Atta, B., Rizwan, M., Sabir, A.M, Gogi, M.D, & Ayub, M. (2019). Silicon mediated induced resistance in plants for the management of agricultural insect pests: A review. *World Journal of Biology and Biotechnology, 4*(1), 19-28.
DOI: https://doi.org/10.33865/wjb.004.01.0192

(Online) ISSN2522-6754 | 2019 | (Print) ISSN 2522-6746
WORLD JOURNAL OF BIOLOGY AND BIOTECHNOLOGY
Volume: 04 | www.sciplatform.org | Issue: 01

SILICON MEDIATED INDUCED RESISTANCE IN PLANTS FOR THE MANAGEMENT OF AGRICULTURAL INSECT PESTS: A REVIEW

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ABSTRACT

Use of pesticides is the main approach adopted by many farmers to manage agricultural insect pests which not only reduced infestation level of these insect pests, but also responsible for the resistance and resurgence development, causes mortality of beneficial arthropods, and environmental and health hazards. Many researchers are busy to find out alternatives to pesticides due to adverse influences. Pest damage may also be reduced through the proper management of nutrient requirements and modification with mineral nutrients such as silicon. Silicon has been authoritatively designated as a "beneficial substance" by the Association of American Plant Food Control Officials and plant-available Si may now be listed on fertilizer labels. It plays an important role in the resistance of agricultural crops against several insect pests. Numerous direct and indirect effects had been observed on insect herbivores due to this micro-nutrient. Direct effects include decline in the performance, which ultimately minimized plant damage while indirect effects include interruption in establishment, increasing population of natural enemies and reduction in the usage of pesticides. The purpose of this review article is to recapitulate the work of different researchers throughout the world on the management of insect pests by using an alternate strategy which has no side effects on human as well as environment and are easily available to the farmers in cheap price.

Key word: Pesticides; silicon; resistance; resurgence; beneficial substance; AAPFCO.

INTRODUCTION

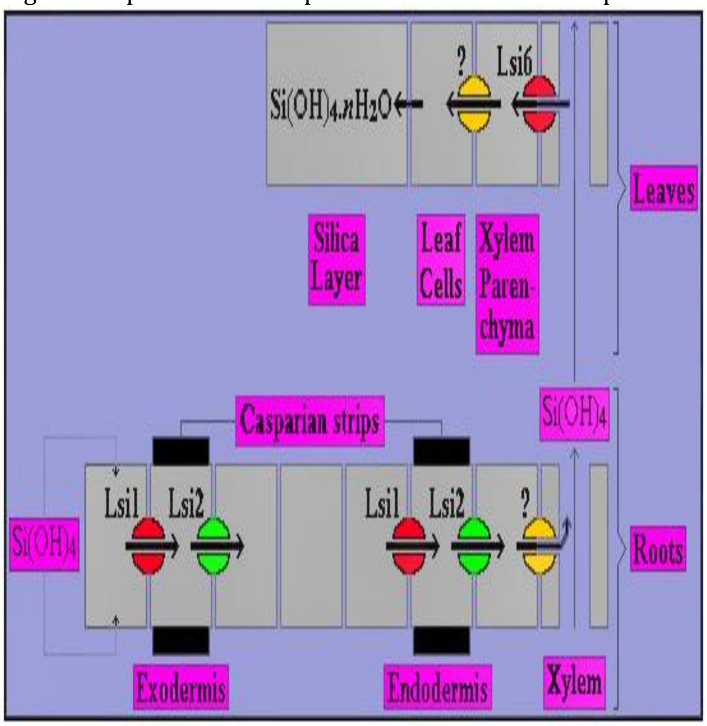
Silicon (Si) occurrence in nature is totally in oxidized form, as the compounds silicates and silicon dioxide. Si is considered the 2nd most abundant element which is present on the surface of the earth, accounting for 25.8% by weight. It considered as the most significant constituent of inorganic materials. Meanwhile, Si is very rarely found in nature as an element, so it was not isolated until (Isay *et al.*, 2015). The average concentration of Si in the lithosphere is around 28% and in soils normally ranges between 23-35%. It is the main component of soil, which lost throughout weathering. The most significant mechanism in the formation of soil depends upon the alteration of Si into secondary minerals and present in the form of principal silicate minerals, secondary alumino-silicates and Silicon dioxide (SiO_2). The amount of Si present in soils depends upon the nature of soils, climatic conditions, geological constituents, nature of rocks and minerals forming soils, etc. However, sandy soils comprise > 40% Si as compared to 9% Si in extremely weathered tropical soils. It is a tetravalent Si^{+4} element, which is not present in free-state (Matichenkov and Calvert, 2002).

