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FUNGAL DISEASES

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Suppressive effect of potassium silicate on powdery mildew of strawberry in hydroponics

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Abstract From 1996 to 1997, potassium silicate (SiO_2) was tested at 0, 25, 50, and 100 mg l^{-1} in hydroponics to control powdery mildew. Other elements were added in the usual amounts, and the strawberries were cultivated hydroponically in a greenhouse for 4 months (from October to January). The powdery mildew spread in the control plot, but little mildew developed in the plot with 25 mg l^{-1} silicate, and none in plots with more than 50 mg l^{-1} silicate. The suppressive effect lasted for about 4 months on fruits and even longer on leaves. On analysis of mineral content in the leaves, only the silicate content differed markedly between the control and treated plants. Nitrogen, phosphate, potassium, and calcium contents did not differ greatly. The maximum silicate content was about 24 times that of the control, and disease severity decreased significantly when the content was more than 1.5% in the leaves. The hardness of the strawberry leaves, measured by a creep meter, was increased by the silicate treatment.

Key words Potassium silicate · Silicate contents · Hardness · *Sphaerotheca aphanis* var. *aphanis*

Introduction

Strawberry powdery mildew [*Sphaerotheca aphanis* (Wallr.) Braun var. *aphanis*] infects all parts of strawberry plants including leaves, fruits, peduncles, and petals. It spreads by aerial infection. Strawberry powdery mildew (SPW) looks like a white powder on the plant surface and later turns red-brown on leaves and pink on petals. The host range of SPW is narrow: *Fragaria vesca* is the only other known host aside from strawberry (Abiko 1990). The teleomorph stage of SPW was unknown in Japan until Nakazawa and Uchida discovered it in 1998, when its scientific name was changed to the current one. This serious airborne disease is especially destructive to fruit in protected cultivation. It decreases the yield directly when it breaks out on fruits. In western Japan, SPW is seen frequently because the strawberry market has been occupied mainly by the particularly susceptible Toyonoka variety since the late 1980s. Major methods of control have been fungicide application or high temperature treatment at the nursery stage. However, fungicidal sensitivity of SPW has decreased (Kanto et al. 1999; Okayama et al. 1996). Triflumizole and thioquinox now have little effect on the disease. Demethylation inhibitor (DMI) fungicides have also become ineffective (Okayama et al. 1996). Exposure over time to new fungicides has engendered decreased susceptibility of SPW. Possible alternative methods for controlling SPW include physical control and induced resistance. However, high temperature treatment presents a risk for strawberry plants if temperature control is not complete. Of the products that induce resistance, none is of practical use on strawberries. We therefore considered whether SPW could be prevented by manipulating soil nutrients on the assumption that healthy plants are not as susceptible to disease. We decided to test silicate because Miyake and Takahashi (1983) reported that silicate was suppressive to cucumber powdery mildew.

Silicon is not an essential element for higher plants, but gramineous plants absorb high levels of silicon (as silicate). Silicate not only accumulates in epidermis cells on leaves, motor cells, and hulls but also strengthens physically paddy rice plants (Takahashi 1987). Silicon also promotes photosynthetic activity, growth, heading, and maturation in paddy rice plants while suppressing rice blast, rice brown spot, and rice sheath brown rot (Akai 1953; Shirai et al. 1999). It also increases leaf dry weight and chlorophyll. At the same time, it is highly suppressive against cuticular infectious fungus-like powdery mildew and corynespora leaf spot of cucumber plants (Adatia and Besford 1986; Hazama et al. 1993; Miyake and Takahashi 1983). As practical examples in Japan, calcium silicate application has been spread in paddy fields and has contributed to an increase in rice yields and

