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Light spectra blocking films reduce numbers of western flower thrips, *Frankliniella occidentalis* (Thysanoptera: Thripidae) in strawberry, *Fragaria x ananassa*

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Abstract

1. *Frankliniella occidentalis* is a pest of horticultural crops, including commercial strawberry (*Fragaria x ananassa*). Control is challenging because certain populations are resistant to insecticides and, in strawberry, now relies on the application of biocontrols. However, this approach is not always successful if *F. occidentalis* populations overwhelm biocontrols. We investigated whether targeted spectral modifications to cladding materials could reduce numbers of *F. occidentalis*, in strawberry flowers.
2. Five UV-attenuating plastic-film materials were tested in three, 6-week, semi-field tunnel experiments containing strawberry plants. *F. occidentalis* were introduced into tunnels from a laboratory culture and subsequent numbers that developed in strawberry flowers were recorded.
3. Limiting UV-A radiation to the crop significantly reduced the numbers of adult and larval *F. occidentalis* in strawberry flowers. The numbers of adult (and larvae) in flowers were reduced by 42 (47)%, 54 (41)%, 70 (73)%, and 82 (73)% in UV350, UV370, UV400, and UV430-attenuating films, respectively, compared with the UVopen (control) film. However, no damage to strawberry fruits was observed regardless of the film treatment.
4. Incorporating UV-attenuating films as tunnel cladding can suppress *F. occidentalis* numbers in strawberry. Reducing populations of *F. occidentalis* in crops is likely to enable the more successful use of other non-chemical control strategies.

KEYWORDS
fruit, horticulture, pest management, plasticulture, ultraviolet, WFT

INTRODUCTION

Frankliniella occidentalis (Pergande), commonly known as western flower thrips, is a polyphagous pest of a wide range of crops globally (Kirk, 2002; Kirk & Terry, 2003). The adults and larvae feed on leaf and flower surfaces, and directly on fruits, reducing photosynthetic ability and marketable yields (van der Blom et al., 1997). In addition, *F. occidentalis* can transmit viruses (Gilbertson et al., 2015; He et al., 2020) and is resistant to most currently approved chemical insecticides (Cubillos-Salamanca et al., 2020; Espinosa et al., 2005; Jensen, 2000; Langfield et al., 2018).

Frankliniella occidentalis is a prevalent pest of cultivated strawberry (*Fragaria x ananassa*). All stages of strawberry flower and fruit are susceptible to thrips feeding, although larvae are more damaging than adults (Sampson, 2014). Feeding damage can cause malformed smaller fruits, reduction in yields, and bronzing of the fruit surface reducing marketable yield (Nondillo et al., 2010). At the flowering stage, feeding damage to the stamens and floral receptacle is observed (Nondillo et al., 2010) and petals can become russetted and wither early. Strzyzewski et al. (2021) reported that two adult *F. occidentalis* females per flower caused a decrease in fruit set and increased distortion (commonly known as 'cat-facing') on the developing fruitlets. However, this impact is cultivar and growing condition dependent (pers. obs.) and can be confounded with interactions with other insect pests, such as mirids (Easterbrook, 2000; Rahman et al., 2010). Feeding on small, green fruit reduces the size of mature fruit (Strzyzewski et al., 2021) and bronzing is often observed under the fruit calyx and around the achenes (Nondillo et al., 2010). In a study with 20 caged *F. occidentalis* adults on strawberry plants for 5 days, 17.6% of the fruits were bronzed, with more than 40% of the fruit surface displaying bronzing damage (Nondillo et al., 2010).

Frankliniella occidentalis is adapted to warm conditions, becoming active particularly early on forced (early flower initiation) tunnel-grown strawberries clad with insulating materials (Sampson, 2014). The optimum temperature for development of *F. occidentalis* on strawberry plants is 25°C (Nondillo et al., 2008; Robb, 1989; van Rijn et al., 1995), where the time from egg to egg can occur in only 15.2 days (Robb, 1989). At temperatures higher than 25°C, adult thrips survival is decreased (Malais & Ravensberg, 2004). In addition, *F. occidentalis* invade crops throughout the growing season from a wide host range including annual flowering weeds (Sampson et al., 2021).

