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e-**X**tra*

Use of Ultraviolet Light to Suppress Powdery Mildew in Strawberry Fruit Production Fields

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Abstract

We designed and deployed an apparatus to apply UV light for suppression of powdery mildew in open field production of strawberry. The unit was evaluated in a commercial production field for one season, and for two additional seasons in open field research plots at the University of Florida Gulf Coast Research and Education Center. The apparatus contained two 180-cm-long hemicylindrical arrays of twenty 55-W low-pressure discharge UV-C lamps (operated at 30 W; peak wavelength = 254 nm) backed by polished aluminum reflectors covering two adjacent beds of the strawberry planting. The lamp arrays were suspended within a steel carriage that was tractor-drawn through the planting at 2.3, 4.6, and 5.6 km h^{-1}. Nighttime applications of UV-C at doses ranging from 65 to 170 $J{\cdot}m^{-2}$ either once or twice weekly provided suppression of foliar and fruit disease that was consistently equal to or better than that provided by a commercial calendar-based fungicide spray program.

Keywords: disease management, *Podosphaera aphanis*, powdery mildew, strawberry, ultraviolet, UV-C

The strawberry powdery mildew pathogen, *Podosphaera aphanis*, is a threat to strawberry production worldwide (Blanco et al. 2004; Pertot et al. 2008; Xiao et al. 2001). The disease particularly threatens fruit production fields planted with mildew-susceptible cultivars. To compound the challenges facing growers, the pathogen has a propensity to develop resistance to synthetic fungicides, including Fungicide Resistance Action Committee codes 1, 3, 7, and 11 (Nakano et al. 1992; Okayama 1996; Sombardier et al. 2009), which encompass nearly all of the commercially available fungicides registered to suppress the disease. Thus, there is great interest in the development of alternative means to suppress strawberry powdery mildew to both protect yield in fruit production and preserve the efficacy of fungicides. The need for additional disease management strategies is accentuated in Florida, where the majority of the total strawberry production area is planted with cultivars moderately to highly susceptible to powdery mildew (Peres and Mertely 2018).

Several studies demonstrated the efficacy of ultraviolet (UV) light in suppressing powdery mildew pathogens attacking a broad range of crops, including rose (Suthaparan et al. 2012a), cucumber (Patel et al. 2020; Suthaparan et al. 2014), strawberry (Janisiewicz et al. 2016; Suthaparan et al. 2016b), tomato (Suthaparan et al. 2016a), and rosemary (Suthaparan et al. 2016b). The fungicidal efficacy of UV is greatest between 250 and 285 nm because of the formation of thymine dimers in fungal DNA (Bintsis et al. 2000), thereby preventing DNA replication and transcription (Kneuttinger et al. 2014). However, little data exist for wavelengths <250 nm. Short-wavelength visible light (violet and blue) will reverse the damage because of up-regulation of a fungal photolyase DNA repair system that cleaves the thymine dimers (Sancar 1994).

Efficacy of UV treatments is greatly increased when UV exposure occurs during nighttime hours and is followed by at least 4 h of darkness before exposure to either natural sunlight or electric lighting with significant output in the blue-violet spectral region, including white light sources (Janisiewicz et al. 2016; Suthaparan et al. 2017). The efficacy of nighttime UV applications has been well studied within the controlled environments of laboratories, greenhouses, and plastic tunnels (Patel et al. 2020; Suthaparan et al. 2012a, b, c, 2014). Doses ranging from ∼30 to 200 $J{\cdot}m^{-2}$, applied once or twice per week during nighttime hours, have generally reduced the incidence and severity of powdery mildews by >90% compared with disease levels observed in nontreated controls, without causing damage to host plants (Janisiewicz et al. 2016; Suthaparan et al. 2012a, b, c, 2014; Van Delm et al. 2014). In all of the foregoing reports, UV applications involved static arrays of fixed lamps in a treatment enclosure, fixed lamps suspended within the superstructure of a greenhouse or high plastic tunnel, or lamps mounted on an automated boom moving at speeds of 25 to 50 $cm{\cdot}min^{-1}$ over benchtops bearing the target plants.

Duplicating the successful use of UV to suppress powdery mildews in field-grown crops presents certain biological and technical challenges. The sheer size of field planting and the consequent expense of erecting a superstructure for fixed lights precludes the use of static lamps in relatively low-density arrays. Such low-density static lamp arrays produce correspondingly low irradiances, requiring exposure times near 100 s to reach an effective dose of 100 to 200 $J{\cdot}m^{-2}$ (Suthaparan et al. 2014). Because of the sharp decline in efficacy for wavelengths >280 nm, UV-B lamps produce relatively low fungicidally effective irradiance; reaching only ∼15% of the weighted irradiance of UV-C lamps, and therefore more lamps are needed to generate a fungicidal dose (Patel et al. 2020). Likewise, mobile booms of UV-B lamps do not carry sufficient lamps to move at speeds much above 50 $cm{\cdot}min^{-1}$ (Suthaparan et al. 2016a). Typical tractor-drawn implements used in farming operations move at speeds closer to 8,000 $cm{\cdot}min^{-1}$ (4.8 $km{\cdot}h^{-1}$). This limitation eliminates UV-B lamps as a choice for all but the most slow-moving arrays and effectively requires the use of UV-C lamps for any array that would operate at speeds of tractor-drawn equipment to cover large field plantings.

The UV dosing technical challenges can be partially addressed by increasing the number of lamps and the density of the lamp array.

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However, a lamp array can only accommodate so many lamps and reflectors before individual lamps interfere with each other, and the lamp array must be configured in a way that distributes the radiant energy of the lamps as uniformly as possible throughout the three-dimensional space of a geometrically complex and multilayered plant canopy. Ultimately, there are only two principal means by which the array can supply the UV energy needed for a faster-moving array: it can be made longer with respect to the direction of movement, such that it is over a target for a longer time at any given speed, and it can be made more powerful (higher irradiance), such that it delivers more energy per unit of area as it moves over a target; in this case, a raised bed of strawberry plants.

