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Pulsed Water Mists for Suppression of Strawberry Powdery Mildew

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Abstract

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Powdery mildew (*Podosphaera aphanis*) is a destructive and widespread disease of strawberry (*Fragaria* × *ananassa*), especially when susceptible cultivars are grown in high plastic tunnels or glasshouses. Many powdery mildews thrive in humid environments, but free water films on plant surfaces can inhibit conidial germination of some species. We hypothesized that *P. aphanis* might be directly suppressed by rain through the action of water films and meteoric water. In repeated experiments, the hydrophobic conidia of *P. aphanis* collected on the surface of water droplets, resulting in their removal when the droplets rolled over the leaf surfaces and fell to the ground. Meteoric water and water films also damaged conidiophores. Brief mid-day water mists applied in pulses lasting one minute each four times per day were as effective as multiple fungicide treatments in suppressing powdery mildew. Rapid drying of the pulsed mists resulted in effective suppression of powdery mildew without consequent increases of fungal pathogens that might benefit from water films. The timing and duration of water sprinkling has been refined to the point where it can provide a commercially relevant degree of suppression of powdery mildew on strawberry in a high tunnel production system.

Keywords: Disease management, hydrophobicity, lotus effect, overhead irrigation, *Sphaerotheca macularis*

Podosphaera aphanis (syn. *Sphaerotheca macularis*), the causal agent of powdery mildew of strawberry (*Fragaria* × *ananassa*), is an economically important pathogen in strawberry nurseries and fruit production fields. The disease can be especially severe when susceptible cultivars are grown in glasshouses or plastic tunnels. Infection on the foliage affects photosynthesis and leads to reduced yield and fruit quality (Horn et al. 1972; Maas 1998), and even a minor infection of strawberry fruit may result in their rejection.

Overuse of fungicides, both in production sites of strawberry planting material and fruit fields, may lead to the development of populations of powdery mildew becoming resistant to them. There are several reports claiming that powdery mildews including *P. aphanis* have developed resistance to several fungicide classes (Pertot et al. 2007; Sombardier et al. 2009). Furthermore, high levels of fungicide residues on strawberry fruit is a concern among consumers (Pertot et al. 2008). Thus, there is a need to search for non-chemical alternatives to manage strawberry powdery mildew.

Water in the form of rain or irrigation removes dust particles and spores of some fungi from plant leaves and reduces disease development. Yarwood (1939) demonstrated the efficacy of water sprays to suppress powdery mildews of barley, bean, cucumber, peas and rose. In tomato, the severity of powdery mildew was reduced on sprinkler irrigated compared to on furrow irrigated plants (Rotem and Cohen 1966). A weekly spray of strawberry plants with acid water or acid water followed by alkaline water resulted in a lower incidence of powdery mildew in water treated compared to fungicide treated strawberry plants (Tsukagoshi et al. 2000). Conidia of some powdery mildews can germinate and infect without an exogenous water film, and indeed the germination of several species is mildly to severely inhibited by water films (Peries 1962; Perera and Wheeler 1975; Sivapalan 1993).

Despite the known and demonstrable deleterious effects of water on some powdery mildews, including *P. aphanis* (Peries 1962; Tsukagoshi et al. 2000), water mists are not universally recommended as a method to suppress strawberry powdery mildew, and guidelines on the nature, volume and periodicity of misting are lacking. The mechanisms by which water droplets or films suppress strawberry powdery mildew have not been described. Without such guidelines, intentional provision of water films to suppress powdery mildews might increase severity of pathogens that benefit from wet foliage and fruit (*e.g., Botrytis* spp., *Colletotrichum* spp., or *Xanthomonas fragariae*). Furthermore, applying excessive quantities of water could degrade extant fungicide deposits or create nutrient deficiencies in plants. Our objective was to develop and refine a method of using brief, day time, low-volume pulses of water mist to selectively inhibit *P. aphanis* without introducing negative impacts, and to understand the mechanism by which water suppresses powdery mildew. Preliminary accounts of our work have been published previously (Asalf et al. 2014, 2015).

Materials and Methods

Pulsed water mists in high tunnels. Plants of strawberry cv. Korona were grown in a perennial production system under a ventilated high plastic tunnel in an experimental field in Ås, Norway (Fig. 1A). The tunnel was 28.6 m long and 8.5 m wide. There were six rows of plants in the tunnel; the four middle rows were used for the experiment and the two rows in each side of the tunnel were left as untreated border plots. Each planted row was 27 m long, and the planting distance was 30 cm. The plots were divided by a double layer of horticultural fleece (Novagryl P19, RPC bpi group, Rushden, UK) with a height of 60 cm, and each plot contained two rows of plants (Fig. 1A). The fleece prevented water drift between adjacent plots during treatments.

Inoculum of *P. aphanis* was produced on clean strawberry plants of cv. Korona obtained from a certified strawberry planting material supplier. First, *P. aphanis* inoculum were produced on leaflets in growth chamber conditions. In brief, leaves were surface-sterilized by soaking them in a solution of 0.5% sodium hypochlorite and 0.05% Tween-20 for 5 min. Thereafter, they were rinsed three times (2 min each) in distilled water and air dried for 1–2 min under a laminar flow hood. Next, the petioles were removed, and three to five leaflets were placed in each of several Petri dishes (diameter 9 cm) on solidified water agar (0.5% agar) amended with 0.03% benzimidazole to prevent contamination and increase longevity of the leaflets (Asalf et al. 2012). The leaflets were inoculated with conidia from fresh colonies of *P. aphanis* by gently touching the lower (abaxial) surface with either another leaflet or a paintbrush containing inoculum and incubated in a growth chamber at 20 °C, 80% RH, and a 16:8 h L:D photoperiod for 8–10 days before they were used to inoculate inoculum source plants in the greenhouse. Old leaves were removed from the plants and susceptible leaf stages (S1 and S2) were inoculated by touching the leaves with leaflets containing powdery mildew conidia (Asalf et al. 2016). The inoculated plants were then maintained in a greenhouse at 18 °C, 80% relative humidity (RH) and a day and night period of 16 and 8 h, respectively. After three weeks, plants with the same level of disease severity were selected and used as inoculum source for plants in the high plastic tunnel (Fig. 1A).

