



# Effect of Silicic Acid Formulation (Silicon 0.8%) on Two Major Insect Pests of Tomato under Greenhouse Conditions

Aqeel Alyousuf<sup>1</sup> · Dawood Hamid<sup>1</sup> · Mohsen A. Desher<sup>1</sup> · Amin Nikpay<sup>2</sup> · Henk-Marten Laane<sup>3</sup>

Received: 25 November 2020 / Accepted: 25 March 2021  
© Springer Nature B.V. 2021

## Abstract

Tomato (*Solanum lycopersicum* L.) is an important vegetable crop in Iraq. This horticultural crop is attacked by several insect pest species. Among them, the whitefly *Bemisia tabaci* Gennadius (Hemiptera: Aleyrodidae) and the tomato leaf miner *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae) are the major threat of greenhouse tomatoes in Basrah province in southern Iraq. The management of these pests is heavily based on application of chemical pesticides. Vast application of pesticides caused harmful damage to the environment, human health and may increasing the risk of pest resistance on insect populations. One of the promising strategies which are compatible with organic farming is application of silicon for enhancing plant vigor and resistance to pest damage on various agricultural crops. Due to these facts, the experiments have been carried out at Basrah University to evaluate the effects of silicon (Si) fertilization on tomato plants for reducing damage of these two major pests. Treatments comprised two type of Si applications (Soil drench treatment and foliar spraying) with four Si concentrations (0, 0.5, 1 and 2%) of AB Yellow® silicic acid formulation. The population density of *B. tabaci* and *T. absoluta* were studied weekly during the growth season. The results clearly demonstrated that Silicon applications significantly decreased the population of immature of both whiteflies and tomato leaf miner on tomato crop in the greenhouse; Si-Foliar spraying was more effective in reducing the population density of these key pests compared to Si- soil drench application.

**Keywords** Silicon · Foliar application · Soil drench · Tomato · Fertilization

## 1 Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most economic important crop of commercial plantations in Basrah Province, Iraq. The total area planted with this crop reached 2206 ha, with a production rate of 239.8 thousand tons (almost half of the total production in Iraq, 467.6 thousand tons) in the growing season of 2018/2019 [1]. Annually, the crop is infested by many pests, but the whitefly *Bemisia tabaci* Gennadius (Hemiptera: Aleyrodidae) is the most destructive insect pest infesting the crop; It causes economic losses

reaching 100% in the case of severe injury [2, 3]. The economic loss is due to the serious feeding on the phloem of the infested plants, as well as the transferring of the pathogenic viruses to the healthy plants [4, 5]. The tomato leaf miner *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae) is a serious invasive pest, which was first recorded infesting tomato crop of Basrah in 2011 [6]. This pest can easily infest both fresh and processed tomatoes under greenhouse or field cultivated conditions. The tomato leaf miner may scatter rapidly and attack all stages of tomato and without appropriate management; heavy infestation of the pest usually destroys the unprotected tomato fields. Moreover, this pest can infest potatoes, sweet peppers, eggplants and several species of solanaceous crops [7–9]. The tomato leaf miner feeds on the leaves of tomato across all growth stages and on the fruits during productive growth stages [10, 11].

For effective management of *T. absoluta*, various control strategies such as cultural and biological control are applied; however, chemical control is extensively used against the pests globally and are especially disseminative in agricultural systems [12]. Due to the negative effects of chemical

✉ Aqeel Alyousuf  
aqeel.alyousof@okstate.edu

<sup>1</sup> Department of Plant Protection, College of Agriculture, University of Basrah, Basrah, Iraq

<sup>2</sup> Department of Plant Protection, Sugarcane & By-Products Development Company, Ahwaz, Iran

<sup>3</sup> ReXil Agro BV, Demmersweg 92a, 7556 Hengelo, BN, Netherlands

insecticides, scientific efforts have been focused on the successful alternatives enhancing the plant resistance against insects in the fields. These ways enable the plant to perform as an undesirable resistant plant to the pests or/and prevent herbivores from feeding and laying eggs [13–16]. One proposed action has been development application of silicon-based formulations as nutritional amendment as a part of proper integrated pest management scenario [17–20].

Silicon (Si) is one of the most abundant elements in the soil components that is mainly present in the inert state and is rarely found in the soluble state [21]. Si is absorbed by plant in the phase of silicic acid ( $\text{Si}(\text{OH})_4$ ) [22]. Although Si is not considered a major nutrient in plant growth, it functions in the development and production of some plant species; currently the element is recognized as an important factor increasing the tolerance of the plant to the biotic (insect and mite pests and plant diseases) and abiotic stresses (such as drought, metal toxicity, cold, lodging, high temperatures) [20, 23]; Si enhances the plant's resistance to arthropod pests due to the ability of Biosilica to accumulate in the plants cellular walls that prevents pest feeding, and decreases the digestibility of the leaves and the biological performance of the pests [24–26]. Moreover, Si stimulates the chemical plant defense by increasing the synthesis of phenolic compounds and lignin [13, 27–30].

