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Effect of potassium silicate and electrical conductivity in reducing powdery mildew of hydroponically grown tomato

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Summary. The effect of silicon on powdery mildew, caused by *Oidium neolycopersici*, was evaluated in five trials using two cultivars of tomato, 'Ikram' or 'Cuore di bue', grown in hydroponic systems. Silicon, as potassium silicate, was added at 100 mg L^{-1} of nutrient solution at three levels of electrical conductivity; 1.8–2 mS cm^{-1} (EC1), 3.9–4 mS cm^{-1} (EC2, 0.87 g L^{-1} NaCl) and 5–5.5 mS cm^{-1} (EC3, 1.74 g L^{-1} NaCl). Tomato plants were first inoculated with *O. neolycopersici* conidia 15–20 days after transplanting, with a maximum of five inoculations before final disease assessment. Drip or sub-irrigation methods, compared in two of the five trials, did not affect powdery mildew incidence and severity on leaves, 60 or 90 days after the first inoculation. The addition of NaCl to the nutrient solution generally reduced the incidence and severity of powdery mildew, with 0.87 or 1.74 g L^{-1} NaCl providing a similar effects. The addition to the nutrient solution of potassium silicate resulted in a significant reduction of powdery mildew incidence and severity at the EC2 conductivity tested in all trials. The addition of potassium silicate to the control nutrient solution resulted in a similar or better level of powdery mildew management than the use of a nutrient solution with higher conductivity but no added with potassium silicate. The possibility and benefits of applying potassium silicate amendments in practice are discussed.

Key words: *Oidium neolycopersici*; potassium silicate; electrical conductivity; disease management.

Introduction

Among foliar diseases of tomato grown in soilless systems, powdery mildew and grey mould (caused by *Botrytis cinerea*), are the most economically important in northern Italy. The causal agent of powdery mildew in greenhouse tomato crops is frequently *Oidium neolycopersici*, a pathogen which has spread into several tomato production areas in Europe, North America and Japan (Fletcher *et al.*, 1988; Kiss *et al.*, 2001, 2005; Matsuda *et al.*, 2001), causing significant damage. Despite considerable effort expended in the search for resistance in wild tomato species to powdery mildew (Lindhout *et al.*, 1994; Laterrot *et al.*, 1995; Ciccarese *et al.*, 1998), most of the tomato hybrids available for commercial cultivation are susceptible to *O. neolycopersici* (Jones *et al.*, 2001). Furthermore, few chemicals are registered for use in soilless crops. For these reasons, other methods of disease control need to be found.

Many plant species accumulate silicon (Si) in their tissues and its beneficial role in the nutrition of higher plants, such as rice (Ma *et al.*, 2001), is well established (Epstein, 1999 and 2009). Many dicotyledonous plants seem to respond positively to an enhanced Si supply, especially when they are exposed to both abiotic and biotic stress conditions (Ma, 2004; Fauteaux *et al.*, 2005). Silicon amendments have proved effective in suppressing soil-borne, foliar and post-harvest pathogens on several crops, including turfgrass (Zhang *et al.*,

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2006; Nanayakkara *et al*., 2008). In recent years, researchers have demonstrated that application of various Si sources to rice plants increased resistance to blast, incited by *Pyricularia oryzae* (Ishiguro, 2001; Rodriguez *et al*., 2004). Silicon-mediated resistance to plant pathogens has also been demonstrated in several pathosystems, such as cucumber-*Podosphaera fuliginea* (Fawe *et al*., 1998), zucchini-*P. xanthii* (Savvas *et al*., 2009), wheat-*Blumeria graminis* (Bélanger *et al*., 2003; Guevel *et al*., 2007) and *Lolium perenne*-*Magnaporthe oryzae* (Nanayakkara *et al*., 2008). In the case of the pathosystem strawberry-*Sphaerotheca fuliginea*, Kanto *et al*. (2004) reported a suppressive effect of potassium silicate on powdery mildew of strawberry grown in hydroponics. Silicon salt has been associated with disease resistance through its role in inducing the production and accumulation of antifungal low-molecular weight metabolites during pathogenesis (Fawe *et al*., 1998). Silicon induces the chemical defense of cucumber in a manner similar to systemic acquired resistance (SAR). The ability of plants to defend themselves is increased and is maximally expressed following infection. However, Si-induced resistance is quickly lost when the Si source is removed (Samuels *et al*., 1991), whereas SAR is characterized by long-lasting effects (Dalisay and Kuć, 1995).