Currently, pest management primarily relies on the release of biocontrol agents (Reitz et al., 2020), including various phytoseiid mites (e.g., *Neoseiulus cucumeris*, Shakya et al., 2010) and pirate bugs (*Orius* spp.) (e.g., Alauzet et al., 1994; Fitzgerald & Jay, 2013; Sampson, 2014; Wu et al., 2017). Ground-dwelling predators can also be incorporated in biocontrol programmes to predate pupal stages (Cloyd, 2019). Entomopathogenic fungi (e.g., *Metarhizium anisopliae*) cause 50%–70% mortality in laboratory tests (Li et al., 2021) and are also effective in glasshouse crops (e.g., cucumber) (Wu et al., 2017). Applications of entomopathogenic fungi can also be employed to target the pupal stage in the soil (Lee et al., 2017). However, entomopathogenic fungi are not commonly used for *F. occidentalis* control in polytunnel-grown crops as they do not give adequate control, potentially because humidity is too low or thrips do not come into contact with enough spores. In addition, arthropod biocontrol solutions can fail when *F. occidentalis* becomes too numerous in the crop (pers. obs.).

Frankliniella occidentalis is attracted to blue-coloured surfaces (Broughton & Harrison, 2012; Díaz et al., 2006; Doukas & Payne, 2007; Johansen et al., 2018), and this is exploited for mass trapping. In semi-protected strawberry crops, mass trapping with blue sticky roller traps reduced adult thrips numbers by 61% in flowers, and fruit bronzing by 55%, compared with an untreated control. Follow on studies where the *F. occidentalis* aggregation pheromone, neryl (S)-2-methylbutanoate, was added to traps, doubled the trap catch (Sampson, 2014; Sampson & Kirk, 2013). However, the type of glue used can also influence *F. occidentalis* attraction to traps and interfere with colour perception (Van Tol et al., 2021).

More often control approaches are combined to target different life stages of *F. occidentalis* for season-long management (Cloyd, 2019), as a single approach is not adequate to reduce crop damage below economic thresholds (Reitz et al., 2020). While many approaches are highly effective at low pest pressure (Saito & Brownbridge, 2018), under optimal conditions for the pest, *F. occidentalis* populations can increase too rapidly for biologicals to keep the pest in check. An approach that suppresses thrips rapid population build-up would enhance other methods of control.

The potential for suppressing *F. occidentalis* populations by disrupting visual perception through the interference of available light has been reviewed by Fennell et al. (2019). In choice tests, *F. occidentalis* was more likely to enter chambers clad in UV (ultraviolet) transparent materials compared with chambers fitted with UV-attenuating materials (Kigathi & Poehling, 2012), and thrips appeared to fly towards areas where UV was present (Fennell et al., 2019). In addition, UV attenuation reduces the dispersal of *F. occidentalis* (Kigathi & Poehling, 2012). However, contrary to those findings, thrips show a reduced preference for tunnels with high UV-B (Mazza et al., 1999), indicating that their responses to light may depend on the predominant behaviour, for example, feeding or dispersing (Fennell et al., 2019).

F. occidentalis response to UV attenuation has been studied in cucumber, *Cucumis sativus* (Antignus et al., 1996), *Lisianthus* (Costa et al., 2003), and lettuce, *Lactuca sativa* (Díaz et al., 2006; Díaz & Fereres, 2007). In cucumber, trap catches were lower under reduced UV films, compared with conventional polyethylene; however, neither trap catches nor plant infestation were reduced in *Lisianthus* or lettuce.

As part of a study to test if UV-attenuating tunnel films suppressed *Drosophila suzukii* Matsumura in strawberry fruits (Fountain et al., 2020), we aimed to investigate whether the same innovative materials would reduce *F. occidentalis* numbers in the same crop, hence giving a dual pest control benefit. The aim of this study was to investigate if UV-radiation attenuating plastic-film materials over strawberry crops could reduce the numbers of *F. occidentalis* in strawberry flowers, and what level of UV attenuation is required to do this.