Commercially, silicon-based fertilizer has been found as potassium silicate ( $\text{K}_2\text{SiO}_3$ ) [31], which used against sugarcane yellow mite *Oligonychus sacchari* on sugarcane [32]. Si formulation can be supplied also as Calcium silicate ( $\text{CaSiO}_3$ ), which decreased the population and damaged of some sucking-mouthpart pests *Frankliniella schultzei* Trybon (Thysanoptera: Thripidae) infesting tomato plants [33]. Application of silicon fertilizers has been successful used to enhance the resistance against pest infesting different crops such as sugarcane [19, 34–37], rice [38], cucumber [39], cabbage [40] and soybean [41]. Generally, calcium silicate formulations contain Si in the inert forms, which is difficult to be absorbed by the plant. The soluble state, Orthosilicic acid ( $\text{H}_4\text{SiO}_4$ ), has been stabilized as commercial formulations such as Silixol Granules, which used to decrease the infestation rate of Rice Stem borer *Scirpophaga incertulas* (Walker) and leaf folder *Cnaphalocrocis medinalis* on rice [42–44]. Several studies have indicated the vital role of silicon-based treatments improving resistance of tomato against different pests including herbivores insect *T. absoluta* by using calcium silicate treatments [45], and phloem feeder two-spotted spider mites, *Tetranychus urticae* Koch (Acari: Tetranychidae) by applying Soil and foliar application of rock dust including more than 60%  $\text{SiO}_2$  [46]. One recently new silicon formulation has been developed by Rexil-Agro (Netherlands) and ranked as bio stimulants which recommended for different agricultural and horticultural crops under field and greenhouse conditions [47]. The objective of the study was to evaluate the

response of tomato crop to the soluble state of Si formulation that could enhance anti-herbivore resistance against whitefly *B. tabaci* and tomato leaf miner *T. absoluta*.

## 2 Materials and Methods

### 2.1 Silicon Formulation

The Silicic Acid Agro Technology (SAAT) is the suitable form of stabilized silicic acid. AB Yellow® is a new silicic acid patent which is synthesized by Rexil-Agro Company (The Netherlands). It is stabilized silicic acid in which polymerization of silicon is halted. AB Yellow® is containing 2.5% plant-available silicic acid (0.8% Si) in combination with 0.3% boron, 1.5% zinc, 0.15% copper and 0.1% molybdenum [47].

### 2.2 Trial Site, Experimental Design, Silicon Treatments and Sampling Methodology

The study was conducted in a greenhouse at the agricultural research station, College of Agriculture, University of Basrah (Basrah, Iraq) during the growing season 2019–2020. Tomato seeds (variety: REDFLORA F; Company: Apollo Seeds, USA) were cultivated on August (2019). After one month, the seedlings have been transplanted to a greenhouse where the treatments were laid out in a Randomized Complete Block Design (RCBD) with three blocks 25 m length, 40 cm width and a distance of 100 cm between each block and all experimental field area was divided into 8 experimental plots. Each plot size was 3 m length, and unit-to-unit was 50 cm. The treatments comprised two types of Si applications (Soil drench treatment and Foliar spraying) with three Si concentrations (0.5, 1 and 2%) of AB Yellow® silicic acid formulation. Untreated plots were considered as control check which received no silicon amendment. For the foliar spraying, tomato plants were sprayed from the bottom to the top, with 50 ml of the concentrations. All foliar sprays were applied by a 16 l volume knapsack sprayer (Hardi International, England). In the soil treatments, each plant was drenched also with 50 ml of the solution. Two applications of the treatments were carried out at 20 days intervals. The first application was investigated at 30 days after the seedling transplantation. Irrigation, organic fertilization and other cultural practices were conducted as the common recommended protocol.

The population density of *B. tabaci* and *T. absoluta* were studied weekly during the grown season, starting from the second week of December (11/12/2019) until the second week of March (11/3/2020) (All pests infestations occurred naturally during growing season). Three fully expanded leaves (basal, middle and upper parts) were randomly collected from three plants per an experimental unit. Then, the sampled

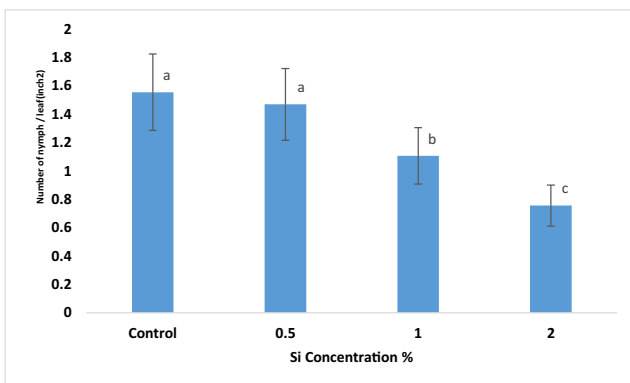
leaves were put in plastic bags and brought to the lab for counting the number of whiteflies and the *T. absoluta* larvae by using an accurate optical microscopy. *T. absoluta* larvae were calculated in each leaves, whereas, whitefly nymphs were counted from a one inch<sup>2</sup> area in each of the three leaves.