The objectives of our study were to design a lamp array providing sufficient and uniform irradiance that could be affixed to a mobile carriage and operated at speeds generally utilized for tractor-drawn implements; evaluate the efficacy of UV-C in suppression of powdery mildew in field planted strawberry; and to determine the efficacy of three given UV-C doses applied either once or twice per week for suppression of strawberry powdery mildew under field conditions.

Materials and Methods

The mobile UV-C lamp array. The configuration of UV-C lamps within the arrays was dictated by the need to accommodate the dimensions of the raised beds used in annual production systems for field-grown strawberries. The raised beds at the 2017 test site (G&D Farms, Duette, FL) were spaced on 122-cm centers. The base of the raised bed was 74 cm wide, narrowing to 67 cm wide at the shoulder, with a height of 33 cm at its center (Fig. 1). To produce a unit that could treat two adjacent beds simultaneously in a single pass required that the adjacent arrays fit within the alley between beds, which was 48 cm wide. The dimensions vary only slightly among commercial strawberry fruit production fields in Florida. Lamps near the center of the array had to accommodate the presence of irrigation risers extending 30 cm above the center of the raised bed.

Lamp number, array shape, and lamp position were determined through the construction of prototype frames using conventional cool-white fluorescent lamps, with the same geometries of UV-C lamps, at the Lighting Research Center at Rensselaer Polytechnic Institute in Troy, NY. The arrangement of lamps and high optical efficiency within the space constraints were accomplished by an approximately hemicylindrical arrangement of the lamps and reflectors (Fig. 1). Each hemicylindrical array was composed of 10 low-pressure mercury discharge germicidal lamps (OSRAM HNS 55W G13 T8/OF). Each lamp was 90 cm long, operated at 30 W by a single ballast (OSRAM QTP-OPTIMAL 1 × 54-58), and backed by a recurved and polished aluminum reflector. Over each plant row, two such arrays were positioned end-to-end (Fig. 1). Thus, the combined length of the lamps in the end-to-end arrays was 180 cm. Critical dimensions of the array are shown in Figure 1.

The lamp arrays were suspended within a steel frame ($W \times L \times H =$ 2.8 m × 2.5 m × 1.5 m) with attachment points mated to a three-point hitch (Fig. 2A). This allowed the entire apparatus to be towed behind a tractor, and the height of the apparatus over plant beds could be adjusted using the hydraulic system of the three-point hitch and adjustable gauge wheels at the rear of the apparatus (Fig. 2B). The apparatus height was adjusted such that the lowermost lamps of the array were at the level of the bases of plants on the raised bed (Fig. 2C). The top, front, rear, and side walls of the frame were clad in 0.25-mm galvanized steel to shield the operator and bystanders from any direct exposure to the UV-C lamps. A curtain composed of 30-cm-wide strips of 3-mm-thick PVC was arranged across the lower edges of the front and rear walls of the unit to further shield any direct view of the lamps (Fig. 2A). Power for the array was supplied by a portable generator, model Generac GP3300 50 ST (Generac Holdings, Waukesha, WI), carried on the top left corner of the apparatus (Fig. 2A).

Uniformity of irradiance within the three-dimensional space occupied by plants under the array was determined using a model no. BTS2048-UV-S (Gigahertz-Optik, Amesbury, MA) spectroradiometer positioned within the lamp array. Low-pressure discharge UV-C lamps require a warm-up period before irradiance stabilizes. Lamps were turned on at least 15 min before measurements or treatment applications. Irradiance was measured from 240 to 270 nm within an arc that circumscribed a 10-cm diameter approximating the canopy periphery of a strawberry plant three weeks after establishment, as well as a 38-cm diameter approximating the canopy periphery of a strawberry plant at maturity (Fig. 1). Irradiance was recorded at 0°, 45°, and 90° angle from a horizontal plane at 25-cm intervals along the length of the array (Fig. 3).

The UV-C treatment dose, D, was calculated by integrating the UV-C irradiance, $E(s)$, as a function of distance, ds, over the length of the array, l, and dividing by the velocity of the tractor, v, as given by Equation 1:

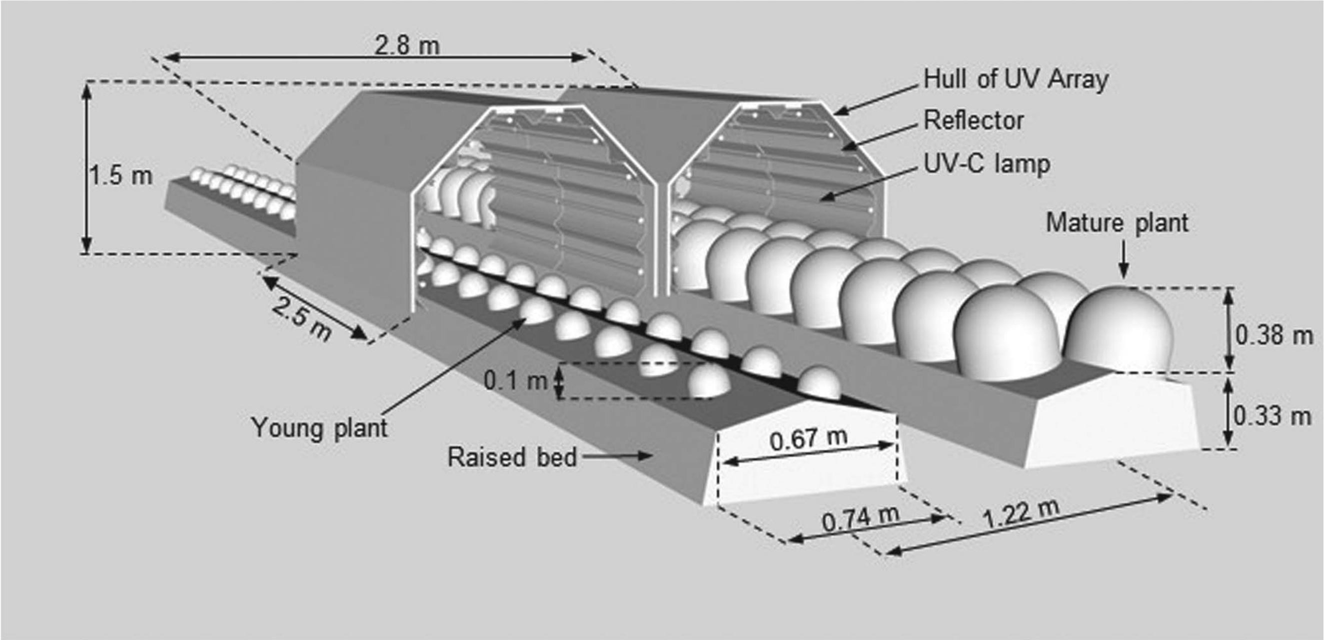

Fig. 1. Dimensions and orientation of the UV-C tractor-drawn array. The illustration shows the critical dimensions of the array, strawberry beds, and young and mature plants.

$$D = \frac{1}{v}\int_{0}^{l} E(s)ds \quad (1)$$

Velocity of the tractor was set to achieve target dose levels of 68, 85, and 170 J·m^{-2} for a horizontal surface 15 cm above the center of the planting bed, corresponding to the height of the canopy periphery of the above-described 3-week-old strawberry plant. This yielded target tractor speeds of 5.6, 4.6, and 2.3 km·h^{-1}, respectively.

Efficacy of UV-C in field trials. During the 2016 to 2017 season, experiments were conducted in a commercial open-field strawberry fruit production farm in Duette, Florida. Bare-root strawberry transplants of the cultivar Sensation Florida127, known to be highly susceptible to powdery mildew, were planted on 15 November 2016 into fumigated, plastic-mulched raised beds. Beds were 71 cm wide, 122 cm between bed centers, and 92 m long, each supporting two rows of plants per bed, with 38 cm between plant rows and 38 cm between plants within a row. All plants were overhead-irrigated for 10 days to aid establishment, and then irrigated and fertilized with drip-tape according to standard regional production practices.

Six treatments were arranged in a randomized complete block design with three replications per treatment. Each block consisted of four raised beds that were ~100 m in length. The four-bed blocks were separated by eight adjacent beds that were treated with fungicides according to the grower's schedule. Experimental units consisted of 14 plants within a 2.7-m section of a bed that was randomly selected for disease and yield assessment. Treatments included the following: a nontreated control; a fungicide standard applied every 2 weeks; twice weekly exposure to 85 J·m^{-2} UV-C; twice weekly exposure to 170 J·m^{-2}; the fungicide standard in combination with twice weekly exposure to 85 J·m^{-2} UV-C; and the fungicide standard in combination with twice-weekly exposure to 170 J·m^{-2} (Table 1). The fungicide standard consisted of applications every 2 weeks of cyflufenamid (Torino, Gowan, Yuma, AZ) alternated with quinoxyfen (Quintec, Dow AgroSciences, Indianapolis, IN) at rates of 248 ml of product per ha and 438 ml of product per ha, respectively. Fungicides were applied with a CO_2 pressurized backpack sprayer using a two-nozzle wand (935 liters·ha^{-1}). UV-C was applied to the experimental area using the above-described apparatus beginning 1 h after sunset. All UV-C applications were completed within 6 h before sunrise. UV-C was applied 18 times, beginning on 13 December 2016, and ending on 22 March 2017 (Table 1). Fungicides were applied six times during the same period (three cyflufenamid and three quinoxyfen; Table 1).

The experiment was repeated at the University of Florida Institute of Food and Agricultural Services Gulf Coast Research and Extension Center (UF/IFAS–GCREC) located in Wimauma, FL, during the 2017 to 2018 and 2018 to 2019 growing seasons with the following modifications. Treatments were applied within an area composed of 12 raised beds spaced on 122-cm centers, with each bed 99 m in length. The raised beds were transplanted to the strawberry cultivar Sensation Florida127 on 17 October 2017, and 15 October 2018. Within each bed there were two planted rows with 38 cm between plants and 38 cm between rows. The bases of the raised beds were 74 cm wide, narrowing to 67 cm wide at the shoulder, and were 33 cm in height at the center.

Treatments were assigned in a randomized complete block design with three replications per treatment. Each block consisted of four raised beds, two of which were buffers separating the beds containing the experimental units. Buffer beds were treated twice weekly with UV-C at 85 or 170 J·m^{-2}. Experimental units consisted of a 2.7-m section of a bed containing 14 plants. Treatments during the 2017 to 2018 season were applied from 17 November 2017 to 2 January. Treatments during the 2018 to 2019 growing season were applied from 26 November 2018 to 7 January. During the 2017 to 2018 and 2018 to 2019 seasons, 14 and 13 UV-C applications were made in twice a week UV-C treatments, respectively (Table 1). The fungicide standard consisted of three (two cyflufenamid + one quinoxyfen) and three (two cyflufenamid + one quinoxyfen) fungicide applications during the 2017 to 2018 and 2018 to 2019 seasons, respectively (Table 1).

