Benefits of using silicon as a nutrient in sustainable strawberry production

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Abstract

Silicon is not considered an essential plant element and strawberries are not considered to be silicon accumulators. However, work at the University of Hertfordshire shows that the use of a bioavailable silicon nutrient has multifaceted benefits on strawberry plants. Field experiments (2012-2018) on a commercial strawberry farm at Wisbech, UK, consistently showed that weekly application (spray or root via the fertigation system) of the silicon nutrient at a concentration of 0.017% (volume/volume) on strawberries reduced the severity of strawberry powdery mildew (*Podosphaera aphanis*), regardless of cultivar. Silicon also delayed the epidemic build-up in the silicon nutrient alone treatment for up to 14 days when compared with untreated control. Reductions in the severity of two-spotted spider mite (*Tetranychus urticae*) on strawberries ($P<0.05$) were also observed (2014 and 2015). Glasshouse hydroponic (in Hoagland's solution) experiments (2018 and 2019) investigating silicon deficiency and toxicity showed that weekly application of 0.017% (v/v) silicon nutrient on strawberries resulted in more leaves and fruits, higher chlorophyll content, and higher Brix levels in the fruit ($P<0.05$); no classic deficiency symptoms were observed in untreated plants, however, there was stunting compared with silicon treated plants. The weekly application of 1.7% (v/v) silicon nutrient was found to have toxic effects on plants but no albinism was observed. Silicon was found mainly deposit in the leaf cuticle, epidermis and palisade layers; it resulted in increased cuticle thickness and the density of leaf wax, enhancing the passive defence pathway. The silicon nutrient is not essential but has stimulatory effects on strawberry growth; it protects plants against disease and pests, thus reducing pesticide usage, and making a valuable contribution to sustainable strawberry production.

Keywords: strawberry, *Podosphaera aphanis*, *Tetranychus urticae,* silicon, physical defence, biomass

INTRODUCTION

All plants grown in soil contain silicon (Si) in their tissues, with concentrations that vary from 0.1 to 10% of their dry weight (Epstein, 1999; Debona et al., 2017). A bio-available form of Si (H_4SiO_4) is taken up by plants when the soil solution pH is <9, transported through the xylem and deposited in the leaf epidermal surfaces (Ma et al., 2011). It is then condensed into a hard, polymerized silica gel (SiO_2-nH_2O), also referred to as phytoliths in higher plants (Richmond and Sussman, 2003). The concentration of Si in plant shoots among species differs due to their different ability to uptake by roots (Broadley et al., 2012). Plants that contain Si as more than 1% of their dry weight are Si accumulators. Strawberry (*Fragaria ananassa*) is classified as a Si non-accumulator (Epstein, 1999; Datnoff et al., 2007). Si is not considered as an essential element; however, the beneficial effects of Si have been observed in many dicotyledon and monocotyledon species (Ma, 2009). Nowadays, Si is referred to as "quasi-essential" for the growth of higher plants due to its important role in alleviating abiotic and biotic stresses (Ma, 2009; Ma et al., 2011), which was mostly attributed to the physical barrier provided by Si deposition within plant cells (Debona et al., 2017). For example, Si increases drought (Gong et al., 2005) and salinity tolerance (Tuna et al., 2008) in wheat, and cadmium tolerance (Liang et al., 2005) in maize and *Brassica chinensis* L. (Song et al., 2009), etc.

Previous work showed that strawberry plants treated with Si had less severe strawberry powdery mildew (*Podosphaera aphan*is) (P<0.05) and fewer two-spotted spider mites (*Tetranychus urtiae)* (P<0.001) present on the leaves (Liu, 2017).

Si has also been reported to stimulate the plant biomass. Experiments showed that Si nutrient increased the biomass of cotton plants (Li et al., 2018) and stem strength and upright growth of *Schoenoplectus* spp. (Sloey and Hester, 2018). Si deficiency in strawberry plants can affect the normal development of leaves, petioles and roots, thereby be more susceptible to diseases, resulting in reduced yield (Hajiboland et al., 2018).