### 2.3 Data Analysis

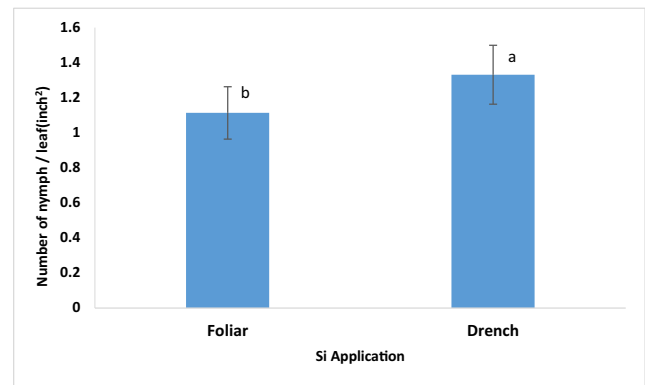
All data were analyzed for normality and homogeneity of variance (Bartlett's test), and appropriate transformations [arcsin, or log (x + 1)] were done where these conditions were not encountered, before analysis of variance was carried out. Data of the average numbers of immatures (nymphs or larvae) per leaf/ in.<sup>2</sup> of leaf were analyzed by two-way ANOVA; followed by a Least Significant Difference (LSD) test ( $P \leq 0.05$ ) using the statistical software R [48]. Significant differences between pairs are indicated as \*\* ( $p > 0.05$ ), highly Significant differences between pairs are indicated as \*\*\* ( $p > 0.05$ ) and ns = non-significant ( $p > 0.05$ ).

## 3 Results

The results of Fig.1 indicated that there was a negative response between Si concentrations and the whitefly nymph population density; at the highest concentration of Si (2%), average nymph numbers were reduced 50% compared to the control, with average of 0.76 and 1.55 nymph/ unit area of leaf (inch<sup>2</sup>), respectively ( $F = 79.488$ ,  $P < 0.00$ ). The results of foliar-applied versus drench-applied Si (Fig. 2) showed a significant difference in nymph population between Si applications; the density of whitefly nymphs was lower on the foliar application, with average of 1.11 and 1.33 nymph/ leaf (inch<sup>2</sup>), respectively ( $F =$



**Fig. 1** Effect of Silicon concentrations on the population density of whitefly infesting tomato during the reproductive stage; means followed by the same letter with each concentration are not significantly different using LSD test at  $P \leq 0.05$  (\*\*\*)



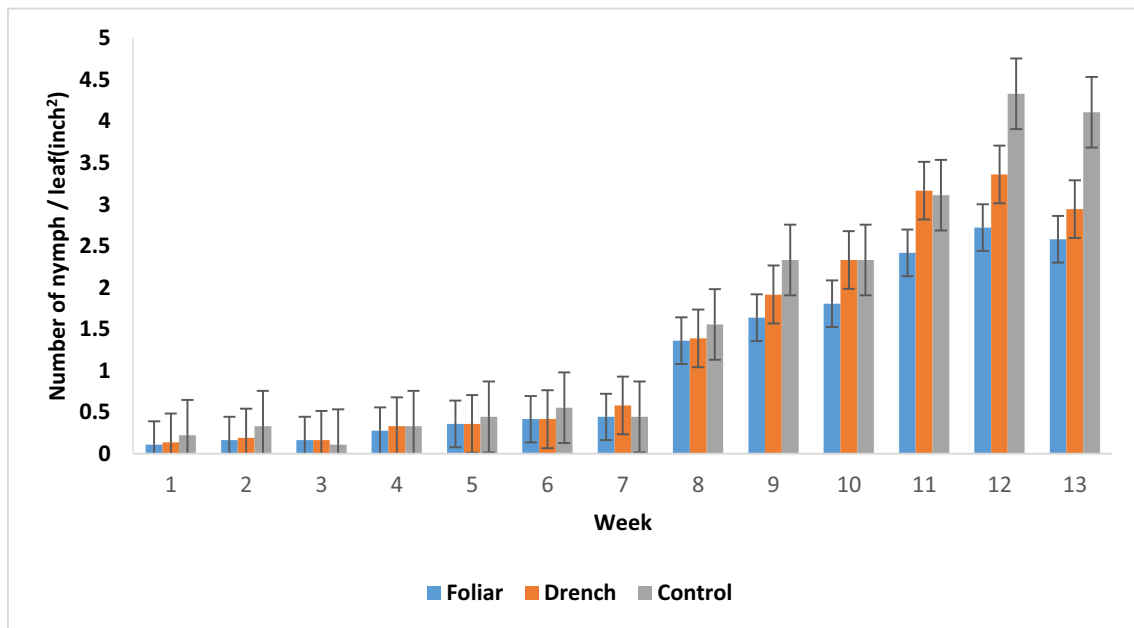
**Fig. 2** Effect of Silicon application on the population density of whitefly infesting tomato during the reproductive stage; means followed by the same letter within each application are not significantly different using LSD test at  $P \leq 0.05$  (\*\*\*)

