scirpophaga incertulas* (Walker), who showed that adding 2 kg m^{-2} carbonized rice husk (rich in silicon) to rice plants increased silicon content significantly and decreased pest damage.

In wheat crop (*Triticum sativum* Lam), aphid populations of *Metopolophium dirhodum* (Walker) and *Sitobion* avenae (Fabr.) (Hemiptera: Aphididae) decreased after foliar Si application (1 % Na_2SiO_2), not only as a result of its deposition in epidermal cells, but also because of its greater solubility inside leaves[C].

With six treatments of sodium silicate (0,4 % SiO_2) applied at intervals of five days at a dose of 50 mL per pot, it was able to reduce green aphid *Schizaphis graminum* (Rond.) (Hemiptera: Aphididae) nymph longevity and preference; thus, Si was considered to confer resistance to such plants against insects (25).

Others aurhors found that silicon fertilization induces wheat plant resistance against *S. graminum*, since this element increases the synthesis of wheat plant defense compounds such as peroxidase, polyphenol-oxidase and phenylalanine ammonia lyase, reduces growth rate and insect-pest preference in plants treated with this mineral (18). In another study, it was found that silicon-treated wheat plants (1 % silicic acid) were resistant to green aphid *S. graminum* (26).

In a study to observe the indirect effect of silicon on the development of two important natural enemies of green aphid, *Chrysoperla externa* (Hagen) (Neuroptera: Chrysopidae) and *Aphidius colemani* Viereck (Hymenoptera: Aphidiidae) on wheat plants, it was shown that neither the predator nor the parasitoid experienced biological changes, when fed with aphids from silicon-treated plants (27).

The agricultural use of silicon has not been proved to alter communication between plants and natural enemies. Given the importance of integrating pest control methods, the study of changes in trophic relationships involved is essential to understand the effectiveness of biological control of aphids in silicon-fertilized plants (28).

Six commercial sugarcane varieties (*Saccharum* spp) were treated in a study with two levels of calcium silicate (5000 and 10 000 kg ha^{-1}). After artificially infested by *Eldana saccharina* Walker (Lepidoptera: Pyralidae), larval borer weight was reduced by 19,8 % and its length by 24,4 %. Variables evaluated for Si treatment at 5000 ha^{-1} were intermediate in relation to treatment of the highest dose and control. The interaction between variety and Si treatment was not significant when varieties were individually examined. Susceptible varieties could benefit most from silicon treatment than resistant ones, since the latter did not show a significant effect on the beneficial element application (29).

In sugarcane, pest attacks could be reduced by using cultivars with greater Si storage capacity, as in the case of *E. saccharina* borer in South Africa (30).

It is unable to establish a relationship between Si absorption and the effect of sugarcane (*Diatrarea saccharalis* F.) borer in an investigation conducted under field conditions in Brazil (31), which was attributed to a low pest impact on the control and treatment (less than 4 %), meanwhile more recent results confirmed that a greater Si absorption at the aerial part of sugarcane was associated with a lower borer effect on more susceptible varieties (32).

Another crop where silicon effect on pests has been mostly studied was maize (*Zea mays* L.) (9); it was found that 48 hours after supplying corn leaves treated and untreated with silicon, there were not any differences in *Spodoptera frugiperda* Smith larval mortality, although it was considered too early to infer the true silicon effect on its immature stages.

Other studies with this lepidopterum report no silicon (sodium silicate) effect on larval and pupal stage length, or pupal weight and mortality. However, larval mortality and cannibalism increased in groups fed by Si-treated leaves. It was observed that sixth-instar larval jaws showed a marked incisor weakening when they came in contact with leaves of high silicon content (9).

In order to evaluate Si (applied to soil and leaves) effect interacted with insect growth regulator (lufenuron) to manage *S. frugiperda* in corn, trials were conducted under laboratory and greenhouse conditions.

[C] Hanisch, H. C. *Zun einfluss der stickstoffdungung und vorbeugender spritzung von natronwasser glas zu weizenpflanzen auf deren widerstands-fahigkeit gegen getreideblattlause*. no. 15, Inst. Kali-Driefe, 1980, pp. 287-296.

In the laboratory, caterpillar preference as well as pest consumption and mortality were evaluated in detached maize leaves under different treatments. Caterpillar injure intensity in leaves, live caterpillar number and biomass were evaluated in greenhouse. Treatments did not affect caterpillar preference in the free screening test. Silicon and lufenuron interaction in handling *S. frugiperda* was positive in relation to insecticide applied alone, which was attributed to the mechanical resistance conferred to leaves by its silicon layers deposited on them (33, 34).