The paper here reported results from field experiments between 2012 and 2018 on a commercial strawberry farm, consistently showed that weekly application of a Si nutrient via the fertigation system reduced the severity of strawberry powdery mildew. Separate glasshouse experiments in 2018-2019 on a hydroponic system also showed that a weekly supply of Si increased biomass of strawberry plants.

MATERIALS AND METHODS

2012-2018 field experiment

All field experiments (Table 1) were done on a commercial strawberry farm at Wisbech, Cambridgeshire, UK (PE14 0HS). The farm has an area of 14 ha used for growing strawberries. The use of the commercial farm ensured that strawberries were being grown in optimum conditions to meet supermarket standards. The Si nutrient product used was Sirius® (main active ingredient: 70-80% tetraethyl silicate) provided by Orion Future Technology (Kent, UK). Si fertigation experiments were conducted in commercially operated polyethylene tunnels, each contained five raised soil beds (180 m long) running in parallel (1 m spacing between beds). Strawberry plants were grown in coir bags (six plants bag^{-1}) placed on raised soil beds.

The 2012 and 2013 Si nutrient field experiments were done in commercially operated open fields without fungicide application (Table 1). Three treatments 0.25% Si nutrient (0.1 mg cm^3) (v/v), 0.5% Si nutrient (0.2 mg cm^3) (v/v) and a control were arranged in a randomized design with replications, each consisting of a plot containing 15 to 20 strawberry plants. The control treatment consisted of plants sprayed with deionized (DI) water, to maintain the consistency of the application method among treatments. Each plot was sprayed with 500 mL Si nutrient weekly on the adaxial surface of the leaves until run off.

The 2013-2018 Si nutrient fertigation field experiment was done in commercially operated polyethylene tunnels using five (2013-2015) or four (2017-2018) beds in each of two tunnels with four treatments; no Si (control), Si nutrient alone, commercial fungicide alone and Si nutrient plus commercial fungicide. The Si nutrient was applied through the fertigation system (root Si treatment). The control treatment was the normal commercial fertigation (including fertilizer). The Si nutrient was applied as an additional nutrient at 0.017% Si nutrient (v/v) and the concentration of available Si nutrient was 0.003 mg cm^{-3}. The Si nutrient was added to the fertigation system twice a week in 2013, 2017 and 2018, and once a week in 2014, 2015 and 2016.

The disease severity was expressed as number of *P. aphanis* colonies $leaf^{-1}$ (2012-2013) or % leaf area covered by *P. aphanis* colonies (amount of mycelium) (2014-2018). In 2014-2015, the presence of two spotted spider mites on the leaves was also assessed. Each sampled leaf was placed under a dissecting microscope (as described above for *P. aphanis* assessment) at×10 magnification, and the number of *T. urticae* (at all life-stages apart from eggs) that were present on the leaf surface was recorded. Area under the disease progress curve (AUDPC) (The American Phytopathological Society, https://www.apsnet.org) was used for the analysis of *P. aphanis* development. The calculation of the AUDPC for each treatment was based on disease assessment results from five strawberry beds). In addition, apparent infection rate (r) was calculated to assess the rate of epidemic development for each treatment using the equation r = (lnq2- lnq1)/(t2-t1).

Table 1. Field experiments carried out between 2012 and 2018 at Maltmas Farm.