Silicon is currently applied to rice and other Poaceae crops as a fertilizer, especially in Si-depleted soils (Epstein, 1999). Silicon is generally abundant in soils; a sub-optimal supply of this element is more likely in soilless cultivation rather than in soil-grown crops. Therefore, Sonneveld and Straver (1994) have already recommended the inclusion of Si in nutrient solutions supplied to cucumber, melon and lettuce grown in water or inert substrates. The protective effect of Si against disease as well as its positive effect on quality in saline conditions has been well documented for various plant species, including cucumber (Zhu *et al*., 2004), tomato (Al-Aghabary *et al*., 2004) and zucchini (Savvas *et al*., 2009). At high salinity, silicon increases both the fresh and dry mass of all plant parts, specifically roots, shoots, and fruits, thus implying a positive effect on whole-plant photosynthesis.

Although application of silicon has been shown to reduce disease in a number of pathosystems, including powdery mildew of several crop species, there is little or no published information on the effect of silicon supplementation on powdery mildew on tomato grown in soilless culture.

The objective of the present study was to evaluate the effect of potassium silicate supplementation of nutrient solution on powdery mildew incidence and severity in tomato cultivated without soil. The efficacy of potassium silicate amendments was tested using different irrigation methods and varying levels of electrical conductivity (EC) of the nutrient solutions.

Materials and methods

Growth and experimental conditions

Five trials (Table 1) were carried out at the Agricultural Experimental Center of Albenga (Savona, Italy) (trials 1 and 2), at CReSO experimental station of Boves (Cuneo) (trial 3), and at Grugliasco (Torino), in the AGRINNOVA glasshouses (trials 4 and 5). Tomato plants of cv. Ikram (trials 1 and 2) and cv. Cuore di bue (trials 3–5) were maintained on benches in a glasshouse (20–28°C), at a density of four (trials 1 and 2) and five (trials 3–5) plants m^{-2}. The irrigation delivery system and nutrient solutions used are described in Tables 1 and 2.

Fifteen-day-old tomato plants were planted in 25 cm-diam. (trials 1 and 2) and 18 cm-diam. plastic pots (one plant per pot) filled with the substrate indicated in Table 1. The pots were placed over 36 (trials 1 and 2), 16 (trial 3) or six (trials 4 and 5) channels of 6 m in length and 25 cm in width. Each hydroponic unit consisted of one channel connected to a storage tank (300 L) filled with the nutrient solution, automatically delivered to the plants with the aid of an electronic control unit program (Idromat2, Calpeda S.p.a., Vicenza, Italy), at the timing, duration and volumes indicated in Table 1. In this fully automated system, the nutrient solution was pumped from the water storage tank, fed to the plants through drip emitters or by the channels and left to drain back to the storage tank by gravity. For the control nutrient solution (EC1), the components were added to irrigation water obtained by reverse osmosis (model Hi-Flo®2 HB90, Culligan, Kitchener, ON, Canada) at the concentrations reported in Table 2. A closed soilless system with slow sand filtration of nutrient solution, designed as described by Wohanka (1995), was adopted in all trials with the exception of trial 3, where an open soilless system was used.

Table 1. Summary of the design and operation of five trials in carried out in this study.