MATERIALS AND METHODS

F. occidentalis rearing and colony maintenance

Frankliniella occidentalis used in the three field experiments were originally obtained from a laboratory colony originating from Keele University, UK. The mixed age populations of thrips were held in cages (47.5 cm × 47.5 cm × 93.0 cm, mesh size 150 × 150 μm aperture;

TABLE 1 Overall mean (±S.E) numbers of Frankliniella occidentalis adults and larvae per strawberry flower, across all time points, in tunnels clad with UV-attenuating films in 2016, 2017, and 2018.

Year	Film	*n* =	Material	Adults		Larvae	
2016	UVopen	3	Clear	2.69 ± 0.32	**ab**	2.34 ± 0.40	a
			Diffuse	3.80 ± 0.37	**a**	3.58 ± 0.48	a
	UV350	3	Clear	1.49 ± 0.24	**bc**	1.36 ± 0.29	a
			Diffuse	1.84 ± 0.26	**c**	2.05 ± 0.38	a
2017	UVopen	3	Clear	1.75 ± 0.35	a	2.97 ± 0.53	**a**
	UV350	3		1.63 ± 0.33	a	1.94 ± 0.39	**ab**
	UV370	3		1.70 ± 0.34	a	2.54 ± 0.47	**ab**
	UV400	3		0.80 ± 0.18	a	1.22 ± 0.27	**b**
2018	UVopen	8	Clear	2.09 ± 0.23	**a**	3.73 ± 0.40	**a**
	UV370	8		0.68 ± 0.10	**b**	2.08 ± 0.28	**b**
	UV430 (Lumitec)	8		0.35 ± 0.06	**c**	1.29 ± 0.20	**c**

Note: Different letters (**bold**) denote significant differences between the treatments within a year (Tukey's HSD, α = 0.05). *n* = number of replicates.

Bug-dorm, MegaView Science, Taichung, Taiwan), stored in climate chambers at 17°C, 40% ± 5% relative humidity, 10 klux light (LED) intensity, and a photoperiod of 16:8 h light:dark. Insects were supplied with four chrysanthemum (*Dendranthema grandiflora*) plants per cage of mixed cultivars sourced from a local retailer. There were two cages with four chrysanthemum plants per cage. The oldest plant in each cage was replaced with a new plant every 7–14 days according to thrips demand and plant quality. Prior to experiments, existing cultures were subdivided into eight cages with additional chrysanthemum plants to increase the numbers of *F. occidentalis* for inoculation.

Experimental set-up

Field experiments (2016–2018) were located at NIAB, East Malling, Kent, UK ('Ditton Rough', N 51.289148, E 0.455042) and part of the same experiment detailed in Fountain et al. (2020). The average temperature during each experiment was 11.2°C, 11.4°C, and 11.5°C, and annual precipitation was 578 mm, 470 mm, and 598 mm in 2016, 2017, and 2018, respectively (Agrii weather station, East Malling, Kent, UK, N 51.287629, E 0.448587). Twelve tunnels (12 m × 2 m × 2.1 m high [24 m^2]; Knowle Nets Ltd, Bridport, Dorset, UK) were covered with insect mesh (aperture 1 mm × 1 mm, Knowle Nets Ltd, Bridport, Dorset, UK) with film materials (treatments) over the top. Tunnels were orientated north–south, spaced ~20 m apart, and were accessed through a door at either end. Films were 30 cm above ground level to allow ventilation to the strawberry plants. Tunnels were independent of each other and spaced at least 20 m apart in a regularly mown grass field.

There were three experiments, one in each year, which ran for ~6 weeks each. Both clear and diffuse films (scatter inbound radiation) were used in 2016 with two UV light transmission films (UVopen and UV350). As diffuse films did not impact pest numbers, the following year, four clear films were tested (UVopen, UV350, UV370, and UV400). There were three replicates of each treatment (Table 1). In the final experiment (2018), the replicates were increased to eight to improve statistical power. The 12 tunnels were divided with fine mesh (Plain Leaded Net Curtain Fabric; Dunelm Ltd., Syston, Leicestershire, UK) into two compartments (12 m^2). Three films were compared: UVopen, UV370, and UV430 (Lumitec) (Table 1).