Impact of UV-C dose and frequency of application. To determine the impact of varying the number of weekly application of UV-C, as well as the dose of UV-C applied per application, a trial was conducted at the GCREC, and included the following: a nontreated control; a fungicide standard applied every 2 weeks; UV-C applied once per week at 68, 85, or 170 J·m^{-2}, respectively; and UV-C applied twice per week at 68, 85, and 170 J·m^{-2}, respectively (Table 2). Treatments were replicated four times and assigned within a randomized complete block design wherein the four blocks were a single raised bed 92 m in length. Each experimental unit consisted of 14 Sensation 'Florida127' plants planted on 17 October 2017, and 15 October 2018. Bed dimensions and plant and row spacings within the beds were as previously described for GCREC trials. Plots within a bed undergoing UV-C treatments, but not scheduled to receive UV-C treatment, were covered with a black polyethylene sheet that blocked all UV-C during the application. Treatments during the 2017 to 2018 season were applied from 17 November 2017 to 2 January. Treatments during the 2018 to 2019 growing season were applied from 26 November 2018 to 7 January. During the 2017 to 2018 season, seven and 13 UV-C applications were made in the once-a-week and twice-a-week UV-C treatments, respectively (Table 2). During the 2018 to 2019 season, seven and 14 UV-C applications were made in the once-a-week and twice-a-week UV-C treatments, respectively (Table 2). During the 2017 to 2018 and 2018 to 2019 seasons, the fungicide standard treatment received four applications (two cyflufenamid + two quinoxyfen) in each season (Table 2). During the 2018 to 2019 season, the trial was duplicated on the cultivar Florida Beauty, which is moderately susceptible to *P. aphanis*.

Disease and yield assessments. The increase of foliar powdery mildew in strawberry is typified by the progressive infection of susceptible leaves as they emerge and unfold. Thereafter, the leaves rapidly acquire ontogenic resistance, and further increase on matured leaves is minimal. Therefore, severity of powdery mildew was visually estimated weekly on four arbitrarily selected plants from each experimental unit by recording the percentage of three abaxial (lower) leaf surfaces at stage five (Asalf et al. 2014) colonized by *P. aphanis*. Severity percentages values were recorded at equal weekly time intervals and were summed to calculate the cumulative foliar disease severity. Assessments were initiated when the disease was first observed and continued from 21 December 2016 to 14 February 2017, 21 November 2017 to 4 January 2018, and 28 November 2018 to 9 January 2019.

Fig. 2. UV-C tractor-drawn wheeled equipment for UV treatments. **A,** Side view of the UV-C tractor-drawn unit. **B,** Unit during nighttime field operation. **C,** View of interior showing the dense reflectorized hemicylindrical array of germicidal UV-C lamps.

Fruit was harvested twice a week from 4 December 2016 to 29 January 2017, 7 December 2017 to 29 January 2018, and 3 December 2018 to 3 January 2019. The weight and number of marketable fruit, the total number of fruit, and the number of fruit affected by powdery mildew were assessed. Powdery mildew fruit disease incidence was visually determined based on the presence of any mycelial growth or conidia on the fruit surface.

Statistical analyses. Statistical analyses were conducted using the program SAS (SAS Institute, Cary, NC) by fitting the data in a generalized linear mixed model using PROC GLIMMIX, with treatments as fixed effects, and blocks as random variables. For the efficacy of UV-C in field experiments, data from each season were analyzed independently by a two-way analysis of variance with Tukey's multiple comparison test for fungicide, UV-C dose, and the interaction between fungicide and UV-C dose. Log-transformation was used for cumulative foliar severity and marketable fruit yield data. Arcsine square root transformation was used for fruit disease incidence. Back-transformed data are presented in the results. Normality and homogeneity of variance were verified. The cumulative foliar disease severity, as described above, the incidence of fruit infection, and the marketable fruit yield were response variables. For the impact of UV-C dose and frequency of application experiment, foliar disease severity at the peak of the disease progress curve from each season was the response variable. The fixed factor mean separation was done by using Fisher's Protected Least Significant Difference test ($\alpha = 0.05$).

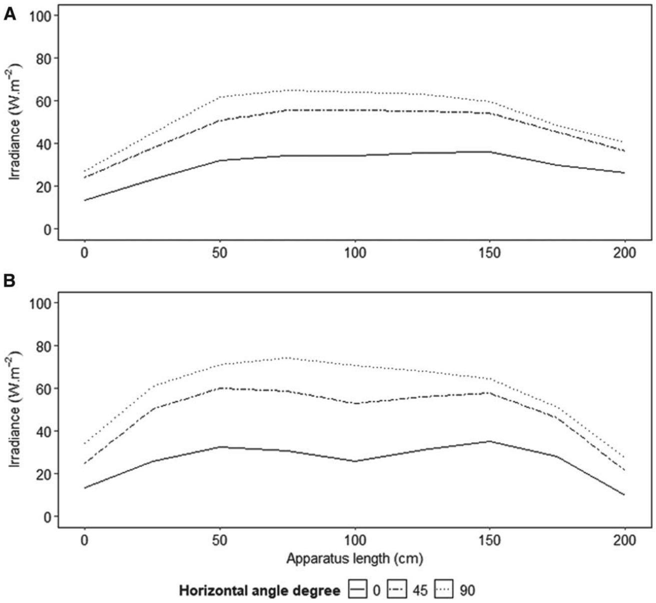

Fig. 3. Irradiance readings at 0°, 45°, and 90° from horizontal. Irradiance measurements were taken, **A,** 15 cm above the raised bed, a distance corresponding to the canopy periphery of an immature strawberry plant; and **B,** 35 cm above the top of the raised bed, a distance corresponding to the canopy periphery of a mature strawberry plant.

Results

Efficacy of UV-C in field trials. Applications twice weekly with UV-C at 85 or 170 $\text{J}\cdot\text{m}^{-2}$ provided suppression of foliar powdery mildew that was equal to or greater than the fungicide standard treatment in all three growing seasons of the study (Fig. 4). In all years, the interaction between fungicide and UV-C treatment was not significant ($P > 0.05$; Table 3), meaning the trends were similar. During 2016 to 2017, the fungicide treatment alone reduced foliar severity by $\sim$50% compared with the nontreated control but was not significantly different from it. However, all UV-C applications during that season provided significant control (up to 90% disease reduction, $P < 0.001$) when compared with the nontreated control, with or without concurrent fungicide application (Table 3). During the 2017 to 2018 season, both the fungicide treatment applied without UV-C and the UV-C doses with and without fungicide significantly reduced cumulative foliar severity ($P < 0.0001$; Table 3). The fungicide treatment without UV-C and UV-C at 85 $\text{J}\cdot\text{m}^{-2}$ both reduced disease by $\sim$70% compared with the nontreated control. A significant, but slight, increase in efficacy (15%) was observed when the fungicide standard was applied in combination with UV-C at either 85 or 170 $\text{J}\cdot\text{m}^{-2}$.