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the prevention of rice blast. Higher plants are separated into two types: silicate plants and calcium plants (Takahashi 1987). Silicate plants absorb silicon, and calcium plants absorb much calcium and little silicon. Generally, supplying silicon to silicate plants increases absorption of silicon and resistance against pathogens (Akai 1953). In plants such as cucumber and strawberry, which share characteristics of silicate plants and calcium plants, supplying silicon increases the silicon content in plants and increases yields (Miyake and Takahashi 1986). In hydroponics, the pollen fertility ratio and fruit weight of strawberry plants increased by adding soluble silicon in liquid media (Miyake and Takahashi 1986). Therefore, we presumed that supplying soluble silicon would induce strawberry plants to absorb silicon and improve resistance against insects and pathogens. In this study, we added liquid potassium silicate as the soluble silicon in hydroponics to examine whether it would suppress powdery mildew. We also assessed silicon accumulation in the plants and physical changes in leaves.

Materials and methods

Cultivation method

Three strawberry varieties were examined. Toyonoka is highly susceptible to powdery mildew, whereas Nyoho and Hokowase are not as susceptible. We prepared eight plastic boxes (length 63 cm, width 47 cm, height 23 cm), and 45 l of distilled water was put into each box (Fig. 1). Liquid fertilizers Ohtsuka No. 1 and Ohtsuka No. 2 were added to water, with facial concentration of N 65 mg l^{-1}, P_2O_5 30 mg l^{-1}, K_2O 90 mg l^{-1}, CaO 50 mg l^{-1}, and MgO 25 mg l^{-1}. Then eight styrene foam plates with eight holes each were floated on water (as shown in Fig. 1); the strawberries were transplanted after immersion in myclobutanil solution on October 7, 1996. Among the eight seedlings in each box were four seedlings of Toyonoka and two each of Nyoho and Hokowase. Potassium silicate (regent grade) was added to the nutrient solution to achieve concentrations of 25, 50, or 100 mg l^{-1}, before the seedlings were transplanted. All plots, including control plots, comprised two replicates of four plots.

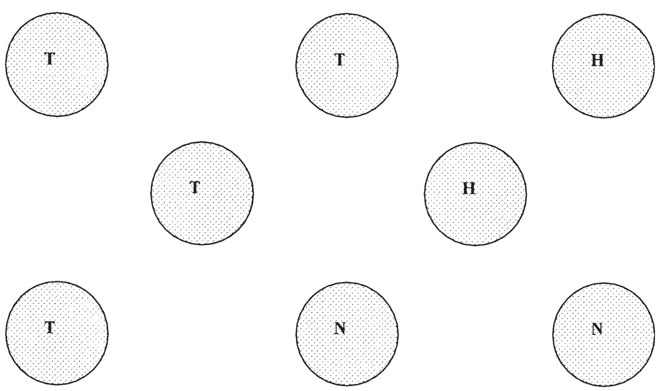

Fig. 1. Layout strawberry plants in plastic hydroponic box. *T*, variety "Toyonoka"; *N*, variety "Nyoho"; *H*, variety "Hokowase"

Nutrient solutions

Nutrient solutions were aerated during cultivation and the concentrations maintained or adjusted to N 130 mg l^{-1}, P_2O_5 60 mg l^{-1}, K_2O 180 mg l^{-1}, CaO 100 mg l^{-1}, and MgO 50 mg l^{-1} with distilled water and liquid fertilizer 1 month of transplanting. Soluble silicon was added only once, just before transplanting, in soluble form as potassium silicate. K_2O was added with silicate; the pH was not adjusted because of concern that strawberry growth would be poor if electric conductivity were too high. Strawberries were sprayed with a conidial suspension of powdery mildew (10^4 conidia/ml of race 1 in Japan) on November 7. A writing brush sterilized with 70% ethanol was used for pollination. Disease severity was recorded on November 19, December 5, and January 9 according to the proportion of the affected area to the total leaf area: A: >51%, B: 26%–50%, C: 11%–25%, D: <10%; and E: not affected.

$$\Sigma[(\text{no. of examined leaves by category}) \times \text{index}]/4/(\text{total no. of examined leaves}) \times 100$$