Trial design/operation	Trial				
	1	2	3	4	5
Location of the trial	Albenga (SV)[a]	Albenga (SV)	Boves (CN)	Grugliasco (TO)	Grugliasco (TO)
Cultivar	Ikram	Ikram	Cuore di bue	Cuore di bue	Cuore di bue
Date of transplant	19/02/2007	21/08/2007	18/07/2008	12/01/2010	19/04/2010
Substrate	Perlite Agrilit3[b]	Perlite Agrilit3[b]	Coconut fiber[c]	PerliteAgrilit3[b]: peat Tecno 2[d] (1:1 v/v)	PerliteAgrilit3[b]: peat Tecno 2[d] (1:1 v/v)
Irrigation method	Drip and sub-irrigation	Drip and sub-irrigation	Drip	Drip	Drip
Irrigation time (time) and duration					
4, 7, 9, 11 a.m.	2 min	2 min	3 min	2 min	2 min
1, 3, 5 p.m.	4 min	4 min	4 min	3 min	3 min
8, 12 p.m.	2 min	2 min	2 min	2 min	2 min
Temperature (°C)	23–26	20–25	22–28	20–25	22–26
Relative humidity (RH%)	75–90	70–90	60–85	80–90	75–85
Nutrient solution tested [b]	EC1, EC2, EC3	EC1, EC2, EC3	EC1, EC2, EC3	EC 1, EC 2	EC 1, EC 2
Plants per replicate	12	12	15	15	10
Artificial inoculation date					
1st	04/04/2007	05/09/2007	12/09/2010	15/02/2010	05/05/2010
2nd	6/04/2007	21/09/2007	30/09/2010	22/02/2010	11/05/2010
3rd	10/04/2007	–	–	26/02/2010	17/05/2010
4th	16/04/2007	–	–	–	20/05/2010
5th	20/04/2007	–	–	–	–
Date of last assessment (end of the trial)	08/06/2007	10/12/2007	07/11/2008	08/03/2010	22/06/2010

[a] SV, Savona province; CN, Cuneo province; TO, Torino province, Northern Italy.
[b] Perlite Italiana, Milano, Italy.
[c] Ageon S.r.l. Cuneo, Italy.
[d] Turco S.r.l, Savona, Italy.
[e] EC1 Nutrient control solution.

The nutrient solutions were delivered by either drip or sub-irrigation as experimental treatments (in trials 1 and 2) or by drip irrigation (in trials 3, 4 and 5. For drip irrigation the nutrient solution was provided by means of emitters (one per plant) at a flow rate of 6 L h^{-1}. For sub-irrigation, the nutrient solutions flowed along each row so were delivered to the plant root zone from below the soil surface. Irrigation was adjusted according to the environmental conditions, particularly temperature.

The EC in the low salinity nutrient solution (EC1) was 1.8–2 mS cm^{-1}. The concentrations of nutrients for solutions EC2 and EC3 were identical to EC1, except that NaCl was added at a rate of 0. 870 and 1.74 g L^{-1} to achieve ECs of 3.9–4 mS cm^{-1} and 5–5.5 mS cm^{-1}, respectively. EC1, EC2 and EC3 were prepared with or without 100 mg L^{-1} of potassium silicate (K_2SiO_3, 33.7–34.7%, Andrea Gallo S.r.l., Genova, Italy). Since potassium silicate has a strong alkaline reaction, it was de-

Table 2. Composition of the nutrient solutions.

Nutrient solution tested	Component	mM
EC1	NO_3^-	13.49
	NH_4^+	5.80
	KH_2PO_4	0.90
	K_2SO_4	0.90
	Iron chelate EDTA	0.016
	MgO	2.38
	SO_3	2.47
	B	0.26
	Mo	0.002
	Zn	0.19
	CaO	3.70
	Mo	0.002
	Cu^{++}	0.07
	Mn	0.31
	K	14.66
EC1+ Si	K_2SiO_3 (100 mg L^{-1})	
EC2	EC1 + NaCl (0.87 g L^{-1})	
EC2 + Si	EC1 +NaCl (0.87 g L^{-1}) + K_2SiO_3 (100 mg L^{-1})	
EC3	EC 1 + NaCl (1.74 g L^{-1})	
EC3 + Si	EC1+ NaCl (1.74 g L^{-1}) + K_2SiO_3 (100 mg L^{-1})	

livered to the nutrient solutions from a separate stock solution tank.

The pH and EC values were regularly checked by means of a portable pH and conductivity meter, (SevenGo DUO TM SG23; Tettler, Toledo, Spain). The pH of all nutrient solutions was adjusted to 6.0 by using citric acid (Greengeo, Cuneo, Italy).

Twelve and 15 plants per replicate, respectively, with three (trials 1 and 2) and four replicates (trials 3, 4 and 5) per treatment were used. Twelve (trials 1 and 2) or 30 plants (trials 3, 4 and 5) (Table 1) were allocated to a single channel for each delivery system tested. All replicates of the same treatment were managed similarly in terms of delivery, storage and disinfestation of drained nutrient solutions.

Plants received standard agronomic treatments used by growers for pest management and for removing shoots and suckers.