28.119,  $P < 0.00$ ). Significant differences in whitefly nymph population were found among Silicon application and the untreated control. The populations of the nymph in the plots with foliar application of Silicon were the lowest throughout the growing season. The population was 0.11 nymph/ leaf (inch<sup>2</sup>) at the 1st week, and the highest population of 2.722 nymph/ leaf (inch<sup>2</sup>) was recorded at 12th week. While, The number of nymphs was 0.139 nymph/ leaf (inch<sup>2</sup>) at the 1st week, and increased to the highest peak of 3.361 nymph/ leaf (inch<sup>2</sup>) at 12th week in the drench application compared to the control treatment (0.222 and 4.333 nymphs/ in.<sup>2</sup> of leaves at the 1st and 12th weeks, respectively) ( $F = 2.17$ ,  $P < 0.001$ ; Fig. 3).

The results of response of tomato crop treated with different concentrations showed the highest Si concentration of 2% significantly ( $F = 31.631$ ,  $P < 0.00$ ) recorded the minimum number of the larvae (0.53 larvae/ leaf) on the treated plants compared to control treatment which did not differ significantly than the lowest concentration of 0.05% Si, with average densities of 0.98 and 0.94 larvae/ leaf, respectively (Fig. 4). Moreover, the foliar Si application showed significantly lower population of larvae compared to drench application, with average of 0.73 and 0.83 larvae/ leaf, respectively ( $F = 13.320$ ,  $P < 0.00$ , Fig. 5). Over all the growing season, there was no significant differences between the populations of tomato leaf miners on foliar-applied and drench-applied plots compared to the control ( $F = 1.129$ ,  $P < 0.29882$ ; Fig. 6).

## 4 Discussion

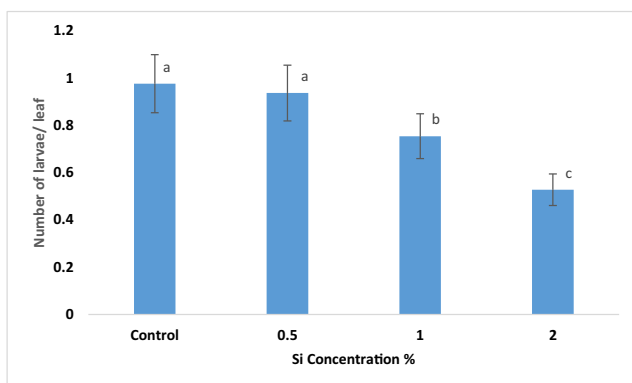
Silicon applications resulted in significantly decreased in population of immature of both whiteflies and tomato leaf miner on tomato crop in the greenhouse. The basic mechanism of Si applications on the pests is mechanical barriers



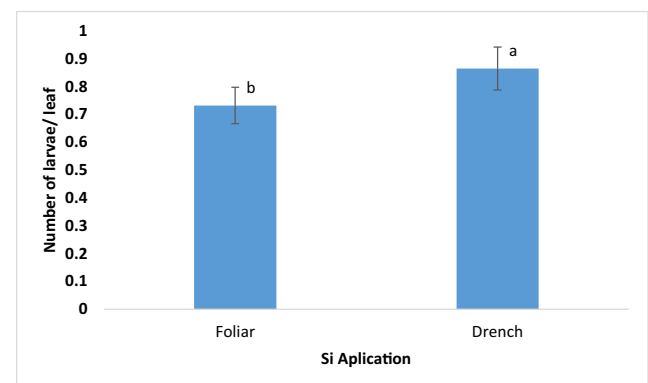
**Fig. 3** Effect of Silicon application on the population density of whitefly during the growing season of 2019/2020, (LSD ( $P \leq 0.05$ ) = 0.2101) (\*\*)

(single or double-layer of silicon) which are connected directly under the cuticle. Silicon is accumulated and polymerized in the veins and leaf epidermal cells [49, 50] that preventing the feeding of phytophagous insect and reducing the host acceptance and suitability [25, 26, 51]. Moreover, Si applications enhance chemical plant resistance against pests by increasing the levels of vital biochemical such as phenols. Our results have been clearly showed that application of silicic acid formulation in the form of foliar or soil drench, may reduce significantly the population density of silver whitefly *B. tabaci* on tomato in comparison with control. Even though, by increasing the concentration of silicon, the reduction in population density was higher. In a research study in Brazil, Ferreira et al. [52] evaluated the efficacy of silicon application on two