Plants were inoculated by introducing two inoculum source plants per plot at start of the experiments; one inoculum source plant was planted in the middle of each row (Fig. 1B). After introducing the inoculum source plants, (i) the mist-treated plants were exposed to four daily 1-min. pulses of overhead water mist lasting 1 min. (approximately 540 ml/min provided by each nozzle) at 90 min intervals (11 AM, 12:30 PM, 2 PM and 3:30 PM). Mist nozzles (Stable Special Sprayer Green, Palaplast AK, Thessaloniki, Greece) were mounted on vertical risers approximately

10 cm above the upper edge of the plant canopy (Fig. 1A and B). Six mist nozzles were located equidistant in each plot (three per row) to provide an even distribution of water.

Comparison treatments consisted of (ii) sulfur (product: Thiovit, Syngenta) once per week at a rate of 7.5 kg/ha (6 kg/ha active ingredient), (iii) alternate weekly treatments of pyraclostrobin + boscalid (product: Signum, BASF) or penconazol (product: Topas 100 EC, Syngenta) at rates of 67 + 267 g/ha and 25 mL/ha a.i., respectively; (iv) water twice per week by the same application method and water rates as the fungicides, and (v) an untreated control. Fungicides were applied to run-off (approximately 1000 L/ha) with a backpack sprayer (SOLO® Kleinmotoren GmbH, Stuttgart, Germany). Treatments were arranged in a completely randomized block design with three replicates of 20 plants per plot. The experiments were conducted in 2013 and 2014.

Disease was assessed at weekly intervals beginning 10 days after start of the treatments. Incidence and severity of powdery mildew were assessed on eight of the inoculated plants in each plot (four in each row) and on the two inoculum source plants. Disease incidence was assessed on five arbitrarily selected leaves on each plant, in total 50 leaves per plot (40 leaves on the plants being non-diseased at start of the experiments and 10 leaves on the inoculum source plants). Disease severity for both the adaxial and abaxial leaf sides was assessed on two severely infected leaves per plant by visually estimating the percentage of the leaf area covered by powdery mildew.

The experiments were repeated during the 2016-2017 growing season at the University of Florida Gulf Coast Research and Education Center located in Balm, FL. In addition to the high tunnel environment, the experiments were duplicated in an open field raised-bed planting. In both growing systems, strawberry transplants of cv. Sensation^{TM} 'Florida 127' were planted 14 October 2016 into fumigated plastic mulched raised beds with 38 cm row spacing and 38 cm plant spacing. Beds were 71 cm wide, with centres 122 cm apart, and beds were 92 meters long. Plants were overhead irrigated for 10 days to aid establishment, and then irrigated and fertilized daily through

drip irrigation. Pulsed mist treatments consisted of (i) water misting for 1 minute four times per day (at 2-hour intervals starting 6 AM), (ii) water misting for 1 min. per day (at 6 AM), and (iii) water misting for 1 min per week (at 6 AM). Mist nozzles (Max-Cone Fan-MAU36D1, Maxijet Inc., Dundee, Florida) were attached to vertical risers 10-15 cm above the plant canopy, and each provided approximately 660 ml/min (Fig. 1C).

Comparison treatments consisted of (iv) a fungicide standard. The fungicide standard treatment was calendar-based bi-weekly applications of cyflufenamid (Torino, Gowan, Yuma, AZ) alternated with quinoxyfen (Quintec, Dow AgroSciences, Indianapolis, IN) at rates of 248 and 438 mL of a.i. per ha., respectively. Fungicides were applied with a CO_2 pressurized backpack sprayer using a two-nozzle wand (935 liters/ha, 310 kPa). An untreated control (v) was also included. Treatments were arranged in a randomized block design with four replicates of 12 plants per plot. No inoculum source plants were introduced in the plots.

Foliar severity of powdery mildew was assessed weekly on four randomly selected plants from each plot from 16 November 2016 to 9 January 2017. Three leaves at ontogenic stage 5 (Asalf et al. 2014) were randomly selected on each plant for assessment of disease severity (percentage of total leaf area covered with signs of *P. aphanis*) on the abaxial leaf surface.

Greenhouse experiments with pulsed water mists. Experiments took place in May to July 2017 in four greenhouse (phytotron) compartments at Ås, Norway, at a constant temperature of 20 °C and RH of 80%. Strawberry transplants of cv. Korona were planted in 12 cm diameter plastic pots containing a standard peat-based fully fertilized growth substrate (VEKSTTORV; Ullensaker Almenning). During the experiments, plants were irrigated with a complete nutrient solution once per week.

To provide a source of inoculum, mildew-free strawberry plants were inoculated by touching their leaves to the leaves of infected plants. The inoculated plants were then kept in a

growth chamber under controlled conditions as described previously (Suthaparan et al. 2016). After two weeks, those with disease severity above 90% were selected and used as inoculum source plants for the experiment.