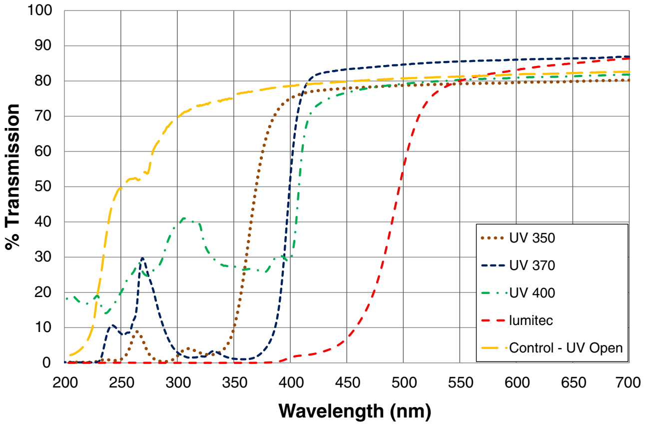

FIGURE 1 Spectral transmission (%) versus wavelength (nm) for all cladding films (UVopen (control), UV350, UV370, and UV400 and UV430 (Lumitec)) measured by Cary 7000-diffuse using reflectance accessories (first published in *scientific reports* Fountain et al., 2020)

Light transmission of the films was measured from 300 to 2500 nm at 2 nm steps using an Agilent Cary 7000 Universal Measurement Spectrophotometer equipped with a diffuse reflectance accessory; an integrating sphere to capture all scattered light post transmission. Transmissions were measured on a 2 × 2 cm of film samples with the beam incident angle at 90° (Figure 1).

Experiments were conducted on ever-bearer strawberry varieties, cv. Finesse (2016, 2018), and a commercially confidential proprietary cultivar (2017, 2018). Bare-root or plug-plants (cv. Finesse and proprietary cultivar, respectively) were planted in 1 m peat bags (8 plants per bag). Bags were arranged end-to-end in the tunnels in one (2016 and 2017) or two rows (2018). In 2018, both cultivars were in all tunnels (10 bags of each, side-by-side in a row). Hence, there were 20 bags in each tunnel/compartment, each year, equating to 160 strawberry plants per plot. Fertigation was set to commercial standard and no sprays were applied to the crops.

At strawberry flowering (phenological stage, BBCH 60–61), *F. occidentalis* (mixed age population) were introduced once in each experimental year, approximately 2 weeks before flower assessments began. Three chrysanthemum flower heads from the stock culture (one each from a different cage) were placed into a clear Perspex box (13.5 × 7.5 × 5 cm, Watkins and Doncaster, UK), which was introduced into the centre of each polytunnel. In 2016 and 2018, we sampled 15 chrysanthemum flowers from the stock culture and assessed for numbers of *F. occidentalis* per flower. There were 6.13 (±SE 1.41) and 274.75 (±SE 34.472) total thrips per flower, respectively.

Strawberry assessments were done by sampling up to 20 strawberry flowers (BBCH 59–65), where available, from each tunnel at each visit (2016: 15, 25 Aug, 5 Sept; 2017: 1, 8, 19, 26 Jun; 2018: 10, 17, 30 May, 14 June). Flowers that had been open for up to 2–3 days were selected, identified as flowers with all petals and pollen clearly visible on the anthers. Flowers from the same tunnel (plot) were collected into one plastic pot (315 ml, RPC Containers Ltd., Blackburn, UK) containing 80 ml of 70% ethanol. To dislodge thrips from flowers, sampling pots were vigorously shaken three times, and subsequently strained through lens cleaning tissue (GE Healthcare UK Ltd, UK). Adult and larval *F. occidentalis* were counted on the lens tissue under a light microscope at ×40 magnification (Leica MZ 8, Leica Biosystems GmbH, Nussloch, Germany).

We originally intended to record damage to strawberry fruits (bronzing/russeting), but the damage in all 3 years was insignificant and hence not analysable.

Statistical analysis

The experimental design for each year was a randomized block with each tunnel as a plot (replicate). Data (number of adults and larvae per flower in each tunnel at each sampling date) were analysed using generalized linear mixed models in R version 4.0.3 (R core Team, 2020). Models were fitted with a quasipoisson distribution with a 'log' link function and the number of *F. occidentalis* adults or larvae as the response variable. Block and sampling date were fixed factors for the 3 years, along with film nested within treatment for 2016. Variety data were pooled for 2018 as there were no variety–treatment interactions. To allow for plots where 20 flowers were not available, log (number of flowers) was included as an offset. To analyse the combined data set, year was included as an additional fixed factor. The total number of strawberry flowers per tunnel was analysed using the same model as described above. Differences were compared using Tukey's honest significant difference (HSD) test in the package 'emmeans' (Lenth, 2021) at a 95% confidence level.