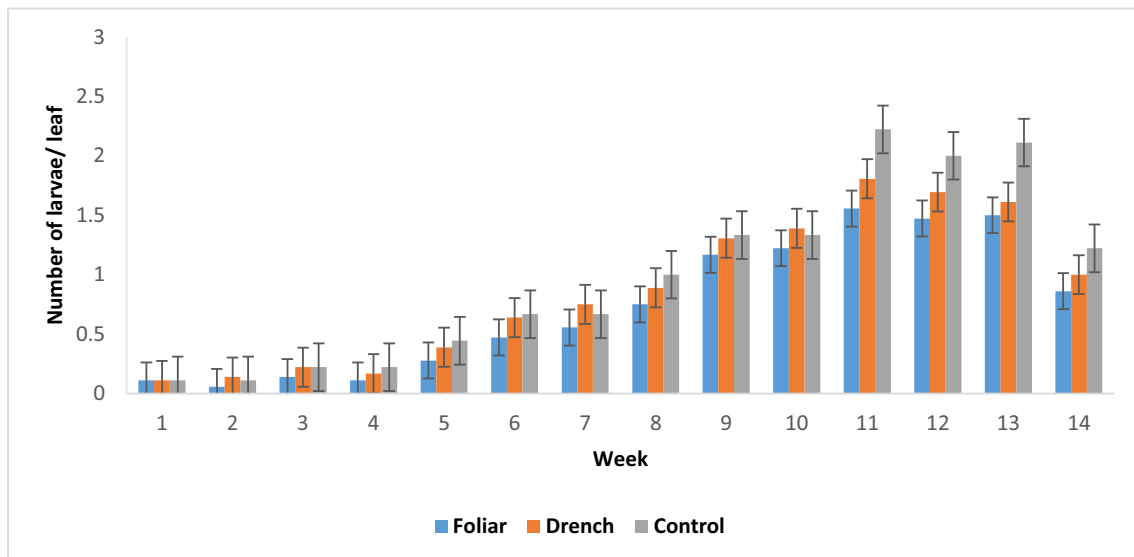
soybean cultivars under greenhouse conditions. The authors applied silicon treatment on the vegetative growth stage of soybean. The results of their study indicated that silicon fertilization significantly affected the pest and enhanced nymphs' mortality. On cucumber, Correa et al. [53] investigated effectiveness of silicon application for management of *B. tabaci*. The findings depicted that number of nymphs on treated plants was significantly lower than untreated cucumbers. In a similar experiment, Callis-Duehl et al. [39] assessed effects of silicon on *B. tabaci* on cucumber. The authors showed that application of potassium silicate solution, could reduce number of *B. tabaci* on cucumber leaves whereas the number of living whiteflies on untreated cucumber leaves was higher (44.5%). This finding revealed that *B. tabaci* populations has less preference



**Fig. 4** Effect of Silicon concentrations on the population density of tomato leaf miner infesting tomato during the reproductive stage; means followed by the same letter with each concentration are not significantly different using LSD test at  $P \leq 0.05$  (\*\*\*)



**Fig. 5** Effect of Silicon application on the population density of tomato leaf miner infesting tomato during the reproductive stage; means followed by the same letter within each application are not significantly different using LSD test at  $P \leq 0.05$  (\*\*\*)



**Fig. 6** Effect of Silicon application on the population density of tomato leaf miner during the growing season of 2019/2020, (LSD ( $P \leq 0.05$ ) = NS)

to treated silicon plants. Silicon has negative effects on other sap-sucking insect pests on different plant crops. Ramirez-Godoy et al. [54] showed that the population density of Asian citrus psyllid *Diaphorina citri* Kuwayama (Hemiptera: Liviidae) a major global threat for citrus industry, affected negatively by application of silicon. The authors concluded that application of silicon in the form of potassium silicate may significantly reduce the oviposition rate of *D. citri* up to 60% in Tahiti lime. In a recent study, Nikpay and Laane [37] assessed the effectiveness of silicic acid treatment on reduction damage of yellow mite on two sugarcane commercial varieties. The field trial data illustrated that foliar spraying of silicic acid at different rates can decrease the number of living mites on treated varieties. However, the effectiveness of silicon treatment may increase by increasing in the number of silicon application.

There is very few data on silicon application against tomato leaf miner *T. absoluta*. Our results clearly showed that the silicon treatment either by foliar spraying or soil drench treatment can significantly reduce leaf miner larvae populations on leaves under greenhouse conditions. The only published research by Dos Santos et al. [45] indicated that application of silicon on the form of liquid foliar treatment on tomato leaves affected the midgut of the treated larvae of *T. absoluta* due to the toxic effect of some bio-chemicals that simulated by the Si-foliar application.

Other species of lepidopteran pests have also been shown similar responding to Si application; Sidhu et al. [55] found that Si application contributed to the management of the sugarcane borer, *Diatraea saccharalis* (F.) (Lepidoptera: Crambidae) reducing the feeding injury by adverting the suitable host plant acceptance by the borers. Hall et al. [50] indicated that Si acted as a direct defensive mechanism against

chewing mouthpart herbivores through enhancing the mechanical plant resistances. Moreover, Melo et al. [56] revealed that foliar application of 1% silicic acid solution ( $\text{SiO}_2 \cdot x\text{H}_2\text{O}$ ) reduced the numbers of whitefly eggs and nymphs in chrysanthemum plants.

## 5 Conclusion

Applying of Silicon formulation significantly decreased the population of key pests (whiteflies and tomato leaf miner) on tomato crop in the greenhouse. Using silicon products has been broadly accepted in organic farming and may be considered as an appropriate, effective and ecologically-sound strategy for alleviating of the biotic stressors such as arthropod pests under field and greenhouse conditions. This new potential concept should be chosen wisely in sustainable agriculture and production of agricultural and horticultural crops.