Plots consisted of two rows of three mildew-free plants, with two inoculum-source plants between the two 3-plant rows. Treatments were replicated three times in a randomized block design, and there were two replicated experiments over time, each lasting 28 days from start of treatments to final assessment. Plants were exposed to 18 h of natural sunlight and 6 h of darkness. The daylight interval was supplemented with HPS lamps if radiation went below 200 W/m².

Pulsed water mist treatments were applied daily at 2 pm for 1 min. Six hollow cone sprinklers (Fogger Orange, NaanDanJain Irrigation Ltd., Israel), each providing a flow rate of 190 ml/min, were spaced over the two plant rows in a 32 cm square grid, approximately 25 cm above the plants. Comparison treatments consisted of (i) an untreated control, and (ii) plants treated with UVB light. UVB-treated plants received a UVB irradiance of 3.6 ± 0.2 W/m² (lamp model UVB-313EL; Q-PANEL Lab Products) daily for 4 min, beginning 1 h after sunset). The experiment was conducted twice.

Percentage of leaf area (severity) covered with powdery mildew on the adaxial and abaxial sides of all leaves on each plant were assessed weekly, beginning one week after start of the experiments. A mean severity of diseased leaf area per plant was used to calculate the area under the disease progress curve (AUDPC).

Removal of conidia from surfaces and sporulating colonies by water droplets. To better understand the mechanisms of how water affects powdery mildew, we observed the interactions of water droplets with conidia and conidiophores of the pathogen. Conidia were dusted onto the following surfaces: (i) young expanding strawberry leaves of cv. Korona, (ii) 9 cm glass Petri plates, and (iii) 9 cm polystyrene Petri plates. The surfaces were inclined at approximately a 15-

degree angle from horizontal, and a 10 µl droplet of distilled water was then dispensed from a pipette approximately 2 cm above each surface, causing the droplet to roll through the conidial deposits. Droplets were collected and immediately observed at 35 to 100× magnification, and interactions between the water droplets and the conidial deposits were recorded. In the same manner, 10 µl water droplets were dispensed above sporulating colonies on detached, inclined, immature strawberry leaves of cv. Korona. The water droplets were then similarly collected and observed at 35 to 100× magnification.

Removal of conidia from sporulating colonies by simulated rainfall. A previously described controlled environment wind tunnel (Gadoury et al. 1996) was used to apply simulated rain to the surface of detached strawberry leaves bearing sporulating colonies of *P. aphanis*. Leaflets from trifoliate leaves of cv. Korona with 11 to 14-day old colonies of *P. aphanis* were placed on the sample platform within the wind tunnel at 25 °C and were subjected to simulated rain for 20 sec. at the rate of 53 mm/h on each of four consecutive days. The leaflets were air dried for 10-15 min until the free water from the leaflets was no longer macroscopically visible. The leaflets were transferred to water agar in Petri plates at 20 °C under 12 h day/night illumination between subsequent exposures to simulated rain. Five replicate leaflets were exposed to simulated rain, and the experiment was repeated three times. After each rain exposure, the rinse water was collected, the total volume of water was recorded, and the number of conidia contained in 5 µl aliquots of the conidial suspension was determined microscopically.

Statistical analyses. Normality and homogeneity of variance of the data were checked to determine whether appropriate transformation was necessary and, if so, data were transformed before analysis and back-transformed data are presented in the results. There was no significant difference between the two experiments when testing the efficacy of water and UV in the greenhouse, and thus the data from the two experiments were pooled. Data were analyzed using

the generalized linear model for analysis of variance (ANOVA) in MINITAB. Mean comparisons were performed with Tukey's pairwise comparisons at P = 0.05.

Results

High tunnel experiments in Norway. Pulsed misting with water for 1 min four times during mid-day significantly reduced the incidence and severity of foliar powdery mildew of plants being non-diseased at start of the experiments (Table 1, Figs. 2A and 3A) compared to the unsprayed control ($P < 0.001$). At the final disease assessment, powdery mildew severity was reduced from 51.3% in the untreated to 4.5% in the mist treatment in the first year (Fig. 2A) and from 14.6% in the untreated to 4.3% in the mist treatment in the second year (Fig. 3A). Overhead sprinkling for 1 min 4 times per day also significantly reduced powdery mildew on the inoculum source plants ($P < 0.001$, Figs. 2B and 3B, and Table 1). Pulsed water mists provided a degree of disease suppression across the duration of the experiment that was equivalent to that provided by both fungicide treatments included in the first experiment (Fig. 2A) and to that of sulfur in the second experiment (Fig. 3). In the sprayed water control (water applications twice weekly), powdery mildew on plants that were disease-free at start of the experiments was reduced by 25 - 65% compared to the untreated control (Figs. 2 and 3, and Table 1).

High tunnel and open field experiments in Florida. Pulsed water mists applied for 1 min 4 times per day was as effective as the fungicides in suppressing powdery mildew, in both the high tunnel and open field (Fig. 4). By 67 days after planting, severity of powdery mildew was reduced from 79.7% in the untreated to 16.8% in the four 1 min. mist treatment in the high tunnel, and from 72.6% in the untreated to 22.1% in the four 1 min. mist treatment in the open field (Fig. 4). Pulsed

water mist applied for 1 min once per day provided a level of mildew suppression approximating 50% across the duration of the experiment, compared to the untreated (Fig. 4).