Silicon (Si) considered as non-essential element for the growth of the plants especially for Poaceae crops (Jones and Handreck, 1967) but now considered as a 'functional' plant nutrient with specific functions includes strengthening the cell wall (Painter, 1951), enhances resistance to different insect pests (Qin and Tian, 2005), leaves no residues in food or the environment, relatively cheap and easily be integrated with other pest management practices (Ukwungwu, 1990).

Rice is considered as a high Si accumulating plant. Average range of Si uptake by rice crop is 230-470 kg ha^{-1}. It is a constructive element for the growth of plants and is agronomically crucial for the improvement and sustainability in rice production. It is also responsible for increasing availability of secondary nutrients (nitrogen, phosphorus, potassium, calcium, magnesium, sulfur and zinc), decreasing toxicity of nutrients (iron, manganese, phosphorus and aluminum) and reducing both biotic and abiotic stresses in plants. It is also responsible for the mechanical strength of the culm which results in the reduction of crop lodging (Savant *et al.*, 1996).

Mechanism of uptake and transportation of silicon in plants: Si is freely absorbed via plant roots as non-chargeable orthosilicic acid [$Si(OH)_4$]. Vigorous absorption of Si has been observed in numerous plant species, particularly monocotyledons (Liang *et al.*, 2005). Meanwhile, rice plant is considered a renowned Si accumulator, mechanism of Si uptake has been studied in this plant species. Two different Si transporters having diverse mode of action are responsible for the transport of silicic acid in rice roots which pass the casparian strips in exodermis and endodermis cells (Figure. 1). Lsi1 (an influx transporter) is situated on the plasma membrane at the distal side of both exodermis and endodermis cells. Lsi2 transporters are located at the proximal side of exodermis and endodermis cells, which are responsible for the exit transportation of silicic acid from these cells (Feng *et al.*, 2011). Silicic acid uptake through Lsi1 is in a passive manner, whereas transport through Lsi2 transporters is passively driven by an ATP-consuming H+ pump. Once taken up by Lsi1 in the exodermis and released by Lsi2, silicic acid diffuses through the apoplast of the aerenchyma. In endodermis cells, Lsi1 transporters take up the silicic acid from the aerenchyma and Lsi2 transporters load it into the stele. An unidentified transporter is responsible for the loading of silicic acid to xylem. Silicic acid took up by the leaf cells from the xylem through Lsi1-like transporter which is Lsi6. An ordinary polymerization progression take place inside the leaf cells, which alter water soluble silicic acid to insoluble silica ($SiO_2 \cdot nH_2O$) whichever inside the cell, as phytoliths and colloidal cytoplasmic silica, or outside the cell as a silica layer or silica bodies positioned just underneath the cuticle (Feng *et al.*, 2011).

Figure 1: Uptake and transportation of silicon in rice plants.



Influence of silicon on plants: Tolerance of plants may be increased by the indirect effect of Si to abiotic stresses, particularly water stress, through which insect population and plant damage may be reduced (Kvedaras *et al.*, 2007a). Two different mechanisms are responsible for increasing the resistance due to Si to insect herbivore feeding.