Inoculum preparation and artificial inoculation

Conidia of *O. neolycopersici*, previously identified on the basis of the description of Jones *et al*. (2001), were harvested from young powdery mildew colonies on naturally infected leaves of tomato plants. Immediately before inoculation, infected leaves were shaken in 200 mL of sterile water containing 5 mL of Tween 20 (Liang *et al*., 2005) and the resulting conidial suspensions were adjusted with the aid of a haemocytometer to 1–5×10^5 conidia mL^{-1}. Inoculation was carried out by spraying the conidial suspension, with a laboratory spray bottle (20 mL capacity), onto all the leaves of 15–20-day old tomato plants. Two mL of conidial suspension were applied to each plant. Two to five inoculations were carried to increase the incidence and severity of the disease during the trials.

Data collection and analysis

Plants were checked weekly for disease development. The percentage of tomato leaves infected by *O. neolycopersici* (disease incidence) was evaluated by assessing the upper surfaces of 50 (trials 1 and 2) and 100 leaves (trials 3–5) per replicate.

Disease severity was evaluated by using a disease index ranging from 0 to 7, by modifying the European Plant Protection Organization disease index (EPPO, 2004). The disease index used ranged from 0 to 100 (0, healthy plant; 1, 0–0.99 % (midpoint 0.5%) of leaf area affected; 2, 1–4.99 % (midpoint 3.0%) of leaf area affected; 3, 5–19.99 % (midpoint 12.5%) of leaf area affected; 4, 20–39.99% (midpoint 30.0%) of leaf area affected; 5, 40–70% (midpoint 55.0%) of leaf area affected; 6, >70% (midpoint 85%); 7, dead leaf (100% of leaf area affected). The final disease rating took place 60 (trial 1), 90 (trials 2 and 3), 30 (trial 4) or 37 (trial 5) days after the first inoculation. Data were expressed as percentage of leaves infected (disease incidence) and percentage of leaf area with the signs of powdery mildew (disease severity) by using the midpoint value.

The data were subjected to analysis of variance (ANOVA) with Tukey's multiple range test (P=0.05), using SPSS software 17.0. The General Linear Model was used to investigate the effect of each factor and their interactions in each trial.

Results

Signs of powdery mildew were first observed 14 and 20 days after the first inoculation of cv. Ikram with *O. neolycopersici* conidia during trials 1 and 2, respectively, while, in trials 3, 4 and 5 the disease was observed 13, 7 and 25 days after inoculation of cv. Cuore di bue. Control plants, grown with EC1 nutrient solution, showed a final mean disease severity ranging from 47 to 52% in trials 1, 2 and 5 (Tables 3, 4 and 7), where there were five, two and four inoculations with the pathogen, respectively (Table 1). A lower mean disease severity on leaves (14 and 36%) was observed in trials 3 and 4, following two and three inoculations with the pathogen, respectively (Tables 5 and 6).

Effect of irrigation method and electrical conductivity on powdery mildew development

The irrigation methods adopted (drip or sub-irrigation) did not affect mean disease incidence and severity (P>0.05) in trials 1 and 2 (Tables 3 and 4). The EC1 control nutrient solution resulted in high disease incidence (from 71–75% at the first evaluation to 72–77% at the last evaluation) in trial 1, but powdery mildew develop later in trial 2 (from 40% at the first evaluation to 93–94% at last evaluation). Under these experimental conditions, disease incidence and severity did not differ significantly under identical electrical conductivity conditions (Tables 3 and 4).

The addition of NaCl to the nutrient solution reduced, although not significantly, the incidence of powdery mildew at the final assessment in trials 1 and 2 (Tables 3 and 4), while the reduction in disease severity from 47 to 14% was statistically significant with the drip delivery system in trial 1 (Table 3). In trial 2, 34 days after the first inoculation, disease severity was significantly reduced by the EC2 treatment delivered by drip irrigation, from 32 to 4%, while at the final assessment the EC2 effect was not significant (Table 4). The addition to the nutrient solution of NaCl at 0.87 g L^{-1} (EC2) significantly reduced powdery mildew incidence and severity in all the assessments carried out in trial 4, where disease incidence was reduced from 50 to 31% at the first assessment and disease severity from 10 to 4% (Table 6). At the second evaluation, the EC2 treatment reduced powdery mildew incidence from 80 (EC1) to 55% and severity from 28 to 11%, while disease incidence and severity were reduced from 88 to 75% and from 36 to 21%, respectively, at the final assessment (Table 6). The reduction in powdery mildew incidence and severity from the EC2 treatment occurred also in trial 5 (Table 7). At the higher electrical conductivity tested in trials 1 and 2 (EC3), for both delivery systems used, disease incidence and severity were statistically similar to those observed for the EC2 treatment (Tables 3, 4 and 5). The best disease suppression was observed at the highest EC value (EC3) in trial 3 on cv. Cuore di bue where disease incidence at the final assessment was reduced from 55 to 1% (Table 5).