**Acknowledgements** The authors thank the staff of the agricultural research station, College of Agriculture, University of Basrah, for allowing us to conduct this study using the station's greenhouse.

**Author Contributions** All authors contributed to the study conception. Data collection and analysis were performed by Aqeel Alyousuf and Dawood Hamid. The first draft of the manuscript was written by Aqeel Alyousuf and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

**Funding Statement** This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.



**Availability of data and material** The data that support the findings of this study are available from the corresponding author, Aqeel Alyousuf, upon reasonable request.

**Declarations** Not applicable.

**Consent to Participate** We declare that we participated in the study and in the development of the manuscript titled (Effect of Silicon fertilization on two major insect pests of tomato under greenhouse conditions).

**Consent for Publication** We hereby declare that we participated in the study and in the development of the manuscript titled (Effect of Silicon fertilization on two major insect pests of tomato under greenhouse conditions), and we give our consent for the article to be published in SILICON.

**Conflict of Interest** The authors declare no conflict of interest.

## References

- Central Statistical Organization (2020) Vegetable production of Iraqi provinces in 2018. from Central Statistical Organization, Iraq. [http://cosit.gov.iq/documents/agriculture/agri\\_other/full%20reports](http://cosit.gov.iq/documents/agriculture/agri_other/full%20reports)
- Tan X-L, Wang S, Ridsdill-Smith J, Liu T-X (2014) Direct and indirect impacts of infestation of tomato plant by *Myzus persicae* (Hemiptera: Aphididae) on *Bemisia tabaci* (Hemiptera: Aleyrodidae). *PLoS One* 9(4):e94310
- Sani I, Ismail SI, Abdullah S, Jalinas J, Jamian S, Saad N (2020) A review of the biology and control of whitefly, *Bemisia tabaci* (Hemiptera: Aleyrodidae), with special reference to biological control using entomopathogenic fungi. *Insects* 11(9):619
- Moriones E, Navas-Castillo J (2000) Tomato yellow leaf curl virus, an emerging virus complex causing epidemics worldwide. *Virus Res* 71:123–134. [https://doi.org/10.1016/S0168-1702\(00\)00193-3](https://doi.org/10.1016/S0168-1702(00)00193-3)
- Matsuura S, Hoshino S (2009) Effect of tomato yellow leaf curl disease on reproduction of *Bemisia tabaci* Q biotype (Hemiptera: Aleyrodidae) on tomato plants. *Appl Entomol Zool* 44(1):143–148
- Abdlrazak AS, Abd-Alraheem HY, Hassan SA, Mustafa AF, Mahmud AA, Abas SA, Mohammed AK (2017) Geographical distribution of *Tuta absoluta* (Meyrick 1917) (Lepidoptera: Gelechiidae) in Iraq. *Iraqi J Agric Res* 22(1):137–146
- Abdul Razzak AS, Al-Yasiri II, Fadhil HQ (2010) First record of tomato borer (tomato moth) *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) on tomato crop in Iraq, 2010. *Arab and Near East Plant Protection Newsletter* no 51:31
- Mohamed E, Mahmoud M, Elhaj M, Mohamed S, Ekesi S (2015) Host plants record for tomato leaf miner *Tuta absoluta* (Meyrick) in Sudan. *Bull EPPO* 45:108–111. <https://doi.org/10.1111/epp.12178>
- Bajracharya A, Mainali RP, Bhat B, Bista S, Shashank PR, Meshram N (2016) The first record of south American tomato leaf miner, *Tuta absoluta* (Meyrick 1917) (Lepidoptera: Gelechiidae) in Nepal. *J Entomol Zool* 4:1359–1363
- van der Straten M, Potting RP, van der Linden A (2011) Introduction of the tomato leafminer *Tuta absoluta* into Europe. In: *Proc. Neth. Entomol. Soc. Meet.* pp. 23–30