The major mechanism which is considered as Si mediated defenses of plant from a long time is the increase in physical resistance which is based on solid amorphous silica, while recently there is a new confirmation for induced physical defense. Reduction in digestibility and/or increase in hardness and roughness of plant tissue have been observed because of deposition of silica as opaline phytoliths in numerous tissues includes epidermal silica cells (Massey and Hartley, 2009).

Additional, much evidence have been obtained about the involvement of soluble Si in induced chemical defenses to attack of insect herbivore by higher production of defensive enzymes such as polyphenoloxidase, peroxidase and phenylalanine ammonia-lyase (PAL) activities in wheat (Gomes *et al.*, 2005) or maybe the enhanced release of plant volatiles. Oxidation of phenolic compounds to quinones is catalyzed by polyphenoloxidase. As a result of this catalysis, nutritional quality of the food becomes reduced and digestibility of protein becomes decrease (Felton *et al.*, 1994). Lignification and suberin synthesis are responsible for the tissue hardness and in the production of quinones and active oxygen (both possess antibiotic properties). So, there is the involvement of peroxidase in lignification and suberin synthesis process (Stout *et al.*, 1994). The production of phenolic compounds have been increased by the activity of phenylalanine ammonia-lyase (PAL), having anti-nutritional, toxic and deterrent properties (Appel, 1993).

Silicon accumulation and deposition: Plants absorbed Si as silicic acid ($SiO_2.nH_2O$). Xylem is responsible for the transportation of silicic acid to all plant parts after absorbance. It is deposited as opal-shaped or amorphous $SiO_2.nH_2O$ (Jones and Handreck, 1967). Si becomes immovable after deposition (Aston and Jones, 1976). A mechanical barrier which is known as "double layer silicon-cuticle" is formed directly below the cuticle as a result of accumulation and polymerization of Si in the epidermal cells as amorphous silica. The functions of this double layer silicon-cuticle are to maintain the leaves erect, reduce the transpiration and protect the plants against the attack of insects and fungus (Yoshida, 1975). However, involvement of Si is not only limited to the mechanical restraints against infection caused by fungi and damage caused by insects but also limited to biochemical changes related to plant defense in general (Peixoto *et al.*, 2011). The response mechanism produced in plants against the attack of sucking insect have some resemblance to those following attack by the pathogens (Dreyer and Campbell, 1987).

Si induced defense mechanisms also includes alterations in the trichome morphology, lignin accumulation, peroxidases, chitinases and phenolics production (Chérif *et al.*, 1994). Several of these factors are also associated to resistance in plants against sucking insects modifying also their probing behavior (Ramírez and Niemeyer, 1999).

Influence of silicon on insect pests: Graminaceous plants include wheat, barley and ryegrass take up much more Si as compared to other plant species (Liang *et al.*, 2005). Si is responsible for the management of different insect herbivores includes folivores (insects that feed on leaves) (Redmond and Potter, 2006), borers (Kvedaras *et al.*, 2007a), phloem feeders (Correa *et al.*, 2005; Goussain *et al.*, 2005) and xylem feeders. Si is responsible for various direct and indirect effects, observed on insect herbivores (Kvedaras and Keeping, 2007). Direct effects include performance of insect herbivores reduced due to the Si and plant damage caused by insect herbivores also reduced. Indirect effects include establishment of insect herbivores become delayed, responsible for increasing the population of natural enemies, adverse weather events and reduction in other insect control strategies which are responsible for mortality of natural enemies such as chemical usage.

Sucking insects are mostly phloem feeders and finding the sieve elements implies to avoid chemical and physical barriers.

Physical barrier includes inflexibility and pectin of middle lamella causes difficulty in stylet penetration (Dreyer and Campbell, 1987). Mechanical barrier include deposition of Si on cell wall causes difficulty in stylet penetration.