Presence of other diseases. In the experiment in the high tunnel in Norway in 2013, there was a slight but not significant increase in gray mold (*Botrytis* sp.) on the fruit in the treatments with 1-min. water misting four times per day (7.7%), compared to the untreated (1.3%). However, in general water misting did not result in more fungal or bacterial pathogens than on fungicide-treated plants.

Greenhouse experiments. Disease severity on untreated control plants was greater on the adaxial (upper) leaf surface than on the abaxial (lower) leaf surface (Fig. 5, $P = 0.01$). However, for both the water misting and UVB treatments the degree of disease suppression compared to the untreated control was greatest on the adaxial surface (Fig. 5). Compared to untreated control, pulsed misting for 1-min once daily provided significant suppression of powdery mildew on the adaxial ($P = 0.01$), but not the abaxial leaf surfaces (Fig. 5). The UV treatment significantly reduced powdery mildew on both leaf sides. If combining water misting and UV, there was a slight but not significant increase in the effect compared to the single treatments on the adaxial side.

Removal of conidia from surfaces and sporulating colonies by water droplets. Water droplets readily removed conidia immediately after they were applied to either strawberry leaf surfaces or glass. Droplets accumulated dense aggregations of conidia on their outer surfaces as they rolled across surfaces dusted with conidia (Fig. 6 A and B). In contrast, few conidia accumulated on the surfaces of droplets applied to recently inoculated polystyrene surfaces. On leaves that bore sporulating colonies, conidia were likewise readily removed, and similarly aggregated on the surfaces of the applied water droplets (Fig. 6).

Removal of conidia from sporulating colonies by simulated rainfall. Simulated rain readily removed conidia from detached leaves (Fig. 6 C and D). When applied over four successive

days, simulated rain removed progressively fewer conidia as rain events continued (Fig. 7). A total of 2.4×10^3 conidia per ml were removed by the four subsequent simulated rain events, with 65, 19, 11, and 5% removed during the 1st, 2nd, 3rd and 4th event, respectively (Fig. 7). Leaves exposed to a single 20-sec rain event and subsequently prepared for scanning electron microscopy indicated that conidia were not only removed, but that conidiophores and hyphae within the colony were damaged by the meteoric force of the water droplets (Fig. 8).

Discussion

All the experiments conducted in Norway and Florida in open field, high tunnel, glasshouse, and laboratory showed that pulsed water mists can control powdery mildew of strawberry. Water droplets from mist treatments interfered with attachment of *P. aphanis* conidia to leaf surfaces, inhibited sporulation, reduced total inoculum production, and reduced the number of conidia available for plant-to-plant dissemination. Moisture in the form of free water present on the plant tissue will also reduce conidial germination of *P. aphanis* (Peries, 1962). Conidia of *P. aphanis* are hydrophobic, and thus became aggregated on the surface of water droplets, resulting in the development of water droplets bearing a near-continuous coating of conidia. These water droplets rolled over and eventually off the leaves, thereby removing the conidia, but they also damaged the conidiophores in their path as they travelled. Leaf surface hydrophobicity and water repellency is a key feature in the self-cleaning mechanism of plant leaves, removing certain fungal spores and other particles (Solga et al. 2007). The leaf surface hydrophobicity is generally due to the waxy cuticle, augmented by the effects of the high surface tension of water droplets as they interact with topographic features such as trichomes and microscopic irregularities of the leaf surface (Neinhuis, and Barthlott 1997). Water droplets landing on strawberry leaves will bead into larger droplets, roll

to the edge of the leaf, and fall to the ground, collecting various particles and fungal spores from the leaf surface. Water also removes conidia of wheat powdery mildew (*Blumeria graminis* f.sp. *tritici*), and conidia form a spore ball both on glass and leaf surfaces (Fig. 6). This self-cleaning effect of leaves is known as the "Lotus effect" (Latthe et al. 2014). In our laboratory experiments, efficacy of water in removing attached conidia depended upon physical properties of the surfaces. Due to electrostatic forces between the polystyrene surfaces and the conidia, the latter were firmly attached to those surfaces, and they were not removed by water droplets. In contrast, on glass and leaf surfaces the conidia were loosely attached and were easily removed by water droplets.

Overhead water sprinkling for one minute four times per day produced a degree of disease suppression comparable to that achieved through use of commercial fungicides. One 1-min application of water per day in a greenhouse with high disease pressure reduced powdery mildew severity on the adaxial leaf side but did not control powdery mildew sufficiently on the abaxial side. If applying water once daily or once weekly in a high tunnel or open field in Florida or only twice weekly in a high tunnel in Norway, this reduced powdery mildew substantially by up to 65% compared to the non-treated control (Fig. 2A). However, more frequent water misting, 1 min 4 times per day, resulted in more effective suppression of powdery mildew by up to 92% relative to the untreated control (Fig. 2A). In the simulated rain experiment, most conidia were removed by the first mist event, and the number of conidia removed during misting declined rapidly after the first event. Frequent pulsed misting of water effectively removed matured conidia and reduced the quantity of conidia available from established colonies.

Results from the present whole-plant experiments are in agreement with earlier reports (Rotem and Cohen 1966; Yarwood 1939). Rotem and Cohen (1966) reported that sprinkler irrigation significantly reduced the severity of powdery mildew on tomato plants. For several powdery mildews, it was found that heavy water sprays damaged the mycelium and the spore

bearing hyphae (Yarwood 1939). In *Erysiphe graminis*, the powdery mildew of various cereal and grass species, water crushed the conidiophores and inhibited spore release for at least two days (Ward and Manners 1974). A weekly spray of strawberry plants with acid water reduces incidence of powdery mildew in strawberry plants (Tsukagoshi et al. 2000).