Analysis

All plants were sampled on January 9. The hardness of the third upper leaves was measured with a creep meter (RE-3305; Yamaden, Tokyo, Japan). The strawberry leaflet was fixed over a hole (5 mm in diameter) in a plastic board. Then a cylindrical plunger (2 mm in diameter) was put on the leaflet through the hole at a speed of 0.5 mm s^{-1}, and the elastic modulus was measured. Measurement was carried out on four leaflets per group. All leaves were sampled for each group and dried in the oven at 80°C overnight. The dried samples, weighing 2 g each, were ground into powder with a Wiley mill (Yoshida Seisakusho, Tokyo, Japan), placed in Teflon beakers with 25 ml each of nitric acid, and heated for decomposition overnight with an electric heater. After they were cooled to room temperature, perchloric acid (15 ml) was added. Samples were heated again overnight, then cooled to room temperature and filtered. The filtrates were stored until measurement of phosphate, potassium, calcium, and magnesium. Precipitates were collected and washed with 10 ml of 6 M HCl, then returned to the Teflon beakers, to which was added 30 ml of 2% NaOH. After being heated in a hot water bath until dissolved completely (about 1 h), samples were filtered and the beakers were rinsed with hot distilled water, which was also filtered. The filtrate volumes were made up to 100 ml with distilled water for use as the sample solutions to determine the silicon concentration. The sample solutions were stored in plastic bottles. Silicon, calcium, and magnesium were analyzed with induction coupled plasma emission spectrometry (SPS1200A; Seiko, Tokyo, Japan) and the potassium with a flame photometer (EKO LF-32). Phosphate was analyzed with the vanadomolybdophosphoric acid method and a

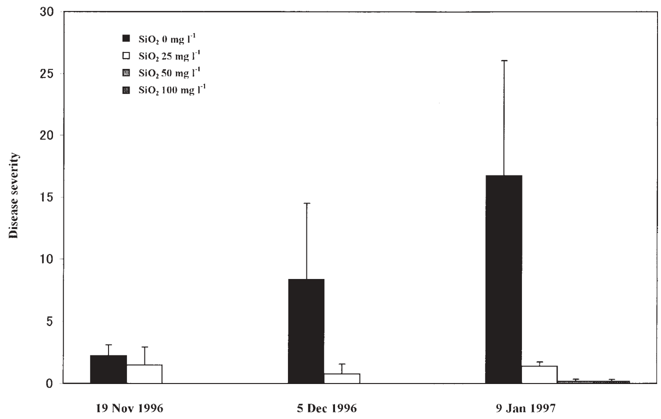

Fig. 2. Variation in severity of powdery mildew in strawberry leaves over time. *0 mg l*$^{-1}$, using distilled water; using silicate (*SiO_2*) *25 mg l*$^{-1}$; *50 mg l*$^{-1}$; *100 mg l*$^{-1}$. Silicate treatment plots were significantly different (5% level) from the control. *Vertical lines* indicate standard error

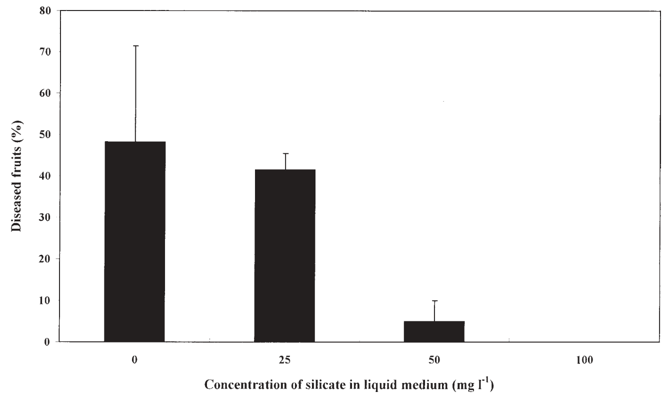

Fig. 3. Relation between disease incidence on fruits and concentration of silicate in liquid medium. Disease was investigated on January 9. *Vertical lines* indicate the standard error