Advantages of silicon usage: Ukwungwu (1990) gives detail advantages of the Si usage: population of pest can be reduced by the application of Si and doesn't leave any type of insecticidal residues not only in the food as well as in the environment. It is comparatively inexpensive and can be easily integrated with other integrated pest management practices which includes cultural, chemical and biological practices.

Several studies have been conducted by scientists from throughout the world on various agricultural crops to reduce the population of insect pests by inducing resistance from Si. Detail of these studies is mentioned in Table 1-9.

Insect pests	Country	Combination	Impact	Reference
Cnaphalocrocis medinalis	China	-	✓	(Liu *et al.*, 2017)
		-	✓	(Han *et al.*, 2016)
		-	✓	(Han *et al.*, 2015)
	India	-	×	(Malav and Ramani, 2015)
Spodoptera frugiperda	Brazil	-	✓	(Nascimento *et al.*, 2018)
		-	✓	(Nascimento *et al.*, 2014)
		-	✓	(Silva *et al.*, 2014)
Scirpophaga incertulas	India	-	✓	(Tripathy and Rath, 2017)
		-	×	(Malav and Ramani, 2015)
		-	✓	(Silva *et al.*, 2014)
		-	✓	(Ranganathan *et al.*, 2006)
Mythimna separate	China	-	✓	(Liu *et al.*, 2017)
Lissorhoptrus Oryzophilus	USA	Chlorantraniliprole seed treatment	✓	(Villegas *et al.*, 2017)
Diatraea saccharalis			×	
Chilo plejadellus			×	
Eureuma loftini			×	
Nilaparvata lugens	China	Nitrogen	✓	(Wu *et al.*, 2017)
Sogatella furcifera		Phosphorus	✓	(Yang *et al.*, 2014)
Chilo suppressalis		-	✓	(Hou and Han, 2010)
✓ = Positive impact of silicon on target insect pest; × = No impact of silicon on target insect pest				

Table 1: Silicon based induced resistance in rice crop for the management of insect pests.

Insect pests	Country	Combination	Impact	Reference
Sitobion avenae	Brazil	-	✓	(Dias *et al.*, 2014)
	China	Nitrogen	✓	(Wang *et al.*, 2013)
Schizaphis graminum	Brazil	Dimetoate	✓	(Gomes *et al.*, 2005)
		Imidachloprid	✓	(Costa *et al.*, 2011)
		-	✓	(Filgueiras *et al.*, 2011)
		Acibenzolar-S-Methyl	✓	(Pereira *et al.*, 2010)
		Imidachloprid	✓	(Costa *et al.*, 2009)
		Acibenzolar-S-Methyl	✓	(Costa *et al.*, 2007)
		Acibenzolar-S-Methyl	✓	(Costa and Moraes, 2006)
		-	✓	(Gomes *et al.*, 2005)
		-	✓	(Goussain *et al.*, 2005)
		-	✓	(Dias *et al.*, 2014)
		-	✓	(Basagli *et al.*, 2003)
✓ = Positive impact of silicon on target insect pest				

Table 2: Silicon based induced resistance in wheat crop for the management of insect pests.

Insect pests	Country	Combination	Impact	Reference
Bemisia tabaci	Pakistan	-	×	(Abbasi and Sufyan, 2017)
Aphis gossypii	Brazil	Acibenzolar-S-Methyl	✓	(Alcantra et al., 2011)
Phenacoccus solinopsis	Pakistan	-	✓	(Gogi *et al.*, 2010)
✓ = Positive impact of silicon on target insect pest; × = No impact of silicon on target insect pest				

Table 3: Silicon based induced resistance in cotton crop for the management of insect pests.