- Baetan R, Oltean I, Addante R, Porcelli F (2015) *Tuta absoluta* (meyrick, 1917) (Lepidoptera: Gelechiidae) adult feeding on tomato leaves. Notes on the behaviour and the morphology of the parts related. *Bulletin UASVM agriculture* 72. Doi:<https://doi.org/10.15835/buasvmcn-agr.10619>
- Illakwahhi DT, Srivastava BBL (2017) Control and management of tomato leafminer-*Tuta absoluta* (Meyrick)(Lepidoptera, Gelechiidae). A review *IOSR-JAC* 10(6):14–22
- Alhousari F, Greger M (2018) Silicon and mechanisms of plant resistance to insect pests. *Plants* 7(2):33
- Davis JA, Radcliffe EB, Ragsdale DW (2007) Resistance to green peach aphid, *Myzus persicae* (Sulzer), and potato aphid, *Macrosiphum euphorbiae* (Thomas), in potato cultivars. *Am J Potato Res* 84(3):259–269
- Smith CM (2005) Plant resistance to arthropods: molecular and conventional approaches. Springer Science & Business Media, 402 pp.
- Alyousuf AA (2011) Integrated control of *Tetranychus urticae* Koch on Cucumder *Cucumis sativus* L. by using acaricides, plant cultivars and potash fertilizer. *Al-Mustansiryah J of Science* 22(3): 31–46
- Bent E (2014) Silicon solutions: helping plants to help themselves: an holistic review. Sestante, Bergamo
- Tubaña BS, Heckman JR (2015) Silicon in soils and plants. In: *Silicon and plant diseases*. Springer, pp. 7–51
- Nikpay A, Goebel F-R The role of silicon in plant defence against insect pests with special reference to sugarcane pests: Challenges, opportunities and future directions in sugarcane IPM. In: *XI Pathology and IX Entomology Workshops*, Guayaquil, Ecuador, 2015. *FLADE*, p 44
- Reynolds OL, Padula MP, Zeng R, Gurr GM (2016) Silicon: potential to promote direct and indirect effects on plant defense against arthropod pests in agriculture. *Front Plant Sci* 7:744
- Savant NK, Komdörfer GH, Datnoff LE, Snyder GH (1999) Silicon nutrition and sugarcane production: a review. *J Plant Nutr* 22(12): 1853–1903
- Belton DJ, Deschaume O, Perry CC (2012) An overview of the fundamentals of the chemistry of silica with relevance to biosilicification and technological advances. *FEBS J* 279(10): 1710–1720. <https://doi.org/10.1111/j.1742-4658.2012.08531.x>
- Balakhnina T, Borkowska A (2013) Effects of silicon on plant resistance to environmental stresses. *Int Agrophys* 27(2):225–232
- Costa RR, Moraes JC (2006) Effects of silicon acid and of a cibenzolar-S-methyl on *Schizaphis graminum* (Rondani)(Hemiptera: Aphididae) in wheat plants. *Neotrop. Entomol.* 35(6):834–839
- Massey F, Hartley S (2008) Physical defences wear you down: progressive and irreversible impacts of silica on insect herbivores. *J Anim Ecol* 78:281–291. <https://doi.org/10.1111/j.1365-2656.2008.01472.x>
- Keeping MG, Miles N, Sewpersad C (2014) Silicon reduces impact of plant nitrogen in promoting stalk borer (*Eldana saccharina*) but not sugarcane thrips (*Fulmekiola serrata*) infestations in sugarcane. *Front Plant Sci* 5(289). <https://doi.org/10.3389/fpls.2014.00289>
- Vega I, Nikolic M, Pontigo S, Godoy K, Mora ML, Cartes P (2019) Silicon improves the production of high antioxidant or structural phenolic compounds in barley cultivars under aluminum stress. *Agronomy* 9:388. <https://doi.org/10.3390/agronomy9070388>
- Chérif M, Benhamou N, Menzies JG, Bélanger R (1992) Silicon induced resistance in cucumber plants against *Pythium ultimum*. *Physiol Mol Plant Pathol* 41(6):411–425
- Keeping MG, Kvedaras OL (2008) Silicon as a plant defence against insect herbivory: response to Massey, Ennos and Hartley. *J Anim Ecol* 77(3):631–633
- Zhang N, Li Z, Xiao Y, Pan Z, Jia P, Feng G, Bao C, Zhou Y, Hua L (2020) Lignin-based phenolic resin modified with whisker silicon and its application. *JB&B* 5(1):67–77. <https://doi.org/10.1016/j.jobab.2020.03.008>
- Hogendorp BK, Cloyd RA, Swiader JM (2009) Effect of silicon-based fertilizer applications on the reproduction and development