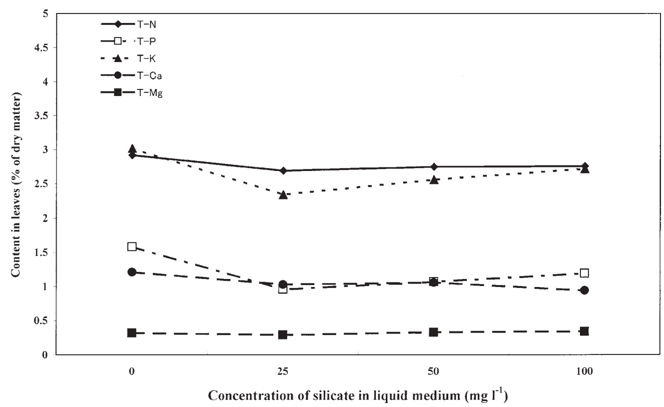

Fig. 4. Effect of soluble potassium silicate in liquid medium on the mineral content in strawberry leaves. Minerals were analyzed after drying and powdering the leaves. Calcium and magnesium were analyzed with induction-coupled plasma emission spectrometry; potassium was measured by flame photometry. Phosphate was analyzed with the vanadomolybdophosphoric acid method and spectrophotometry. Nitrogen was analyzed with an N-C analyzer

spectrophotometer (UV160; Shimadzu, Kyoto, Japan). Total nitrogen was analyzed using 50 mg of powdered strawberry leaves with an N-C analyzer (SUMIGRAPH NC-80AUTO; Sumika Chemical Analysis Service, Osaka, Japan). Note that the water used in these experiments was distilled water made with GSR-27 (Advantec Toyo Kaisha, Niigata, Japan).

Results

Variation of strawberry powdery mildew in the leaves and silicate concentration in the nutrient solution over time

We investigated disease severity of strawberry leaves three times during the growing season. Nyoho and Hokowase had little powdery mildew (data not shown). In Toyonoka in the control plots, which almost completely lacked silicon, powdery mildew increased monthly. The disease was apparent 12 days after inoculation; and at 2 months after inoculation the disease severity in the control plots had increased to 16.7 times its initial value. In contrast, severity did not increase in any silicate plot. Silicate at 25 mgl^{-1} plots maintained a level of about 2.0 in disease severity (Fig. 2). Notably, silicate at 50 mg l^{-1} and 100 mg l^{-1} plots maintained severity at nearly 0 value. Therefore, for hydroponic cultivation, a nutrient solution containing silicate greatly reduced susceptibility to powdery mildew.

Relation between incidence of diseased fruits and concentration of silicate in the nutrient solution

We examined all fruits, including immature fruits, for disease on January 9. Similar to the leaves, the incidence of diseased fruits was highest in control plots. In the silicate 25 mg l^{-1} plots, suppressive effects were less (Fig. 3). Fruits showed marked a reduction in disease at silicate concentrations of 50 mg l^{-1} and 100 mg l^{-1}.

Mineral content in strawberry leaves

The total content of nitrogen, phosphate, potassium, calcium, magnesium, and silicon in leaves was analyzed. As shown in Fig. 4, there were no clear differences for nitrogen, phosphate, potassium, calcium, or magnesium. Only silicon was markedly different (Fig. 5). Silicate was greatest in the 50 mg l^{-1} plot, about 24 times that of the control. The relation between the silicate content in leaves and disease severity is shown in Fig. 6. When leaves contained more than 1.5% silicate, disease was markedly suppressed.