Performance of the fungicide standard had severely degraded by the third year of this study, during the 2018 to 2019 season, when the fungicide alone reduced disease severity by only 10%, in contrast to UV-C at 85 and 170 $\text{J}\cdot\text{m}^{-2}$, which reduced powdery mildew by nearly 60 and 80%, respectively ($P < 0.001$; Fig. 4). The combination of the fungicide standard applied either with 85 or 170 $\text{J}\cdot\text{m}^{-2}$ UV-C-doses provided statistically equal powdery mildew suppression of 86 and 82% ($P < 0.001$; Fig. 4).

Fruit infection never rose above trace levels at the Duette site in 2016 to 2017 for the nontreated control or within any of the treatments, and therefore neither fruit disease incidence nor marketable fruit yield data are shown. At the GCREC site during the 2017 to 2018 season, there was a significant effect of fungicide alone ($P < 0.001$; Table 3). However, this effect was not observed during the 2018 to 2019 season (Tables 3 and 4). The UV-C treatments significantly improved the fruit disease suppression during the 2017 to 2018 ($P < 0.001$) and 2018 to 2019 ($P < 0.001$) seasons when applied alone or in combination with the fungicide standard treatment (Tables 3 and 4). The lowest UV-C dose applied twice weekly reduced incidence of powdery mildew on fruit by 43 and 88% during the 2017 to 2018 and 2018 to 2019 seasons, respectively, compared with the nontreated control (Table 4). Combining the lowest UV-C-dose with the fungicide treatments significantly increased the efficacy during the 2017 to 2018 season by 70% compared with the nontreated control, ($P < 0.001$). The highest dose of UV-C reduced the incidence of powdery mildew on fruit by 53 and 90% compared with the control during the two seasons, respectively.

During the 2017 to 2018 season, marketable yield of strawberry fruit at the GCREC site was significantly increased by both the fungicide ($P < 0.001$) and the different UV-C doses ($P < 0.01$; Table 3).The fungicide standard treatment alone and the combination of UV-C treatments with the fungicide significantly increased marketable yield compared

Table 1. Treatment description, application frequency, and the number of applications during the 2016 to 2017, 2017 to 2018, and 2018 to 2019 seasons for efficacy of UV-C in field trials; FS, fungicide standard

		Number of applications		
Treatments	**Application frequency**	**2016 to 2017**^{y}	**2017 to 2018**	**2018 to 2019**
Nontreated control	–	–	–	–
FS^{z}	Every 2 weeks	6	3	3
UVC-85 $\text{J}\cdot\text{m}^{-2}$	Twice weekly	18	14	13
UVC-85 $\text{J}\cdot\text{m}^{-2}$ + FS	Twice weekly + every 2 weeks	18 + 6	14 + 3	13 + 3
UVC-170 $\text{J}\cdot\text{m}^{-2}$	Twice weekly	18	14	13
UVC-170 $\text{J}\cdot\text{m}^{-2}$ + FS	Twice weekly + every 2 weeks	18 + 6	14 + 3	13 + 3

[y] During the 2016 to 2017 season, the experiment was conducted with cultivar Sensation Florida127 at a commercial strawberry fruit production farm in Duette, FL. During the 2017 to 2018 and 2018 to 2019 seasons, trials were conducted with the same cultivar at the Gulf Coast Research and Education Center in Wimauma, FL.

[z] The fungicide standard consisted of applications every 2 weeks of cyflufenamid (Torino, Gowan, Yuma, AZ) alternated with quinoxyfen (Quintec, Dow AgroSciences, Indianapolis, IN) at rates of 248 ml of product per ha and 438 ml of product per ha, respectively.

Table 2. Treatment description, application frequency, and the number of applications during the 2017 to 2018 and 2018 to 2019 seasons for the impact of UV-C dose and frequency of application trials; FS, fungicide standard

Treatments	Application frequency	Number of applications[x]	
		2017 to 2018	2018 to 2019
Nontreated control	–	–	–
FS[y]	Every 2 weeks	4	4
UV-C@68 J·m^{-2}	Once weekly	7	7
UV-C@85 J·m^{-2}	Once weekly	7	7
UV-C@170 J·m^{-2}	Once weekly	7	7
UV-C@68 J·m^{-2}	Twice weekly	13	14
UV-C@85 J·m^{-2}	Twice weekly	13	14
UV-C@170 J·m^{-2}	Twice weekly	–[z]	14

[x] During the 2017 to 2018 growing season, the experiment was conducted with cultivar Sensation Florida127 only. During the 2018 to 2019 season, two independent trials were conducted with cultivars Sensation Florida127 and Florida Beauty. All trials were conducted at the Gulf Coast Research and Education Center in Wimauma, FL.

[y] The fungicide standard consisted of applications every 2 weeks of cyflufenamid (Torino, Gowan, Yuma, AZ) alternated with quinoxyfen (Quintec, Dow AgroSciences, Indianapolis, IN) at rates of 248 and 438 ml of product per ha, respectively.

[z] The treatment was included only for the 2018 to 2019 season.