- of the citrus mealybug (Hemiptera: Pseudococcidae) feeding on green coleus. *J Econ Entomol* 102(6):2198–2208
32. Nikpay A, Soleyman Nejadian E (2014) Field applications of silicon-based fertilizers against sugarcane yellow mite *Oligonychus sacchari*. *Sugar Tech* 16(3):319–324. <https://doi.org/10.1007/s12355-013-0276-z>
  33. Almeida GD, Pratisolli D, Zanuncio JC, Vicentini VB, Holtz AM, Serrão JE (2009) Calcium silicate and organic mineral fertilizer increase the resistance of tomato plants to *Frankliniella schultzei*. *Phytoparasitica* 37(3):225–230. <https://doi.org/10.1007/s12600-009-0034-7>
  34. Goebel F-R, Nikpay A (2017) Integrated pest management in sugarcane cropping systems. Integrated pest management in tropical regions Ed by C Rapisarda & G E Massimino-Cocuzza, CAB International:113–133
  35. Keeping MG, Kvedaras OL, Bruton AG (2009) Epidermal silicon in sugarcane: cultivar differences and role in resistance to sugarcane borer *Eldana saccharina*. *Environ Exp Bot* 66(1):54–60
  36. Nikpay A, Nejadian ES, Goldasteh S, Farazmand H (2017) Efficacy of silicon formulations on sugarcane stalk borers, quality characteristics and parasitism rate on five commercial varieties. *Proc Natl Acad Sci India Sect B Biol Sci* 87(2):289–297
  37. Nikpay A, Laane H-M (2020) Foliar amendment of silicic acid on population of yellow mite, *Oligonychus sacchari* (Acari: Tetranychidae) and its predatory beetle, *Stethorus gilvifrons* (Col.: Coccinellidae) on two sugarcane commercial varieties. *Persian J. Acarol.* 9(1):57–66
  38. Y-q H, J-h W, Z-p P, D-y Z, M-l H (2018) Effects of silicon amendment on the occurrence of rice insect pests and diseases in a field test. *J Integr Agric* 17(10):2172–2181
  39. Callis-Duehl KL, McAuslane HJ, Duehl AJ, Levey DJ (2017) The effects of silica fertilizer as an anti-herbivore defense in cucumber. *J Hort Res* 25(1):89–98
  40. Teixeira NC, Valim JOS, Oliveira MGA, Campos WG (2020) Combined effects of soil silicon and drought stress on host plant chemical and ultrastructural quality for leaf-chewing and sap-sucking insects. *J Agron Crop Sci* 206(2):187–201
  41. Johnson SN, Rowe RC, Hall CR (2020) Silicon is an inducible and effective herbivore defence against *Helicoverpa punctigera* (Lepidoptera: Noctuidae) in soybean. *Bull Entomol Res* 110(3): 417–422
  42. Jawahar S, Jain N, Suseendran K, Kalaiyarasan C, Kanagarajan R (2015) Effect of silixol granules on silicon uptake, stem borer and leaf folder incidence in rice. *Int J Curr Res Acad Rev* 3:168–174
  43. Jawahar S, Kalaiyarasan C, Ramesh S, Kumar SV, Suseendran K, Arivukkarasu K (2019) Effect of Orthosilicic acid formulations on leaf folder incidence in lowland Rice. *Asian J Mult-Disciplinary Res* 5(1):1
  44. Cuong TX, Ullah H, Datta A, Hanh TC (2017) Effects of silicon-based fertilizer on growth, yield and nutrient uptake of rice in tropical zone of Vietnam. *Rice Sci* 24(5):283–290
  45. Dos Santos M, Junqueira MR, de Sá VM, Zanuncio J, Serrão J (2015) Effect of silicon on the morphology of the midgut and mandible of tomato leafminer *Tuta absoluta* (Lepidoptera: Gelechiidae) larvae. *Invertebr Surviv J* 12(1):158–165
  46. Faraone N, Evans R, LeBlanc J, Hillier NK (2020) Soil and foliar application of rock dust as natural control agent for two-spotted spider mites on tomato plants. *Sci Rep* 10(1):1–9
  47. Laane H-M (2017) The effects of the application of foliar sprays with stabilized silicic acid: an overview of the results from 2003–2014. *Silicon* 9(6):803–807
  48. R Development Core Team (2019) R: A Language and Environment for Statistical Computing 3.5.3 edn. R Foundation for Statistical Computing Vienna, Austria
  49. Liang Y, Nikolic M, Bélanger R, Gong H, Song A (2015) Silicon in agriculture. Dordrecht: Springer doi 10:978–994
  50. Hall CR, Dagg V, Waterman JM, Johnson SN (2020) Silicon alters leaf surface morphology and suppresses insect Herbivory in a model grass species. *Plants* 9(5):643
  51. Massey F, Ennos R, Hartley S (2006) Silica in grasses as a defence against insect herbivores: contrasting effects on folivores and a phloem feeder. *J Anim Ecol* 75:595–603. <https://doi.org/10.1111/j.1365-2656.2006.01082.x>
  52. Ferreira R, Moraes J (2011) Silicon influence on resistance induction against *Bemisia tabaci* biotype B (Genn.)(Hemiptera: Aleyrodidae) and on vegetative development in two soybean cultivars. *Neotrop. Entomol.* 40(4):495–500
  53. Correa RS, Moraes JC, Auad AM, Carvalho GA (2005) Silicon and acibenzolar-S-methyl as resistance inducers in cucumber, against the whitefly *Bemisia tabaci* (Gennadius)(Hemiptera: Aleyrodidae) biotype B. *Neotrop Entomol* 34(3):429–433
  54. Ramírez-Godoy A, del Pilar V-HM, Jiménez-Beltrán N, Restrepo-Díaz H (2018) Effect of potassium silicate application on populations of Asian Citrus Psyllid in Tahiti lime. *HortTechnology* 28(5): 684–691
  55. Sidhu J, Stout M, Blouin D, Datnoff L (2013) Effect of silicon soil amendment on performance of sugarcane borer, *Diatraea saccharalis* (Lepidoptera: Crambidae) on rice. *Bull Entomol Res* 103(6):656–664
  56. Melo BA, Moraes JC, Carvalho LM (2016) Resistance induction in chrysanthemum due to silicon application in the management of whitefly *Bemisia tabaci* biotype B (Hemiptera: Aleyrodidae). *Revista de Ciências Agroambientais* 13 (2)

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.