Application of the general linear model analysis confirmed for all the trials that addition of NaCl to the nutrient solution was a significant factor (P<0.05) influencing the percentage of leaf area affected by *O. neolycopersici*.

Effect of potassium silicate on powdery mildew development

According to general linear model analysis, in all the trials the presence of potassium silicate in the nutrient solution was a significant factor (P<0.05) influencing the percentage of leaves infected and of leaf area affected by *O. neolycopersici*.

The addition of potassium silicate to the standard nutrient solution resulted in similar, and less powdery mildew than for the nutrient solution with higher conductivity. The interaction between the factors 'potassium silicate' and 'electrical conductivity' was significant (P<0.05) for the reduction in severity of powdery mildew in all the trials.

The addition of potassium silicate to the nutrient solution EC1 partially reduced, although not significantly, the incidence of powdery mildew in trial 1 (Table 3). On the contrary, in trial 2 addition of potassium silicate to EC1 nutrient solution supplied via drip irrigation provided a significant reduction in disease incidence from 40 to 4% at the first assessment and from 76 to 21% at the second assessment (Table 4). In trial 3, with low disease incidence in the control treatment (34% of leaves infected) at the first assessment, potassium silicate significantly reduced disease incidence to 2%, while at the second and third assessments, potassium silicate consistently reduced disease incidence from 52–56% to 2–3%, respectively (Table 5). Also in trial 4, potassium silicate added to EC1 nutrient solution,

Table 3. Mean powdery mildew (*Oidium neolycopersici*) incidence and severity on tomato plants (cv. Ikram, trial 1, Albenga, 2007), grown in different hydroponic irrigation systems, and nutrient solutions of differing electrical conductivity (EC) and potassium silicate content.

Irrigation system	EC	Silicate[a]	Percentage of leaves infected at			Percentage of leaf area affected at		
			21/05/07	01/06/07	06/06/07	21/05/07	01/06/07	06/06/207
Drip	EC1[b]	No	75 c[c]	76 b	77 b	32 c	43 c	47 c
Drip	EC2	No	40 abc	44 ab	52 ab	8 abc	16 abc	14 ab
Drip	EC3	No	39 abc	40 ab	50 ab	8 abc	9 abc	12 ab
Drip	EC1	Yes	40 abc	48 ab	47 ab	5 ab	13 abc	15 ab
Drip	EC2	Yes	10 a	15 a	30 a	0 a	2 a	3 a
Drip	EC3	Yes	4 a	12 a	15 a	0 a	1 a	1 a
Sub-irrigation	EC1	No	71 bc	70 b	72 b	27 bc	37 bc	35 bc
Sub-irrigation	EC2	No	31 ab	48 ab	45 ab	7 abc	19 abc	17 ab
Sub-irrigation	EC3	No	35 abc	41 ab	39 ab	5 ab	10 abc	9 ab
Sub-irrigation	EC1	Yes	32 ab	34 ab	43 ab	6 abc	6 ab	11 ab
Sub-irrigation	EC2	Yes	10 a	18 a	24 a	1 ab	1 a	1 a
Sub-irrigation	EC3	Yes	12 a	21 a	26 a	1 a	1 a	3 a

[a] Potassium silicate at 100 mg L^{-1}.
[b] Nutrient control solution (Tables 1 and 2).
[c] The mean values in the same column followed by the same letter do not differ significantly according to Tukey's test (P=0.05). At the last assessment, the effect on disease incidence and severity of EC and of potassium silicate was significant (P<0.0001) but that of irrigation system was not (P=0.27; P=0.20). Considering disease incidence, the following interactions were non-significant (P>0.05); EC and potassium silicate, irrigation system and EC, irrigation system and potassium silicate, irrigation system, EC and potassium silicate. Considering disease severity, the interaction between EC and potassium silicate was significant (P<0.0001), while interactions between irrigation system and EC, irrigation system and potassium silicate, or irrigation system, EC and potassium silicate were not (P>0.05).