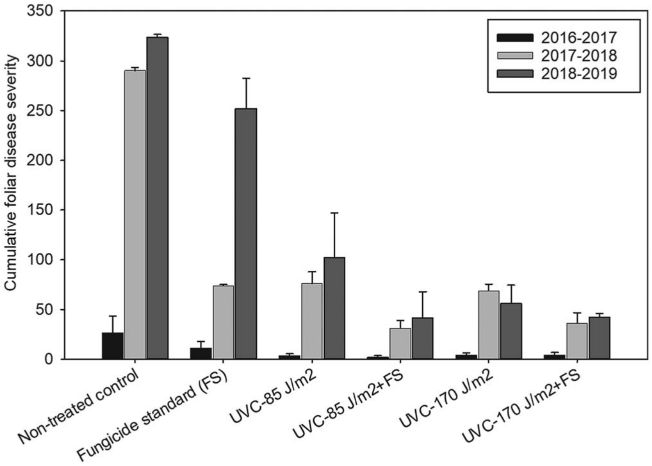

Fig. 4. Cumulative foliar disease severity of powdery mildew on strawberry cultivar Sensation Florida127 during three consecutive growing seasons on plants treated with a fungicide standard, or treated twice weekly with UV-C at 85 or 170 J·m^{-2}, either alone or in combination with the fungicide standard. Error bars represent standard errors of the mean. Data from weeks where severity in nontreated control was <10% were not included.

with the nontreated control in both seasons of the study (Fig. 5). However, during the 2018 to 2019 season, only UV-C had a significant effect on marketable fruit yield ($P < 0.05$; Table 3). Both doses of UV-C alone resulted in yield increases of nearly 36% during both seasons. A total marketable yield of 3,202 and 454 g per plot were observed in the nontreated control during 20 harvests during the 2017 to 2018 and eight harvests during the 2018 to 2019 seasons, respectively.

Impact of UV-C dose and frequency of application. All UV-C treatments significantly but equivalently suppressed foliar powdery mildew severity on cultivar Sensation Florida127 during the 2017 to 2018 ($P < 0.0001$) and 2018 to 2019 ($P = 0.0019$) growing seasons in comparison with the nontreated control. During the week in which disease severity reached a maximum of ∼75% on the cohort of susceptible leaves included in the assessments (6 weeks after the first symptoms, 2017 to 2018), applying 85 J·m^{-2} on cultivar Sensation Florida127 twice weekly was ∼50% more effective than the same dose applied once weekly ($P = 0.003$; Fig. 6A). No difference was observed when a dose of 68 J·m^{-2} was applied either once or twice weekly during the same season (Supplementary Fig. S1).

During 2018 to 2019, disease severity reached a maximum of 40% in the nontreated control, and no significant differences were observed between once or twice weekly applications (7 weeks after the first symptoms, 2018 to 2019; Fig. 6B). On cultivar Florida Beauty in 2018 to 2019, foliar powdery mildew never rose above 10% on the nontreated control or within any treatments, and therefore data were not shown. The three UV-doses (68, 85, and 170 J·m^{-2}) applied once weekly provided similar cumulative disease suppression as the fungicide standard.

With respect to fruit infection, the fungicide standard failed to significantly suppress the incidence of powdery mildew on either cultivar in 2018 to 2019 and only slightly so in 2017 to 2018 (Table 5). During the 2017 to 2018 season, applications once weekly on cultivar Florida127 of 68 and 85 J·m^{-2} did not significantly reduce fruit incidence compared with the nontreated control ($P = 0.0067$; Table 5). During the 2018 to 2019 season, the 68 J·m^{-2} treatment showed a similar lack of efficacy on suppressing fruit disease on cultivar Florida Beauty compared with the nontreated control. The lowest UV-C-dose, 68 J·m^{-2}, applied twice weekly were consistently more effective in suppressing fruit infection across seasons and cultivars compared with once-weekly applications (Table 5). In contrast, once-a-week application of the highest UV-C-dose, 170 J·m^{-2} provided similar fruit disease suppression across seasons and cultivars compared with applications twice weekly.

Discussion

This study is the first report of commercially relevant levels of suppression of strawberry powdery mildew obtained through applications of UV-C under open field conditions. The results are consistent with previous studies that found UV-C application to effectively suppress powdery mildews in controlled environments of laboratories, greenhouses, and tunnel production systems (Janisiewicz et al. 2016; Kanto et al. 2014;

Table 3. Analysis of variance of the effects of fungicide and UV-C doses on strawberry ‘Florida127’ on powdery mildew cumulative foliar disease severity and fruit disease incidence, and marketable fruit yield during three consecutive strawberry seasons

Season	Source	DF[x]	*F* value[y]		
			Cumulative foliar disease severity	Fruit powdery mildew incidence (%)	Marketable fruit yield (g/plot)
2016 to 2017	Fungicide	1	1.51	z	z
	UV-C dose	2	16.56***	–	–
	Interaction	2	2.22	–	–
2017 to 2018	Fungicide	1	70.14***	30.29***	32.61***
	UV-C dose	2	39.47***	19.06***	5.13**
	Interaction	2	2.81	0.74	1.01
2018 to 2019	Fungicide	1	4.60	2.56	4.82
	UV-C dose	2	25.07***	20.6***	4.27*
	Interaction	2	1.33	0.0	1.47

[x] Degrees of freedom.

[y] Data were analyzed by two-way analysis of variance with Tukey’s multiple comparison test for fungicide, UV-C dose, and the interaction between fungicide and UV-C dose. Log-transformation was used for cumulative foliar severity and marketable fruit yield data. Arcsine square-root transformation was used for fruit disease incidence. For *F* values, *, **, and *** represent *P* values of ≤0.05, ≤0.01, and ≤0.001, respectively.

[z] Data from fruit disease incidence and marketable fruit yield were not shown.

Suthaparan et al. 2016b; Van Delm et al. 2014; van Hemelrijck et al. 2010). This work has reproducibly demonstrated the efficacy of UV-C treatments at doses ranging from 68 to 170 J·m^{-2}, and at application frequencies of once or twice per week in the suppression of strawberry powdery mildew. Moreover, these effects were obtained under severe disease conditions in field plantings of highly susceptible cultivars. The difficulties encountered in obtaining comparable levels of suppression using some of the best available fungicides (Mertely et al. 2017, 2018) illustrate why alternative measures to suppress powdery mildews are needed.