A significant reduction of the conidial concentration of *P. aphanis* in the air was demonstrated following rainfall events, and it took up to three days to return to the pre-rain concentration levels (Peries 1962). This agrees with our observations in the simulated rain experiment, where sporulation of *P. aphanis* was halted following water treatments. In experiments with *Uncinula necator*, the cause of grape powdery mildew, it was shown that overhead watering reduced the formation of conidia (Chellemi and Marios 1991). Furthermore, Blanco et al. (2004) reported a negative correlation between rainfall and the number of powdery mildew conidia trapped from the air in a strawberry field. The number of conidia decreased with an increase in frequency and intensity of rainfall (Blanco et al. 2004).

Residual water films on the leaf surface may be sufficient for the infection and development of other fungi pathogenic to strawberry, and it is thus essential to avoid water misting under moist conditions or during night, to prevent extended periods before the plant tissue dries after treatment. Except from the first experiment conducted in the high tunnel in Norway, where there was a slight but not significant increase in gray mold, there was no increase in diseases favored by moist conditions in any of the other experiments. A quick evaporation of the residual moisture from the leaf surface is essential to minimize the risk of other fungal diseases. Due to the hydrophobic nature of the strawberry leaves and the slight vertical arrangement of the leaflets, water droplets normally rolled off the leaves. The residual moisture left on the leaf surface, dried quickly in our experiments, but the evaporation will depend on the weather conditions and density of the canopy. The strawberry foliage was generally dry within 30 min. of the mid-day water applications. Advanced

sensors or weather forecasting tools are available and may be used to support decisions to apply water only on days with rapid evaporation of residual water.

Pulsed water misting can be used in combination with UV-B for more effective control of powdery mildew in protected environments such as glasshouses. The phytotron experiments showed that the pulsed misting for 1-min once daily provided significant suppression of powdery mildew on the adaxial surface but not on the abaxial surface. This is partly due to that the abaxial surface of the leaves were not fully in contact by the water misting, so powdery mildew was not removed effectively from the abaxial surface. When pulsed misting was combined with UV light, the effect was significant. Brief night-time UV-B irradiances of 0.8 or 1.6 W/m^2 in durations of 2 to 18 min with UV-B reflective surfaces effectively suppressed powdery mildews on the lower surface of the strawberry leaves (Suthaparan et al. 2016).

The timing and duration of water sprinkling of strawberry plants to suppress powdery mildew has been refined to the point where it can provide a commercially relevant degree of suppression of powdery mildew without elevating the risk of other pathogens. If used cautiously and systematically, pulsed misting of water on strawberry plants could help to manage powdery mildew in glasshouse, high tunnel, and possibly also in field production systems and strawberry nurseries. Not the least, it can significantly reduce the need for fungicide applications against powdery mildew, with a subsequent reduction in the development of fungicide resistant strains of *P. aphanis*.

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Table 1. Incidence of strawberry powdery mildew from experiments in a high plastic tunnel in Norway in 2013 and 2014; data are presented as cumulative weekly assessments of the area under the disease progress curve (AUDPC).

Treatments	2013		2014	
	AUDPC disease-free plants[w]	AUDPC inoculum source plants[x]	AUDPC disease-free plants	AUDPC inoculum source plants
Untreated control	1013.8 a[y]	1800 a	1061.7 a	2088 a
Water twice weekly	665.8 b	1781.7 a	650.5 b	2030 a
Water 1 min. 4 times per day	252.1 c	1348.3 b	265.4 c	1866.7 a
Thiovit jet once weekly	102.9 c	1341.7 b	230.4 cd	1575 b
Signum or Topas weekly[z]	65.4 c	1234.2 b	46.7 d	1563 b

[w] Plants that were disease-free at start of the experiments.

[x] Plants containing powdery mildew that were placed in all plots at start of the experiments.

[y] Values in the same column denoted with different letters are different according to Tukey's test at P = 0.05.

[z] Pyraclostrobin + boscalid or penconazole weekly

Fig. 1. Experimental set up in a high plastic tunnel in Norway (A); illustrating the placement of an inoculum source plant (marked with a bamboo stick) and sprinklers for the high tunnel experiment in Norway (B); sprinklers in action in experiments conducted in open field (C) and a high tunnel (D) in Florida.

Fig 2. Effect of brief 1-min. pulses of water misting 4 times daily in comparison with spray applications of water twice weekly, sulfur once weekly and pyraclostrobin + boscalid in weekly alternations with penconazole on disease severity of strawberry powdery mildew in 2013 on plants that were disease free at start of the experiments (A) and on the inoculum source plants (B), in a high plastic tunnel in Norway; assessments made 10, 17, 24 and 30 days after inoculation, error bars are standard error of the mean values.

Fig 3. Effect of brief 1-min. pulses of water misting 4 times daily in comparison with spray applications of water twice weekly, sulfur once weekly and pyraclostrobin + boscalid in weekly alternations with penconazole on disease severity of strawberry powdery mildew in 2014 on plants that were disease free at start of the experiments (A) and on the inoculum source plants (B), in a high plastic tunnel in Norway; assessments made 10, 17, 24 and 30 days after inoculation, error bars are standard error of the mean values.

Fig. 4. Effect of brief 1-min. pulses of water misting either 4 times daily, once daily or once weekly in comparison with bi-weekly applications alternately with cyflufenamid and quinoxyfen on the severity of strawberry powdery mildew in open field (A) and high plastic tunnel (B) in Florida in 2016-17; assessments made 32, 39, 45, 52, 60 and 67 days after planting, error bars are standard error of the mean values.