Table 4. Mean powdery mildew (*Oidium neolycopersici*) incidence and severity on tomato plants (cv. Ikram, trial 2, Albenga, 2007), grown in different hydroponic irrigation systems, and nutrient solutions of differing electrical conductivity (EC) and potassium silicate content.

Irrigation system	EC	Silicate[a]	Percentage of leaves infected at			Percentage of leaf area affected at		
			25/09/07	09/10/07	18/10/07	25/09/07	09/10/07	18/10/07
Drip	EC1[b]	No	40 b[c]	76 cd	93 c	2 a[c]	32 c	46 b
Drip	EC2	No	15 ab	41 abcd	85 c	0 a	4 a	21 ab
Drip	EC3	No	12 ab	53 abcd	83 bc	0 a	8 ab	20 ab
Drip	EC1	Yes	4 a	21 ab	65 abc	0 a	2 a	10 a
Drip	EC2	Yes	3 a	6 a	29 a	0 a	0 a	2 a
Drip	EC3	Yes	4 a	26 ab	38 ab	0 a	1 a	4 a
Sub-irrigation	EC1	No	40 b	88 d	94 c	1 a	31 bc	48 b
Sub-irrigation	EC2	No	24 ab	61 bcd	86 c	1 a	16 abc	27 ab
Sub-irrigation	EC3	No	9 a	29 abc	67 abc	0 a	2 a	10 a
Sub-irrigation	EC1	Yes	26 ab	56 bcd	89 c	1 a	13 abc	29 ab
Sub-irrigation	EC2	Yes	9 a	37 abc	70 abc	0 a	3 a	11 a
Sub-irrigation	EC3	Yes	18 ab	24 ab	36 a	0 a	1 a	2 a

[a] Potassium silicate at 100 mg L^{-1}.
[b] Nutrient control solution (Tables 1 and 2).
[c] The mean values in the same column followed by the same letter do not differ significantly according to Tukey's test (P=0.05). At the last assessment, the effect on disease incidence and severity of EC and of potassium silicate was significant (P<0.00001) but that of irrigation system was not (P=0.052; P=0.076). Considering disease incidence, the following interactions were non-significant (P>0.05); EC and potassium silicate, and irrigation system, EC and potassium silicate, while interactions between irrigation system and EC (P=0.013), or irrigation system and potassium silicate (P=0.003) were significant. Considering disease severity, interactions between EC and potassium silicate (P=0.019), irrigation system and EC (P=0.01), irrigation system and potassium silicate (P=0.036) were significant, but that of irrigation system, EC and potassium silicate was not (P>0.05).

Table 5. Mean powdery mildew (*Oidium neolycopersici*) incidence and severity on tomato plants (cv. Cuore di bue, trial 3, Boves, 2008), grown hydoponically in nutrient solutions of differing electrical conductivity (EC) and potassium silicate content.

EC	Silicate [a]	Percentage of leaves infected at			Percentage of leaf area affected at		
		25/09/08	08/10/08	30/10/08	25/09/08	08/10/08	30/10/08
EC1[b]	No	34 b[c]	52 b	56 b	2 b	8 b	14 b
EC3	No	10 a	1 a	7 a	0 a	0 a	0 a
EC1	Yes	2 a	2 a	3 a	0 a	0 a	0 a
EC3	Yes	0 a	0 a	1 a	0 a	0 a	0 a

[a] Potassium silicate at 100 mg L^{-1}.
[b] Nutrient control solution (Tables 1 and 2).
[c] The mean values in the same column followed by the same letter do not differ significantly according to Tukey's test (P=0.05). At the last assessment, the effect on disease incidence and severity of EC and of potassium silicate, as well as their interaction, was significant (P<0.00001).

Table 6. Mean powdery mildew (*Oidium neolycopersici*) incidence and severity on tomato plants (cv. Cuore di bue, trial 4, Grugliasco, 2010), grown hydoponically in nutrient solutions of differing electrical conductivity (EC) and potassium silicate content.