Silicon effect is also evaluated to manage corn aphid (*Rhopalosiphum maidis* Fitch) (Hemiptera: Aphididae). Treatments consisted of applying silicon to the soil (sodium silicate 8 %), a foliar application (0,5 % SiO_2), two foliar applications, combination of soil and foliar application and an untreated control. It was confirmed that treatments in which silicon was applied to the soil plus another foliar fertilization (0,5 % SiO_2) or two foliar applications presented the least aphid number, increased leaf resistance and hindered insect feeding (35).

Other studies such as that of Carvalho *et al*. (36) in sorghum (*Sorghum bicolor* L. Moench) evaluated silicon effect as a resistance inducer to green aphid, *Schizaphis graminum* (Rond) (Homoptera: Aphididae), which reduced aphid reproduction and preference; it was complemented by an article reporting satisfactory results when silicon was used to confer sorghum resistance against *S. graminum* (37).

The resistance of 19 pasture genotypes to weevil attack, *Listronotus bonariensis* (Kuschel) (Coleoptera: Curculionidae), was studied by Barker (38), who confirmed that laid number per plant was negatively correlated with Si deposit density on the lower pod surface, which also hindered larval feeding.

Another more recent study evaluated the effect of different calcium silicate doses on chestnut bug nymph population, *Scaptocoris carvalhoi* Becker in *Brachiaria brizantha* (Hochst) in roots, and it was concluded that 2,6 t ha^{-1} calcium silicate was the best dose applied to reduce insect nymphs (39).

There are several studies in literature related to silicon and pest resistance in potato (*Solanum tuberosum* L.) and other Solanaceae. Regarding *Myzus persicae* (Sulzer) aphid, an important potato pest as a virus vector which also causes direct damage by sap extraction, a study was conducted to test Si effect (silicic acid 1 %) as resistance inducer to this insect. Silicon fertilization did not affect aphid preference; however, it decreased insect fertility and population growth rate. Lignin percentage increased in leaves from silicon-fertilized plants through the soil and leaves, whereas tannin percentage was only higher in silicon-fertilized plants through leaves than the soil (40).

In another study conducted to evaluate silicon and imidacloprid effect on potato plants colonized by *M. persicae*, it was found that Si reduced *M. persicae* colonization and used half the recommended dose of imidacloprid (126 g ha^{-1}).

It was also effective in preventing colonization, so that silicate fertilization can be recommended as another strategy in integrated potato pest management (41).

Potato crop results report the effect of *Diabrotica speciosa* (Coleoptera: Chrysomelidae) and aphids (Hemiptera: Aphididae) was not influenced by weekly foliar application of silicon (silicic acid 0,5 %) (42).

Nymph mortality and injure number of *Thrips palmi* Karny on eggplant (*Solanum melongena* L.) leaves were evaluated after 3, 6, 9 and 12 foliar applications of calcium silicate, which decreased both *T. palmi* population and nymph damage, besides showing a possible increased plant resistance to this pest (43).

In a paper aimed at evaluating the use of different silicon sources and levels on the biological aspects and preferential oviposition of tomato leaf miner (*Tuta absoluta*) (Meyrick) (Lepidoptera: Gelechiidae), it was evident that insects emerging from eggs in treatments based on silicon foliar application showed a greater larval and pupal stage length, reduced larval and pupal survival, decreased pupal (male and female) weight and oviposition preference, which did not occur when it was applied to the soil (44).

In more recent studies, silicon solutions at 100, 300 and 500 mg L^{-1} derived from potassium silicate (K_2SiO_3) were applied to pepper plants (*Capsicum annuum* L.) by foliar spraying and saturated soil solution to assess the effects of chili thrips (*Scirtothrips dorsalis* Hood) in populations.

Tissue analysis showed that through saturated soil solution, plant roots were able to absorb up to nearly 2,5 % Si (p/p), but it was not transferred to stem or leaf tissues at an equivalent rate. Foliar application of silicon presented about 0,5 % (p/p) in leaf tissues. It was concluded that pepper plants treated with potassium silicate solutions do not accumulate sufficient Si levels in tissues to protect them from thrips feeding and reproduction (45), as the levels are very low with respect to what is reported for accumulative plants (14).