Elasticity of leaves

The first indicator of elasticity measured with a creep meter is the hardness of a leaf. The hardness of the control leaves was clearly less than that of silicate-treated leaves. Elasticity

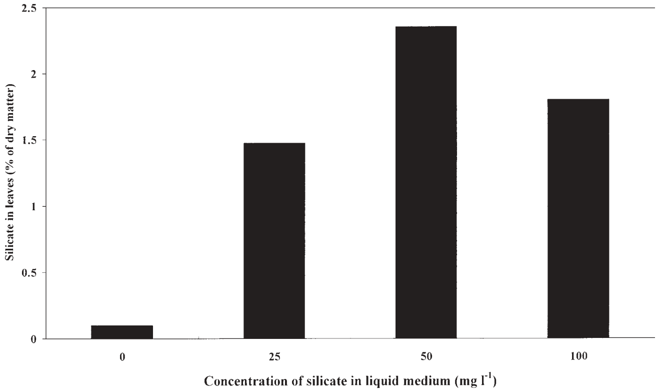

Fig. 5. Effect of soluble potassium silicate in liquid medium on the silicate content in strawberry leaves. Silicate was analyzed with induction-coupled plasma emission spectrometry after drying and powdering the leaves

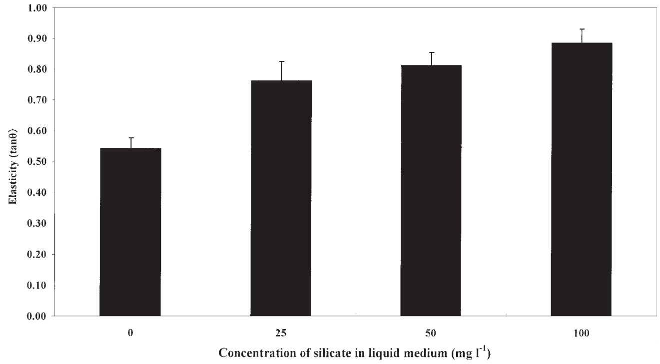

Fig. 7. Relation between elasticity in strawberry leaves and the concentration of silicate in the liquid medium on January 9. The first indication of elasticity measured with a creep meter is the hardness of a leaf. Silicate treatments were significantly different (1% level) from the control. *Vertical lines* indicate the standard error

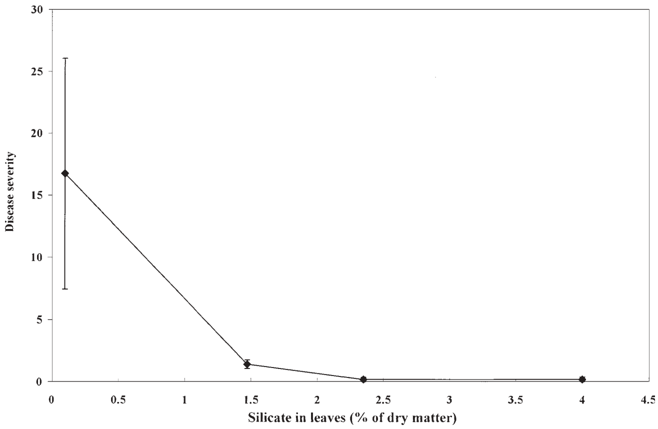

Fig. 6. Relation between silicate content in leaves and disease severity. Disease severity was examined on January 9. Leaves were also sampled on January 9; then silicate was analyzed with induction-coupled plasma emission spectrometry after drying and powdering. *Vertical lines* indicate standard error

increased with increasing silicate concentrations in the nutrient solution (Fig. 7). Thus, adding soluble silicate to the nutrient solution hardened strawberry leaves.

Discussion

Silicate has been known to suppress plant diseases in gramineous plants such as rice blast and brown spot since the 1920s in Japan (Kawashima 1927). During the 1980s, Miyake and Takahashi (1983) in Japan and Adatia and Besford (1986) in the United Kingdom reported independently that silicate suppressed powdery mildew in cucumber. Later, silicate was found to suppress other powdery mildews in grape (Bowen et al. 1992), muskmelon, and zucchini (Menzies et al. 1992), dandelion, and rose (Belanger et al. 1995). However, few reports addressed silicate in strawberry plants (Lanning 1960; Miyake and Takahashi 1986). Lanning referred to the disease in strawberry, but the relation between the disease and silicon remained uncertain.