EC	Silicate [a]	Percentage of leaves infected at			Percentage of leaf area affected at		
		22/02/10	01/03/10	08/03/10	22/02/10	01/03/10	08/03/10
EC1[b]	No	50 c[c]	80 c	88 c	10 c[c]	28 b	36 c
EC2	No	31 b	55 b	75 b	4 b	11 a	21 b
EC1	Yes	14 a	44 a	60 a	1 a	6 a	12 a

[a], [b], [c], See Table 5.

Table 7. Mean powdery mildew (*Oidium neolycopersici*) incidence and severity on tomato plants (cv. Cuore di bue, trial 5, Grugliasco, 2010), grown hydoponically in nutrient solutions of differing electrical conductivity (EC) and potassium silicate content..

EC	Silicate[a]	Percentage of leaves infected at			Percentage of leaf area affected at		
		07/06/10	16/06/10	22/06/10	07/06/10	16/06/10	22/06/10
EC1[b]	No	41 b	75 b	99 b	5 b	27 b	52 b
EC2	No	23 a	57 a	84 a	2 a	12 a	20 a
EC1	Yes	23 a	71 ab	98 b	1 a	7 a	15 a
EC2	Yes	25 a	54 a	97 b	2 a	6 a	27 a

[a], [b], [c], See Table 5.

significantly reduced powdery mildew incidence from 50, 80 and 88% in the EC1 control to 14, 44 and 60% at the three times of assessment, respectively (Table 6). In trial 5, only at the final evaluation, the potassium silicate treatment was not significantly different from the control in terms of disease incidence, which was high after four inoculations (Table 7). The addition of 100 mg potassium silicate L^{-1} of nutrient solution EC1 resulted, at the last assessment, in a significant reduction of powdery mildew severity in all trials with the exception of trials 1 and 2 on plants grown with the sub-irrigation delivery system. With different levels of disease severity, potassium silicate added to EC1 resulted in reduction in the percentage of leaf area affected by the pathogen of 68–70% (trial 1), 79–40% (trial 2), 100% (trial 3), 66% (trial 4) and 70% (trial 5).

Addition of potassium silicate reduced powdery mildew on plants grown in the nutrient solution amended with NaCl. In the case of EC2 nutrient solution, the inclusion of potassium silicate significantly reduced disease severity at the final evaluation, from 47 to 3% in the drip irrigation system and from 35 to 1% in the sub-irrigation delivery system in trial 1, from 46 to 2% in the drip irrigation system and from 48 to 11% in the sub-irrigation system in trial 2 and from 52 to 27% in trial 5, when compared with the EC1 control without NaCl and potassium silicate (Tables 3, 4 and 7). The same trend, in terms of disease control, was observed by using potassium silicate in the presence of the highest EC tested (Tables 3, 4 and 5). However, the addition of potassium silicate to EC3 nutrient solution sometimes resulted in the presence of sediments, which tended to block filters in trial 3 (Table 5).

Discussion

Potassium silicate supplied via nutrient solution, at a concentration corresponding to 100 mg L^{-1}, to two cultivars of hydroponically grown tomato effectively suppressed powdery mildew incited by *O. neolycopersici*.

The effects of silicate in reducing the incidence and severity of several diseases on a number of crops have been known for some time (Fauteaux *et al*., 2005; Walters and Bingham, 2007). Ability of this element to reduce the severity of powdery mildew has been demonstrated for a number of crops, such as cucumber (Adatia and Besford, 1986), strawberry (Kanto *et al*., 2004), barley (Wiese *et al*., 2005), wheat (Bélanger *et al*., 2003; Rémus-Borel *et al*., 2005), zucchini (Savvas *et al*., 2009), muskmelon (Menzies *et al*., 1992), rose (Voogt, 1992), as well as dandelion (Bélanger *et al*., 1995). Treatment with a silicon solution at 1.7 mM provided a nearly complete protection of wheat from infection by *Blumeria graminis* f. sp. *tritici* (Chain *et al*., 2009).