We found that the UV-C dose of 170 J·m^{-2} applied twice per week in combination with fungicide applications every 2 weeks resulted in a higher disease reduction when compared with the nontreated control. The superior control achieved from combining UV-C twice per week with fungicide application could be attributed to the additional control of new infections on emerging leaves and flowers that may occur between fungicide sprays. UV-C applications are inherently eradicant in their mode of action and have not yet been demonstrated to protect against infections occurring after UV-C treatment. However, when combined with fungicide applications, the eradicant activity may have complemented the protectant activity of fungicides by suppressing infections that had become established between fungicide applications.

All UV-C-doses (68, 85, and 170 J·m^{-2}) when applied once weekly provided a significant reduction in the cumulative severity of foliar powdery mildew when compared with the nontreated control. This is an important practical finding for end-users, as the lower rate (68 J·m^{-2}) was accomplished by higher tractor speed (5.6 km·h^{-1}), allowing a larger treatment area to be covered in less time. Nevertheless, under a higher disease pressure during the 2017 to 2018 season, the 68 and 85 J·m^{-2} doses applied twice weekly provided a greater reduction in foliar disease than the same doses when applied once weekly. Moreover, across the two seasons and two cultivars, Sensation Florida127 and Florida Beauty, a lower fruit disease incidence was observed when the 68 and 85 J·m^{-2} UV-C doses were applied twice weekly, and the 170 J·m^{-2} UV-C dose either once or twice a week. Even the lowest doses of UV-C applied once weekly provided commercially relevant levels of powdery mildew suppression during periods of low disease pressure and might be a valuable component of an integrated pest management program for moderately resistant cultivars such as Florida Beauty (Whitaker et al. 2017b), Florida Brilliance, or Florida Radiance (Whitaker et al. 2019). Although our experiments involved fixed doses and intervals of application, we anticipate that UV-C dose and frequency of application would be varied in response to disease pressure in commercial practice, and in response to in-season observed levels of disease.

The fungicide standard treatment used in our study, cyflufenamid alternated with quinoxyfen, performed well during the 2016 to 2017 and 2017 to 2018 seasons, similar to results observed by Mertely et al. (2017, 2018). However, during the 2018 to 2019 season, the standard fungicide treatment did not suppress foliar disease symptoms as well as in previous years. During the latter season, disease severity was reduced by only 25%, and disease incidence on fruit was not different from the nontreated control. A similar trend of declining efficacy was reported by Mertely and Peres (2018). Fungicide resistance in *P. aphanis* has been a concern for Florida strawberry growers because of the use of the same active ingredients multiple times within a single season, as well as in transplant nurseries. From transplant to commercial fruit production, fungicide-based management of strawberry powdery

Table 4. Effect of applications twice weekly with two doses of UV-C alone or in combination with standard fungicides on the incidence of powdery mildew on fruit of strawberry cultivar Sensation Florida127 during the 2017 to 2018 and 2018 to 2019 seasons; FS, fungicide standard

	Fruit powdery mildew incidence (%)	
Treatments	**2017 to 2018**	**2018 to 2019**
Nontreated control	67.1 a[y]	41.9 a
FS[z]	36.1 b	30.1 a
UV-C@85 J·m^{-2}	37.9 b	4.7 b
UV-C@85 J·m^{-2} + FS	20.2 cd	1.0 b
UV-C@170 J·m^{-2}	31.2 bc	4.2 b
UV-C@170 J·m^{-2} + FS	14.0 d	1.7 b

[y] Numbers within columns followed by the same letter do not differ significantly at $P = 0.05$.

[z] FS treatment was applications of cyflufenamid (Torino, Gowan, Yuma, AZ) every 2 weeks, alternated with quinoxyfen (Quintec, Dow AgroSciences, Indianapolis, IN).

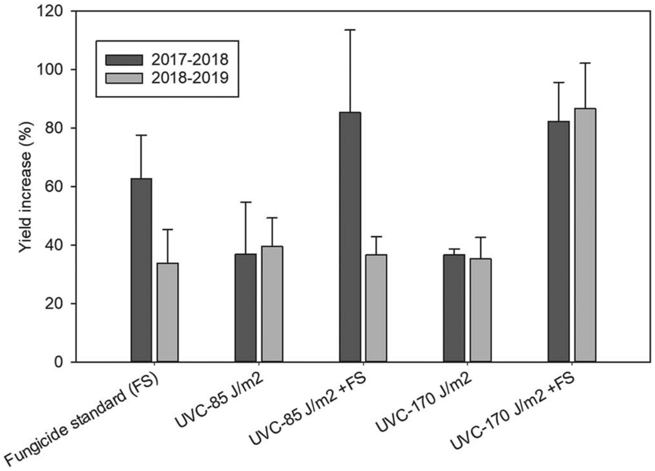

Fig. 5. Increase in marketable yield of cultivar Sensation Florida127 relative to the untreated control in plants receiving either a standard fungicide program or weekly application of UV-C at 85 or 170 J·m^{-2}, either alone or in combination with the fungicide standard. Error bars represent standard errors of the mean.