Miyake and Takahashi (1986) demonstrated that strawberry accumulated silicate from the hydroponic solution and that silicate increased the pollen fertility ratio and fruit yield. Wang and Galletta (1998) reported that foliar application of potassium silicate induced metabolic changes in strawberry plants and reduced powdery mildew severity, but they did not report data demonstrating that reduction. We found that silicate markedly suppressed the severity of powdery mildew in strawberry (Fig. 2). We also verified that silicate was effective against not only cucumber powdery mildew but also against strawberry powdery mildew, and that strawberry accumulated silicate when silicate was supplied hydroponically (Fig. 5). Silicate content was 0.09% of the dry weight in the control plot leaves, whereas silicate content was 1.4%–2.4% of dry weight in leaves from the silicate plot. These data agreed with the data of Miyake and Takahashi (1986), who reported 0.06% silicate in the dry weight of control leaves and 1.22% in those that had silicate treatment.

However, Lanning analyzed strawberry leaves from plants that were raised in soils that differed in the content of available silicate by the weight method when separately analyzing serrated edges and the rest of the leaves. According to Lanning (1960), the serrated edge of leaves contained 15%–30% silicate, whereas the other parts of the leaves contained 1.6%–25% silicate in dry weight. These results differed greatly from ours. In addition, his reported values varied widely. The discrepancy between the two studies can be explained by the fact that our analysis used induction-coupled plasma emission spectrometry, whereas Lanning analyzed by the weight method. Moreover, that study used many varieties for testing. Other factors are unknown. The margin of error can be large when the weight method is used for dicotyledons such as strawberries, which do not absorb much silicate. That increasing the silicate content decreases plant diseases has been well known in rice (Akai 1953; Kawashima 1927) and cucumber (Adatia and Besford

1986; Miyake and Takahashi 1983). Our experiment proved that the high silicate content (more than 1.5% dry weight in hydroponics) in strawberry leaves suppressed powdery mildew (Fig. 6). Furthermore, our third result confirmed that application of silicate hardened the strawberry leaves (Fig. 7). No study before has reported that application of silicate increased the hardness of dicotyledons. Therefore, we believe that our result confirmed for the first time that silicate improves the physical properties of strawberry leaves. Jhooty and McKeen (1965) noted that susceptibility of strawberry plants to powdery mildew depended on the cuticle thickness of the leaves. The cuticle thickness of *Fragaria ovalis* was 0.6 μm, whereas that of *F. chiolensis* was 4.0 μm. In addition, that of *F. ovalis* was far more susceptible than *F. chiolensis*. Lanning analyzed the silicate content of *F. ovalis* and *F. chiolensis*, original species of strawberry plant, according to their dry weight. Lanning showed that *F. chiolensis* contained about 6.2 times more silicate in leaves, except at the serrated edges, than *F. ovalis*. Therefore, the relation among cuticle thickness of leaves, the silicate contents, and resistance against powdery mildew must be resolved by further investigation. Our final result is that silicate was not as effective against mildew on strawberry fruits as on leaves (Fig. 3). We did not ascertain why silicate was relatively ineffective, nor did we analyze silicate in the fruit. Although Lanning found silicate in strawberry achenes (seeds), the fruit pulp was not analyzed. Therefore, an analytical method is needed to determine silicate content in the fruit pulp. Whether there is a relation between silicon concentration in fruit pulp and suppression of powdery mildew on fruits is unknown and requires further investigation. Samuels et al. (1991a,b) and Fawe et al. (1998) examined modes of action of silicate in reducing the severity of powdery mildew of cucumber. Silicate accumulates at the base of the trichome and at sites of attempted penetration by *Sphaerotheca fuliginia*. In addition, silicate application was shown to have a role in triggering the production of flavonoid phytoalexins.

Further research will be done on this issue in strawberry. Our results show that silicate increased resistance against powdery mildew in strawberry and improved the physical hardness of leaves. In the near future, we will study the role of silicate in and around the affected area during attack by powdery mildew.

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