Year	Cultivation type	Cultivar	Application of Si nutrient	Treatments	Assessment
2012	Open field	Elegance, Alexandra Sonata (June bearers)	Weekly	0.25% & 0.5% Si nutrient foliar spray, untreated control (deionized water)	Number of *P. aphanis* colonies (mycelium) leaf^{-1}
2013	Open field	Sonata (June bearer)	Weekly	0.25% & 0.5% Si nutrient foliar spray, untreated control (deionized water);	Number of *P. aphanis* colonies (mycelium) leaf^{-1}
2013	Tunnel	Driscoll Jubilee™ (everbearer)	Twice a week	0.017% Si nutrient root application (via fertigation), 0.017% Si nutrient root application plus commercial fungicide, Commercial fungicide only, Untreated control	Number of *P. aphanis* colonies (mycelium) leaf^{-1}
2014	Tunnel	Driscoll Jubilee™	Weekly	2014-2018 treatments:	% mycelium leaf
2015	Tunnel	Driscoll Amesti™ (everbearer)	Weekly	0.017% Si nutrient root application (via fertigation), 0.017% Si nutrient root application plus commercial fungicide,	coverage, number of two-spotted spider mites leaf^{-1}
2016	Tunnel	Malling Centenary™ (June bearer)	Twice a week	Commercial fungicide only, Untreated control	% mycelium leaf coverage
2017-2018	Tunnel	Driscoll Amesti™	Twice a week		

2018-2019 glasshouse experiment

Two hydroponic experiments to assess effects of Si on the plant biomass were set up in the glasshouse in 2018 and 2019, in 5-L plastic containers with aeration pumps providing an air supply. These contained Hoagland's solution, comprised of deionised water, macronutrients and micronutrients essential for plant growth (no Si) (Jones, 2016). Plastic equipment was used instead of glass throughout the experiments since Si compounds also present in glass (Bray et al., 1982). Bare root 'Malling Centenary' strawberry crops were planted for both experiments. The 2018 experiment contained weekly application of two treatments: 50 mL of 0.017% Sirius, untreated control (50 mL of deionised water). For the 2019 experiment, four treatments were applied weekly, which were: 50 mL of 0.017% Sirius, 50 mL of 0.17% Sirius, 50 mL of 1.7% Sirius and untreated control (50 mL of deionised water).

RESULTS

Disease assessment in the field experiments

Data of the average number of colonies per leaf from the 2012 foliar Si treatment compared with fertigation showed that 0.5% Si nutrient (v/v) treatment resulted in a significant (P<0.001) overall reduction in colony numbers per leaf (Table 2). As compared to the no Si (untreated control), treatment with 0.25% Si nutrient (v/v) (P>0.05) gave less reduction in colony number when compared with 0.5% Si nutrient (v/v) treatment. The 2013 root Si treatment (fertigation system) demonstrated that the Si only treatment (P<0.001) had significantly lower colony numbers compared to the no Si treatment. The Si only treatment delayed the epidemic for two weeks compared to the no Si treatment. Although both foliar and root Si treatments in 2012-2013 showed an effect on inhibiting the development of strawberry powdery mildew, only root Si treatment in 2013 significantly reduced the colony number.

Results from 2014 to 2016 experiments for disease reduction were consistent with previous years (Table 2); strawberry crops that received weekly Si application (with or without fungicide) had reduced severities of both *P. aphanis* (P<0.05) and *T. urticae* (in 2014-2015) than the untreated control crops. In the 2014 and 2015 experiments, strawberry plants from the 0.017% Si plus commercial fungicide treatment had the smallest disease scores (P<0.001) among all treatments. Moreover, crops from the treatment 0.017% Si alone also developed less disease than the untreated control. In addition, the Si nutrient foliar spray treatments in 2012 started to inhibit the disease development after four weeks (i.e., after four Si nutrient foliar spray applications); whereas the onset of epidemic development was delayed by approximately 14 days for two Si root treatments compared with the untreated control in 2013 and 2014. The results indicated that Si could be taken up by plants more effectively through the root compared to be absorbed by the leaf surface, leading to a different level of epidemic delays.

There were very low disease levels in both 2017 and 2018 field experiments, only minimal levels of disease found in the untreated control. No disease epidemics occurred in the Si treatments in both years.