Fig. 5. Effect of treatments with either a brief 1-min. pulse of water misting, UV-B, or water misting + UV-B compared with an untreated control on severity of powdery mildew on the adaxial and abaxial leaf surfaces of strawberry; weekly assessments for 4 weeks shown as area under the

disease progress curve (AUDPC); bars with different letters are different according to Tukey's test at P = 0.05. Mean values for two repeated experiments.

Fig. 6. Water drops rolling over a strawberry leaf blade with a sporulating lesion of powdery mildew (A) and a glass surface covered with conidia (B), both collecting conidia on their surfaces; a strawberry leaf with sporulating colonies of *Podosphaera aphanis* before (C) and after simulated rain (D).

Fig. 7. Number of conidia collected from leaflets with sporulating lesions of *Podosphaera aphanis* exposed to 20 sec. simulated rain (53 mm/h) daily over 4 days; the leaf tissue was kept dry on water agar between the daily treatments and exposed to conditions conducive for sporulation of the fungus; error bars are standard error of the mean values.

Fig. 8. Scanning electron micrograph of sporulating colonies of *Podosphaera aphanis* before (A) and immediately after (B) exposure to 20 sec. of simulated rain (53 mm/h).

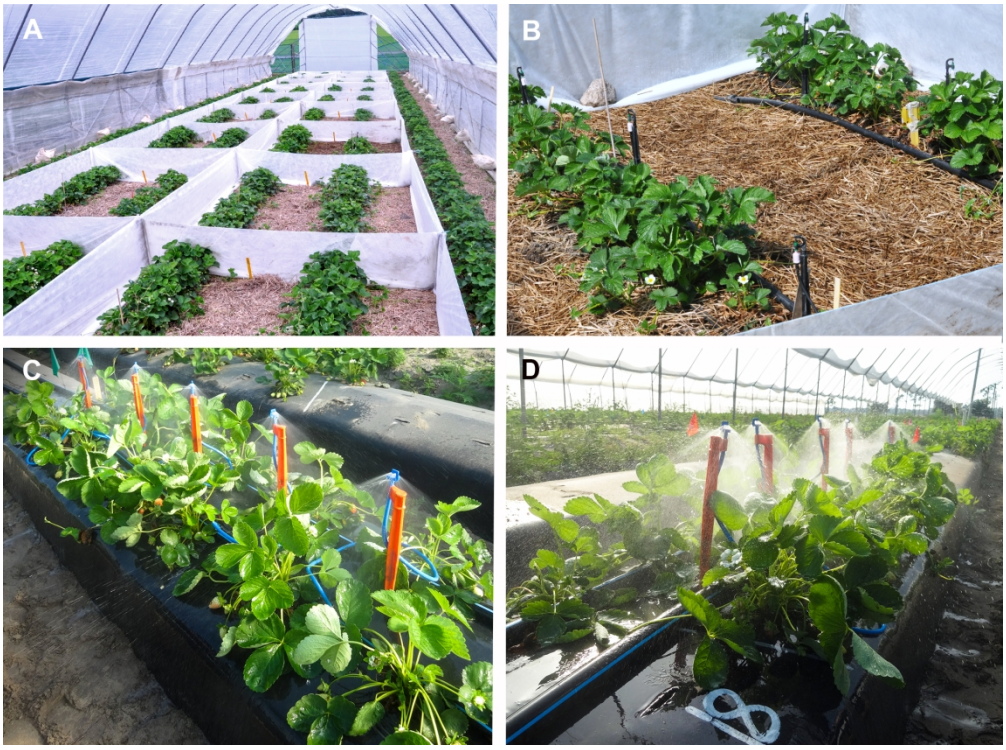

Figure 1

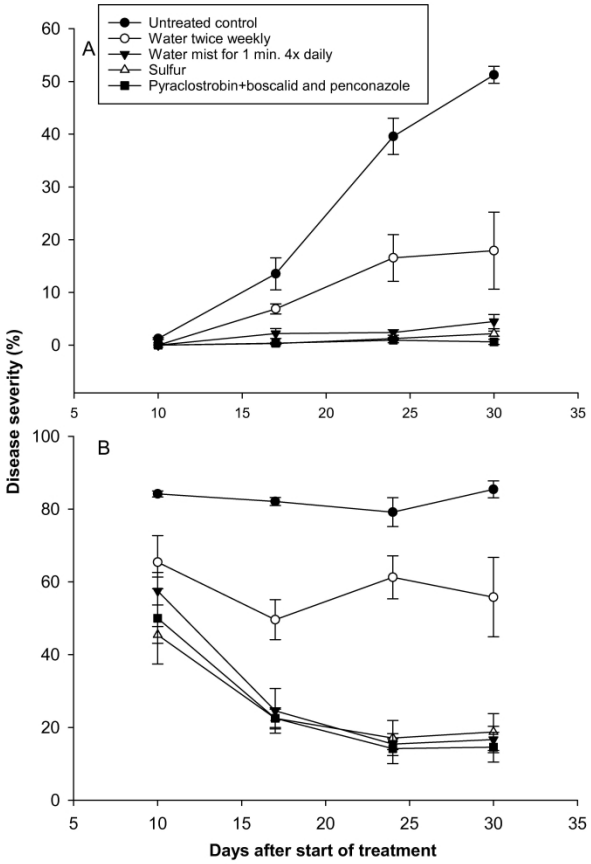

Figure 2

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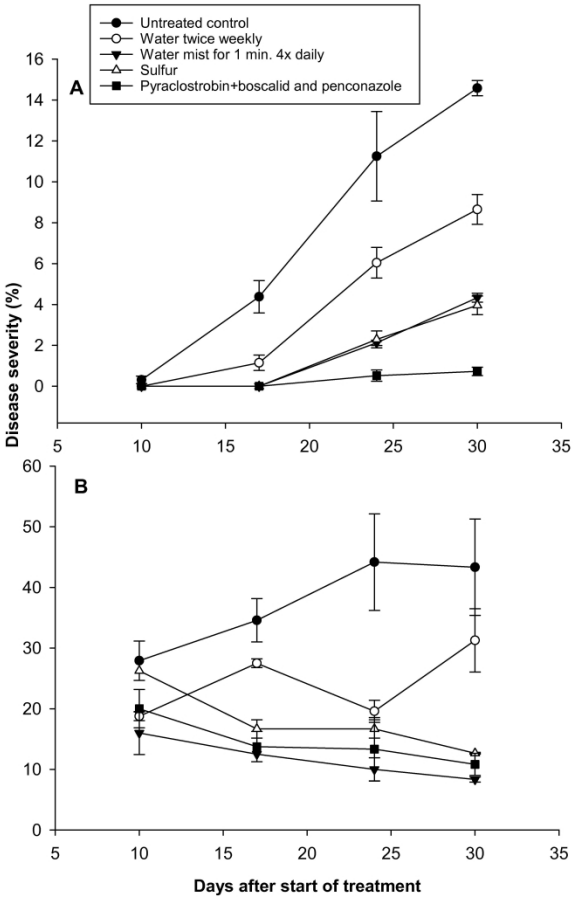

Figure 3

209x297mm (600 x 600 DPI)

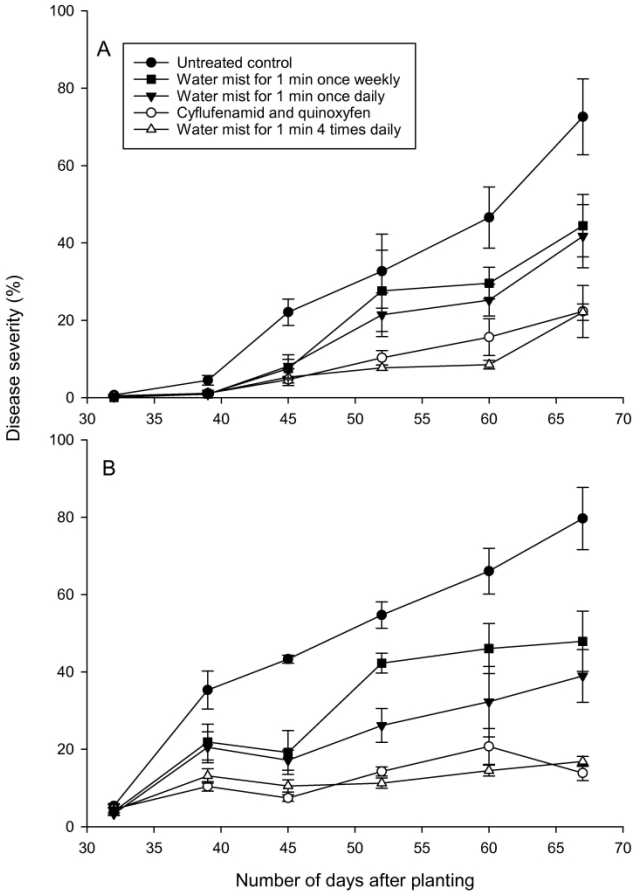

Figure 4

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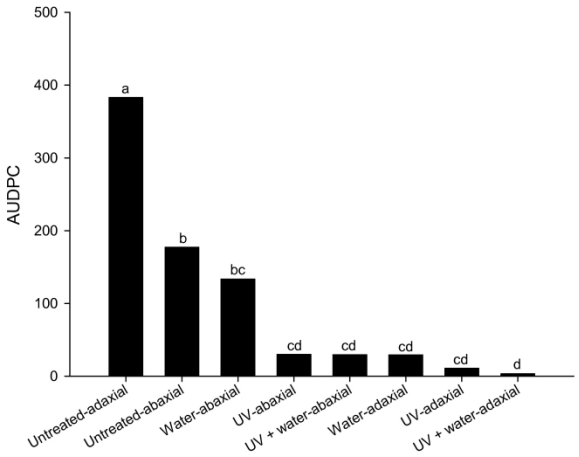