Insect pests	Country	Combination	Impact	Reference
Spodoptera frugiperda	Brazil	Gibberellic acid	×	(Alvarenga *et al.*, 2017)
		-	×	(Antunes *et al.*, 2010)
		Lufenuron	✓	(Neri *et al.*, 2009)
		Lufenuron	✓	(Neri *et al.*, 2005)
		-	✓	(Goussain *et al.*, 2002)
Ostrinia nubilalis	USA	-	✓	(Heckman and Provance-Bowley, 2007)
Rhopalosiphum maidis	Brazil	-	✓	(Moraes *et al.*, 2005)
Tetranychus urticae	South Africa	*Beauveria bassiana*	✓	(Gatarayiha *et al.*, 2010)
✓ = Positive impact of silicon on target insect pest; **×** = No impact of silicon on target insect pest				

Table 4: Silicon based induced resistance in maize crop for the management of insect pests.

Insect pests	Country	Combination	Impact	Reference
Sesamia cretica	Iran	-	✓	(Nikpay, 2016)
Sesamia nonagrioides		-	✓	
Eldana saccharina	South Africa	Nitrogen	✓	(Keeping *et al.*, 2014)
		-	✓	(Keeping *et al.*, 2013)
		Nitrogen	✓	(Keeping *et al.*, 2012)
		-	×	(Sithole *et al.*, 2011)
		cis-jasmone (JA) + Bion®	✓	(Keeping *et al.*, 2010)
		-	✓	
		-	✓	
		-	✓	(Kvedaras and Keeping, 2007) (Kvedaras *et al.*, 2007a)
		-	✓	
		-	✓	
		-	✓	
		-	✓	
		Nitrogen	✓	(Keeping and Meyer, 2002) (Keeping and Meyer, 2000)
		-	✓	
		-	✓	
		-	✓	
		Nitrogen	×	(Keeping *et al.*, 2014)
Oligonychus sacchari	Iran	-	✓	(Nikpay and Nejadian, 2014)
Diatraea saccharalis	Brazil	-	✓	
		-	✓	(Vilela *et al.*, 2014)
	USA	-	✓	(White and White Jr, 2013)
		-	✓	
Chlosyne lacinia saundersii	Brazil	-	✓	(Assis *et al.*, 2013)
Fulmekiola serrate	South Africa	Nitrogen	×	(Keeping *et al.*, 2014)
		cis-jasmone (JA) + Bion®	×	(Keeping *et al.*, 2010)
Mahanarva fimbriolata	Brazil	-	✓	(Korndörfer *et al.*, 2011)
✓ = Positive impact of silicon on target insect pest; **×** = No impact of silicon on target insect pest.				

Table 5: Silicon based induced resistance in sugarcane crop for the management of insect pests

Insect pests	Crop	Country	Combination	Impact	Reference
Chlosyne lacinia saundersii	Sunflower	Brazil	Acibenzolar-S-Methyl	✓	(Antunes *et al.*, 2010)
			-	✓	
Macrosiphoniellas anborni	Chrysanthemum	Korea	-	✓	(Jeong *et al.*, 2012)
Bemisia tabaci	Soybean	Brazil	-	✓	(Ferreira and Moraes, 2011)
Lipaphis pseudobrassicae	Mustard	India	-	✓	(Debnath *et al.*, 2010)
✓ = Positive impact of silicon on target insect pest					

Table 6: Silicon based induced resistance in oilseed crop for the management of insect pests

Insect pests	Crop	Country	Combination	Impact	Reference
Bemisia tabaci	Bean	Brazil	Neem	✓	(Peixoto *et al.*, 2017)
			-	✓	(Peixoto *et al.*, 2011)
	Potato		-	×	(Nombela *et al.*, 2009)
	Cucumber		Acibenzolar-S-Methyl	✓	(Correa *et al.*, 2005)
Plutella xylostella	Wild cabbage		-	✓	(Teixeira *et al.*, 2017)
Brevicoryne brassicae			-	×	
Myzus persicae	Cucumber	Egypt	-	✓	(Elsharkawy and Mousa, 2015)
	Potato	Brazil	-		
			Imidacloprid	✓	(Gomes *et al.*, 2008)
			-	✓	
Scirtothrips dorsalis	Pepper	USA	-	×	(Doğramaci *et al.*, 2013)
Tetranychus urticae	Bean	South Africa	*Beauveria bassiana*	✓	(Gatarayiha *et al.*, 2010)
	Cucumber			✓	
	Eggplant			✓	
Helicoverpa armigera	Cucumber	Australia	-	✓	(Kvedaras *et al.*, 2010)
Dicranolaius bellulus			-	✓	
Diabrotica speciosa	Potato	Brazil	-	×	(Silva *et al.*, 2010)
			-	✓	(Silva *et al.*, 2010)
Liriomyza spp.			-	✓	
Macrosiphum euphorbiae			-	×	(Nombela *et al.*, 2009)
✓ = Positive impact of silicon on target insect pest; **×** = No impact of silicon on target insect pest					