Effects on the plant biomass in the hydroponic experiments

There were no classic deficiency symptoms observed in untreated plants, however, the plants were smaller compared to Si treated plants. The wet biomass of the untreated plants was significantly lower than the Si treated plants (P<0.05). Results in Table 3 found that there were significantly fewer leaves and chlorophyll content (P<0.05) and significantly less fruits (P<0.05) in untreated plants, compared to Si treated plants. Flowering was a week later in untreated plants (May 22, 2018) compared to Si treated plants (May 15, 2018).

Table 2. The analysis of the severity of *Podosphaera aphanis* (AUDPC[a] & r[b]) from 2012 to 2016[c] and *Tetranychus urticae* (AUPPC[d]) from 2014 to 2015 for all four treatments.

Spray treatment	2012		2013	
	AUDPC	r	AUDPC	r
Untreated control (no Si)	70	0.018	27	0.0012
0.25% Si	51	0.0012	26	0.0009
0.5% Si	44	0.002	12	0.0004

Fertigation root treatment	2013		2014		2015			2016	
	AUDPC	r	AUDPC	r	AUPPC	AUDPC	r	AUPPC	AUDPC
Untreated control	60.4	0.026	662	0.0042	6,551	281	0.0011	13,149	3,423
Commercial fungicide only	1.2	0.011	106	0.0017	19,130	69	0.0005	8,149	2,825
0.017% Si alone	12.8	0.019	475	0.0036	2,222	267	0.001	2,265	1,610
0.017% Si plus commercial fungicide	0.6	0.003	63	0.0012	1,977	53	0.0004	2,681	732

[a]The calculation was based on the assessment of the average number of *P. aphanis* colonies per leaf for 2012-2013 and % area of strawberry leaf covered by *P. aphanis* colonies for 2014-2016.
[b]Apparent infection rate, the value indicates the rate of epidemic development.
[c]Results from 2017 and 2018 were not shown as no disease epidemics occurred in the Si treatments due to very low disease levels.
[d]The value indicates the overall sum of *T. urticae* per treatment (five replicates of 15 leaves each) in 2014 and in 2015.

Table 3. Results from 2018 experiment (January 24-June 27, 2018) and 2019 experiment (January 30-June 13, 2019).

Assessment criteria	2018 experiment		2019 experiment			
	Untreated control	0.017% Si nutrient	Untreated control	0.017% Si nutrient	0.17% Si nutrient	1.7% Si nutrient
Average number of leaves at the end of treatment	20	29	15	15	18	7
Average chlorophyll content of leaves (μmol m^{-2})	665.1	813.5	-	-	-	-
Average number of fruits	15	32	55	75	73	25
Average total biomass (g)[a]	144	169	28.42/4.15	23.9/4.55	26.67/4.31	9.06/2.89

[a]Fresh weight of the whole plant was measured in 2018 and dry weight (oven dry for 48 h) of the whole plant/root was measured in 2019.

The 2019 experiment showed that the high concentration of 1.7% Si treatment gave toxicity symptoms and caused plant death. The 1.7% Si treatment reduced leaf number and plant biomass, and caused a reduction in the total number of fruit, average weight and the size of fruit (Table 3). The number of leaves in the 1.7% Si treatment was significantly reduced (P<0.05) compared to untreated control, 0.017 and 0.17% Si treatments. Plants from both 0.017 and 0.17% Si treatments had larger roots and produced more fruits compared to untreated control (Table 3). In addition, some research showed that albino berries were found in the Si (as K_2SiO_3) treatment to strawberry plants grown on peat bags, with higher nitrogen and potassium content in fruits (Lieten et al., 2002). However, no albinism on fruits was observed from all three Si treatments in this experiment.

CONCLUSIONS

Results from this study showed that application of the Si nutrient in the field experiments improved crop resilience against disease and pests, which could potentially reduce the usage of pesticides; it has also shown stimulatory effects on the biomass and crop quality of strawberry plants. It is suggested that good crop management can be achieved by a continuous supply of Si at a recommended rate via the roots; the use of Si can also make a valuable contribution to sustainable strawberry production.

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