In our study, in the presence of a moderate (46–56% of leaves infected) to high (75–99% of leaves infected) powdery mildew incidence on two tomato cultivars grown in soilless culture, NaCl added to EC1 to increase the electrical conductivity and potassium silicate amendments reduced disease severity compared with the EC1 control in all the trials. The nutrient solutions EC2 and EC3, containing more NaCl than the EC1 control, resulted in reduced incidence of powdery mildew. In general, the nutrient solutions with electrical conductivity of 3.9–4 mS cm^{-1} and 5–5.5 mS cm^{-1} provided statistically similar effects.

In this study, the positive effect of potassium silicate has been demonstrated for the first time against *O. neolycopersici* artificially inoculated onto tomato, with a maximum of five inoculations before final disease assessment. Potassium silicate added to EC1 nutrient solution provided a moderate to high level of disease suppression, which persisted over 60 or 90 days after inoculation. The addition of 100 mg potassium silicate per liter of nutrient solution gave reduced powdery mildew severity at EC2 values in all trials. The level of disease control achieved by adding potassium silicate to the control (EC1) nutrient solution was similar to that achieved by increasing the electrical conductivity. Furthermore, silicon amendment may help to protect tomato plants from bacterial wilt, incited by *Ralstonia solanacearum* (Dannon and Wydra, 2004).

Samuels *et al*. (1991) and Cherif *et al*. (1992) showed that cucumber was protected against fungal diseases by silicon provided in solution, not by polymerised or solid silicon. Many types of organic compounds and complexes show affinity to silicon. Silicon can be involved in the polymerization of silicic acid leading to the formation of hydrated silica, and in the formation of organic defense compounds such as lignin-carbohydrate complexes in the cell walls of epidermal cells, thus increasing their resistance to degradation by enzymes released under stresses (Epstein, 2009). Fauteau *et al*. (2006) examined the role of silicon in *Arabidopsis thaliana*; in plants affected by powdery mildew, and showed that numerous genes were differentially expressed, and silicon promoted that response. The mechanism by which potassium silicate may have protected tomato plants from powdery mildew was not examined in the present study.

While there is evidence of the promotive effect of Si on the growth of monocotyledonous plants (Epstein, 1994), a direct role of Si in the growth of horticultural crops is much less clearly established (Bélanger *et al.*, 1995). Although Si did not stimulate growth of zucchini plants (Savvas *et al.*, 2009), the effect of Si on yield was not evaluated in our study. Interpretation of data concerning effecst on plant growth may be confounded by the fact that Si reduces the incidence of diseases such as powdery mildew, which would improve crop growth irrespective of any direct effect of Si on the crop. Further research is needed to determine whether a physiological role for Si exists in commercially important horticultural crops, particularly since most of these crops are grown in soilless systems in the presence of a concentration of Si usually lower than 10 mg L^{-1}. The nature of the production system is especially important in recirculating nutrient solution systems, where Si levels in the nutrient solution can become extremely low because of uptake by the crop (Bélanger *et al.*, 1995).

When applied to tomato for suppression of bacterial wilt, Si accumulated in roots whereas the concentration in stems and leaves was low (Dannon and Wydra, 2004). When applied to cucumber via recirculating nutrient solution, Si accumulated in leaves (Adatia and Besford, 1986) and improved water use efficiency as well as the Si content in fruit in the cv. Carosello (Buttaro *et al.* 2009). Si and lignin content were also significantly increased in Si-treated rice seedlings inoculated with *Magnaporthe grisea* (Cai *et al.*, 2008). The concentration of Si in tomato fruit and its effect on quality were not evaluated in the present study, but Santamaria *et al.* (2005) reported that higher conductivity improved the quality of tomato fruit. If silicon content of fruit were to be increased, this may have benefits from the human health point of view, as silicon positively affects bone mass and skeletal development and prevents osteoporosis (Eisinger and Clairet, 1993; Sripanyakorn *et al.*, 2005).

The cost of the Si treatment has been calculated as 0.09 Euro per 100 L of nutrient solution. The addition of Si to the standard nutrient solution, therefore, appears to be a simple and cost-effective method that could be implemented readily by growers.

In conclusion, the application of potassium silicate via nutrient solution for disease control in vegetable and ornamental crops grown hydroponically is of particular interest, as the use of soilless systems is increasing and few registered fungicides are available. Supplied via nutrient solution, silicon may permit the number of foliar fungicide sprays to be reduced, and is compatible with an integrated disease management approach.

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