Table 7: Silicon based induced resistance in vegetable crops for the management of insect pests.

Insect pests	Crop	Country	Combination	Impact	Reference
Tetranychus urticae	Papaya	Brazil	-	×	(Christalcatalani *et al.*, 2017)
Aleurocanthus woglumi	Citrus		-	✓	(Vieira *et al.*, 2016)
Tuta absoluta	Tomato		-	×	(Santos *et al.*, 2015)
Spodoptera littoralis		Egypt	-	✓	(El-Bendary and El-Helaly, 2013)
Frankliniella schultzei		Brazil	Organic mineral fertilizer	✓	(Almeida *et al.*, 2009)
✓ = Positive impact of silicon on target insect pest; **×** = No impact of silicon on target insect pest					

Table 8: Silicon based induced resistance in fruit plants for the management of insect pests.

Insect pests	Crop	Country	Combination	Impact	Reference
Planococcus citri	Coffee	Brazil	-	×	(Santa-Cecília *et al.*, 2014)
	Green coleus	USA	-	×	(Hogendorp *et al.*, 2009)
Corcyra cephalonica	Pearl millet grains	India	-	✓	(Vani and Brindhaa, 2013)
Blissus insularis	St. Augustinegrass	USA	-	✓	(Cherry *et al.*, 2012)
Trialeurodes vaporariorum	Poinsettia		-	×	(Hogendorp *et al.*, 2010)
Myzus persicae	Elegant zinnia		-	✓	(Ranger *et al.*, 2009)
Scaptocoris castanea	Bread grass	Brazil	-	✓	(Souza *et al.*, 2009)
Cinara atlantica	Loblolly pine		-	✓	(Camargo *et al.*, 2008a)
			-	✓	(Camargo *et al.*, 2008)
✓ = Positive impact of silicon on target insect pest; **×** = No impact of silicon on target insect pest					

Table 9: Silicon based induced resistance in minor crops crop for the management of insect pests.

CONCLUSION

Different entomologist are busy to find out those pest management strategies which have no side effects on human as well as environment and are easily available to the farmers in cheap price. So, researchers find out the strategy of pest management by the Si usage which has same properties which are mentioned above. According to the previous research on the Si and insect pests showed that it can participate considerably in the reduction of insect pests as well as diseases caused by these pests (Meyer and Keeping, 2005). Researches also indicated that Si can be used in pest management with the combination of other pest management strategies such as cultural, biological and cultural practices (Ukwungwu, 1990).

FUTURE RESEARCH

Further research on the Si for the pest management in the future could include:

- Authenticate the application of Si for insect pest management.
- Research on new Si based formulations i.e., solid and liquid.
- Documentation of good sources of Si.
- Documentation of optimal dosages of Si for effective pest management in different crops.
- Clarification of the mode of action of Si resistance in both plants as well as insect pests.
- Integration of applications of Si with biological control for ecologically sustainable pest and disease management.
- Collaboration with different researchers and conduct various experimental trials on different climatic conditions in order to authenticate the data.
- Awareness campaigns among farmers about the benefits of use of Si.

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Date Published (D-M-Y): 15-04-2019