Figure 5

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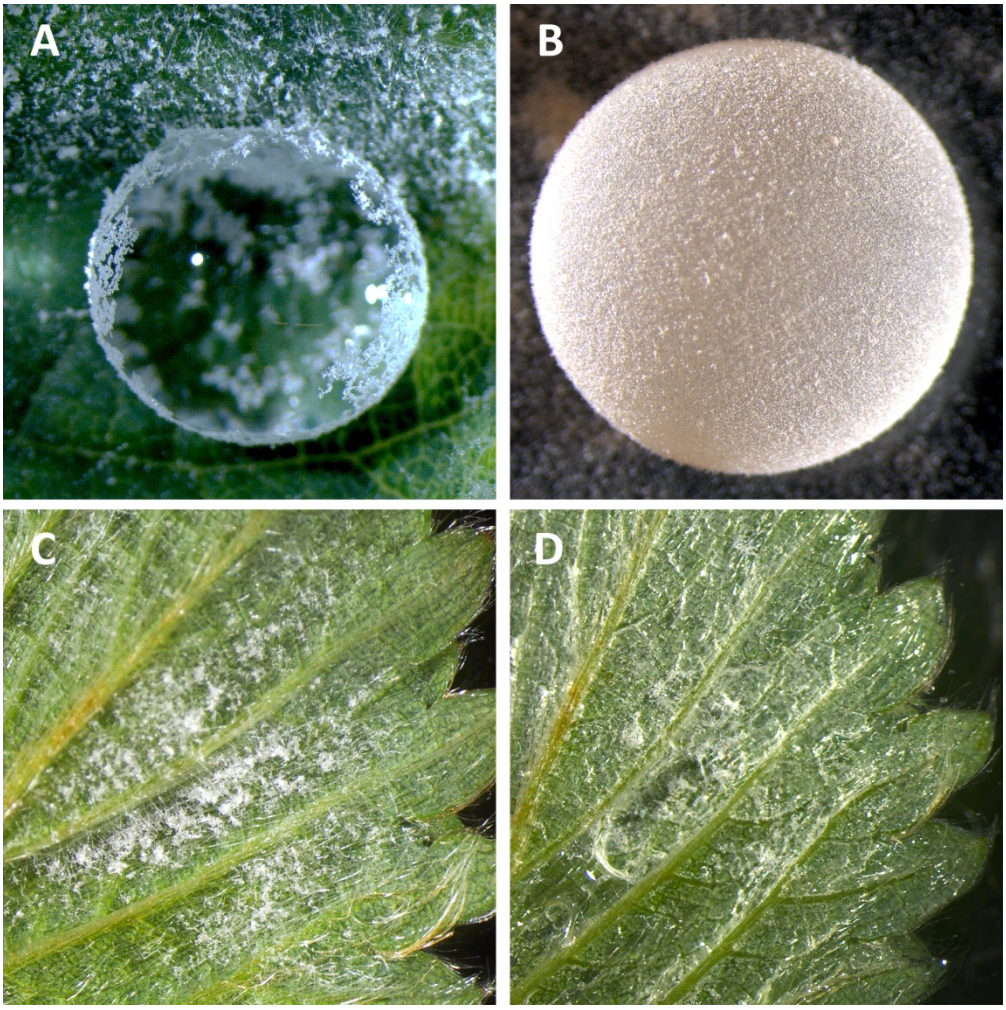

Figure 6

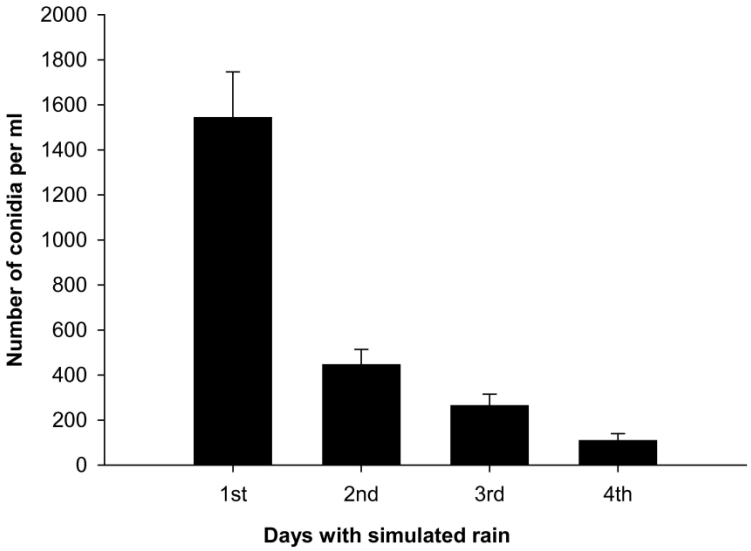

Figure 7

215x279mm (600 x 600 DPI)

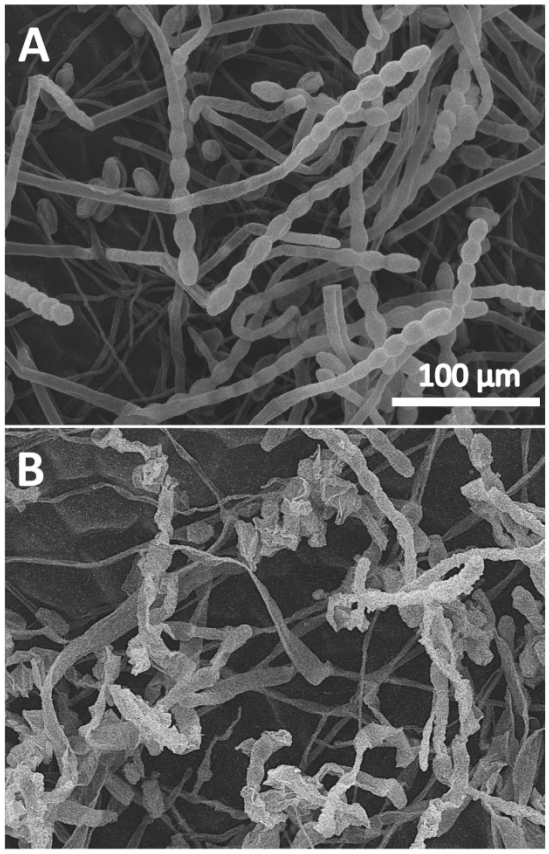

Figure 8

190x254mm (455 x 455 DPI)