The influence of calcium silicate and acibenzolar-S-methyl activator to induce resistance against *Bemisia tabaci* biotype B (Gennadius) (Hemiptera: Aleyrodidae) development has been studied in cucumber (*Cucumis sativus* L.). Were observed adverse effects of calcium silicate and acibenzolar-S-methyl activator on whitefly population by reducing oviposition, increasing biological cycle and nymph mortality; thus, these products are recommended to be used in the integrated whitefly management of this crop (46).

Research studies aimed at evaluating the effect of resistance inducers of two soybean (*Glycine max* L.) cultivars against *Bemisia tabaci* biotype B have proved that silicon applications increase lignin content in IAC-19 cultivar (47). Other studies in this crop showed that foliar applications of potassium silicate influenced variables and reduced larvae that attack soybeans (48).

Silver thrips, *Enneothrips flavens* Moulton, is considered one of the main peanut (*Arachis hypogaea* L.) pests in several countries. In a study where silicon effect was evaluated on this insect population, it was proved that a single silicon application increases peanut plant protection, as it reduces insect number of adults and nymphs (49).

Silicon treatment strategy combined with artificial mechanic injury affected palatability to sunflower (*Helianthus annuus* L.) leaves and *Chlosyne saundersii lacinia* Doubleday & Hewitson (Lepidoptera: Nymphalidae) development; thus, it conferred resistance to sunflower plants due to Si accumulation (50).

In a study aimed to evaluate silicon effect on *Aphis gossypii* Glover behavior in cotton *Gossypium hirsutum* Hutch cultivars, it was concluded that Si applications did not affect preference of *A. gossypii*-treated or not-treated varieties (51).

In an investigation performed to evaluate the potential use of silicon as a physical barrier that helps reduce pesticide application to the integrated management of crucifer moth *Plutella xylostella* (L.), silicate slag (agrosilicon) with 23 % Si was used as a source in treatments. A significant effect of treatments was evident in variables evaluated, observing more attraction and larval mortality in the treatment of 12 kg ha^{-1} slag. Silicon altered jaw anatomy, causing its weakening, which could have hampered insect feeding habits and its high mortality (52).

In the last 10 years, Si has also been applied to forests, in order to know if it confers resistance against insect pests. Dal Pogetto *et al*. (57), in a study using Agro-silicon®, evaluated the effect of its application to *Glycaspis brimblecombei* (Moore) (Hemiptera: Psyllidae) biological development in *Eucalyptus camaldulensis* (Dehn.)[D]. Silicon caused a higher nymph mortality of *G. brimblecombei* and reduced its population.

In another study on *Pinus taeda* L., with the objective to assess silicon (silicic acid) effect on the biological and morphometric parameters of *Cinara atlantica* (Wilson) (Hemiptera: Aphididae), it was determined that applying silicic acid decreased female nymph number compared with the control. Regarding morphometry, it was proved that out of 15 characters evaluated, head width and total length of *C. atlantica* antenna differed for specimens developed in Si-treated plants with respect to those kept in the control (53).

In general, pest management in coffee (*Coffea* spp) takes place just by applying chemical pesticides; however, alternative silicon products appear as a sustainable choice to pest control in this crop. Some studies were conducted to assess silicon efficiency on main pest control including miner (*Leucoptera coffeella* Gué.), compared to chemical treatments (54), and it was proved that the application of 4 L ha^{-1} soluble liquid silicon (Sili-K) and not by a solid form, reduced pest rates.

[D] Dal Pogetto, M.; Wilcken, C. F.; Lima, A. C. V. y Christovam, R. S. ''Efeito da aplicação de Agrosilício em mudas de *Eucalyptus camaldulensis* no desenvolvimento biológico de *Glycaspis brimblrcombei* (Hemiptera:Psyllidae)''. En: *IV Simpósio Brasileiro sobre Silício na Agricultura*, edit. Associação Brasileira de Horticultura, Brasil, 2007, pp. 210-213.

CONCLUSIONS

For more than 40 years, research results about the beneficial effects of silicon on crop resistance to insect-pests have been reported; however, information is still poor in many crops and groups of insects. Although the most encouraging results initially focused on rice, sugarcane, maize and other grasses, they are also reported in solanaceae, cucurbits, crucifers, forests and coffee, the most successful being on insect species mainly from the orders Lepidoptera, Hemiptera and Thysanoptera. Calcium and potassium silicate slag is among the most widely used silicon sources for insect-pest management.

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