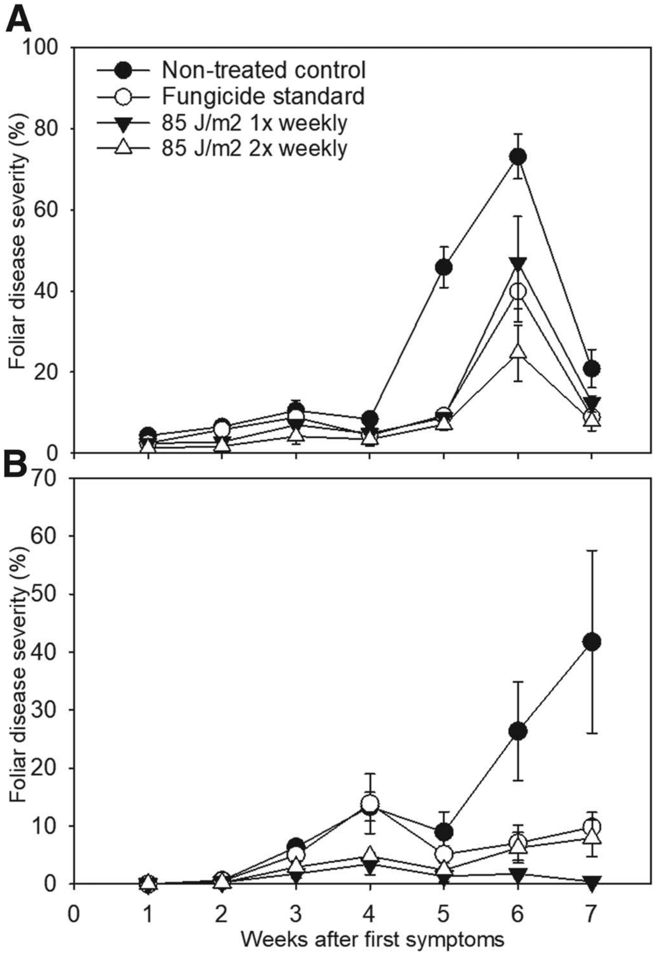

Fig. 6. Effect of 85 J·m^{-2} UV-C-dose applied either once or twice weekly on powdery mildew foliar disease severity of powdery mildew on cultivar Sensation Florida127 during the **A,** 2017 to 2018; **B,** 2018 to 2019 strawberry growing seasons. Data from the two UV-C-doses, 68 and 170 J·m^{-2}, are shown in Supplemental Figure S1.

Table 5. Effect of three doses of UV-C applied once or twice weekly on the incidence of powdery mildew on strawberry fruit during the 2017 to 2018 and 2018 to 2019 seasons, on cultivars Sensation Florida127 and Florida Beauty

	Fruit powdery mildew incidence (%)		
	'Florida127'		'Florida Beauty'
Treatments[x]	2017 to 2018[y]	2018 to 2019	2018 to 2019
Nontreated control	26.5 a	27.5 a	23.9 a
FS	18.6 bc	18.8 ab	21.7 ab
UV-C@68 J·m^{-2} 1×/week	23.7 ab	8.4 bc	15.9 abc
UV-C@85 J·m^{-2} 1×/week	22.0 abc	0.0 c	8.7 c
UV-C@170 J·m^{-2} 1×/week	17.7 c	9.4 bc	14.9 bc
UV-C@68 J·m^{-2} 2×/week	17.7 c	0.0 c	11.9 c
UV-C@85 J·m^{-2} 2×/week	17.1 c	2.3 c	9.7 c
UV-C@170 J·m^{-2} 2×/week	[z]	1.4 c	8.1 c
P value	0.0067	0.0017	0.0048

[x] FS, fungicide standard.

[y] Numbers within columns followed by the same letter do not differ significantly at $P = 0.05$.

[z] The treatment was included only for 2018 to 2019 season.

mildew relies on a limited range of active ingredients, which poses a high risk of selection for resistant isolates (Whitaker et al. 2017a). In addition, most of the single mode-of-action products used to control *P. aphanis* (but not cyflufenamid and quinoxyfen) are also labeled to control *Botrytis cinerea* and *Colletotrichum acutatum*, two other major strawberry pathogens (Whitaker et al. 2017a). Previous studies have already shown resistance in *P. aphanis* populations to demethylation inhibitor fungicides (Fungicide Resistance Action Committee code 3; Nakano et al. 1992; Okayama 1996; Sombardier et al. 2009). Our findings suggest that isolates of *P. aphanis* in Florida might have been selected for resistance to cyflufenamid and/or quinoxyfen, but further studies should be carried out to confirm this. UV-C light represents a useful tool that can be used to strongly reduce the intensity of selection for fungicide resistance in *P. aphanis*, and thereby preserve the efficacy of valuable chemical compounds.

Treatments with UV-C in our experiments did not produce measurable symptoms of phytotoxicity. Van Delm et al. (2014) showed strawberry leaf damage when leaves were exposed to a dose of 500 J·m^{-2} (50 mJ·cm^{-2}) four times per week, which is approximately three times higher and twice more frequent than our highest dose, 170 J·m^{-2}. The same authors did not find leaf damage when the UV-C dose was reduced to 250 J·m^{-2} (25 mJ·cm^{-2}) at the same application frequency. In this study, the treatments did not affect the marketable yield compared with the nontreated control nor did they cause visual damage to the plants. In fact, the UV-C-only treatments resulted in an increase in marketable yield of $\sim$35%, and nearly 80% when combined with a fungicide application. Suthaparan et al. (2017) reported that tolerance of cucurbit plants to UV was directly proportional to the daily light integral received. The comparatively intense solar radiation of field production systems in Florida may also contribute to an increase in protection to potential phytotoxic effects of UV.

There is potential for UV-based treatments to control other strawberry diseases and pests. For example, in the two-spotted spider mite (*Tetranychus urticae*), daily exposure to 288 J·m^{-2} UV-C reduced immature mite and egg production by 99 and 100%, respectively (Johansen et al. 2017; Short et al. 2018). Doses up to 200 J·m^{-2} UV-C have been less harmful against the beneficial predatory mite, *Amblydromalus limonicus*, allowing biocontrol of spider mites to be compatible with UV-C treatments against spider mites (Melis et al. 2019). Further studies may elucidate expanded uses of UV-C in open-field production systems, including against multiple arthropod pests and pathogens.

We are engaged in the automation of UV-C applications in commercial strawberry production fields using a commercially available robotic carriage of a UV array. The robotic carriage is equipped with an array of 20 UV-C lamps based on the array designed in this study and has been deployed at commercial strawberry fruit production farms in Florida, as well as in several commercial locations in Europe. The use of a robotic carriage will resolve the need for a tractor operator for nighttime treatments, a factor that may increase the feasibility of UV-C treatment in commercial sectors facing labor shortages.

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