RESULTS

The total number of strawberry flowers per tunnel did not significantly differ between the respective films in each year (2016: χ^2 (df = 10) = 0.168, p = 0.682: 2017: χ^2 (df = 11) = 1.975, p = 0.578; 2018: χ^2 (df = 14) = 1.812, p = 0.404), regardless of film type. The mean number of flowers per film was 189 (±11.6) and 193 (±11.9) flowers in UVopen and UV350, respectively, in 2016; 30.2 (±4.19), 32.8 (±4.48), 35.7 (±4.78), 39.3 (±5.17) in UVopen, UV350, UV370, and UV400, respectively in 2017; and in 2018, mean number of flowers were 14.2 (±1.87), 16.2 (±2.02), and 17.7 (±2.12) in UVopen, UV370, and UV430 (Lumitec), respectively.

In the first experimental year (2016), there was no interaction between treatment (absorbing UV light up to 350 nm) and sampling date and no significant effect of clear vs. diffuse (scatter inbound radiation) film in the number of *F. occidentalis* (Table 1). There was a significant difference in the numbers of *F. occidentalis* adults and larvae among sampling dates (adults: χ^2 (df = 2) = 9.923, p = 0.007; larvae: χ^2 (df = 2) = 24.296, $p < 0.001$) and film (adults: χ^2 (df = 1) = 11.006, $p < 0.001$; larvae: χ^2 (df = 1) = 7.584, p = 0.006), respectively, and higher numbers of adult *F. occidentalis* in flowers under the UVopen film compared with the UV 350 film (χ^2 (df = 1) = 4.639, p = 0.031, Table 1). Overall, after the first sampling, the mean numbers of adults per flower increased significantly from 1.71 (±0.305) on 15 Aug to 2.75 (±0.435) on 25 Aug, and 2.98 (±0.492) on 5 Sept. Numbers of larvae per flower decreased significantly after the first sampling; 4.93 (±0.744) on 15 Aug to 1.40 (±0.309) on 25 Aug and 1.64 (±0.375) on 15 Sept.

In 2017, in the experiments, there was a significant difference in *F. occidentalis* adults on different sampling dates (χ^2 [df = 3] = 16.513, $p < 0.001$), but not between treatments (χ^2 [df = 3] = 7.001, p = 0.072, Table 1). The number of adults per flower across all treatments increased after the first sampling; 0.915 (±0.166) on 1 Jun, but not thereafter; 1.711 (±0.275) on 8 Jun, 1.546 (±0.255) on 19 Jun, and 1.594 (±0.257) on 26 Jun. However, there was a significant effect of both sampling date and treatment on the numbers of *F. occidentalis* larvae in strawberry flowers (χ^2 (df = 3) = 37.644, $p < 0.001$ and χ^2 (df = 3) = 8.813, p = 0.032, respectively). The numbers of larvae increased significantly after the first sampling; 0.8 (±0.2) on 1 Jun; 1.98 (±0.367) and reached a peak on 19 Jun; 4.66 (±0.706), followed by a significant decrease towards the last sampling date 2.36 (±0.413) on 26 June. Importantly, significantly fewer larvae were extracted from strawberry flowers under UV400 film compared with the open control, but not UV350 and UV370 attenuating films (Table 1).

In the final experiment (2018), there were significant differences in numbers of *F. occidentalis* adults at different sampling dates (χ^2 (df = 3) = 137.22, $p < 0.001$), between treatments (χ^2 (df = 2) = 43.628, $p < 0.001$), and an interaction of date and treatment (χ^2 [df = 6] = 69.057, $p < 0.001$, Table 1).

Numbers of *F. occidentalis* larvae in strawberry flowers varied among sampling dates (χ^2 (df = 3) = 84.404, $p < 0.001$) and treatments (χ^2 (df = 2) = 29.97, $p < 0.001$, Table 1), and there was an

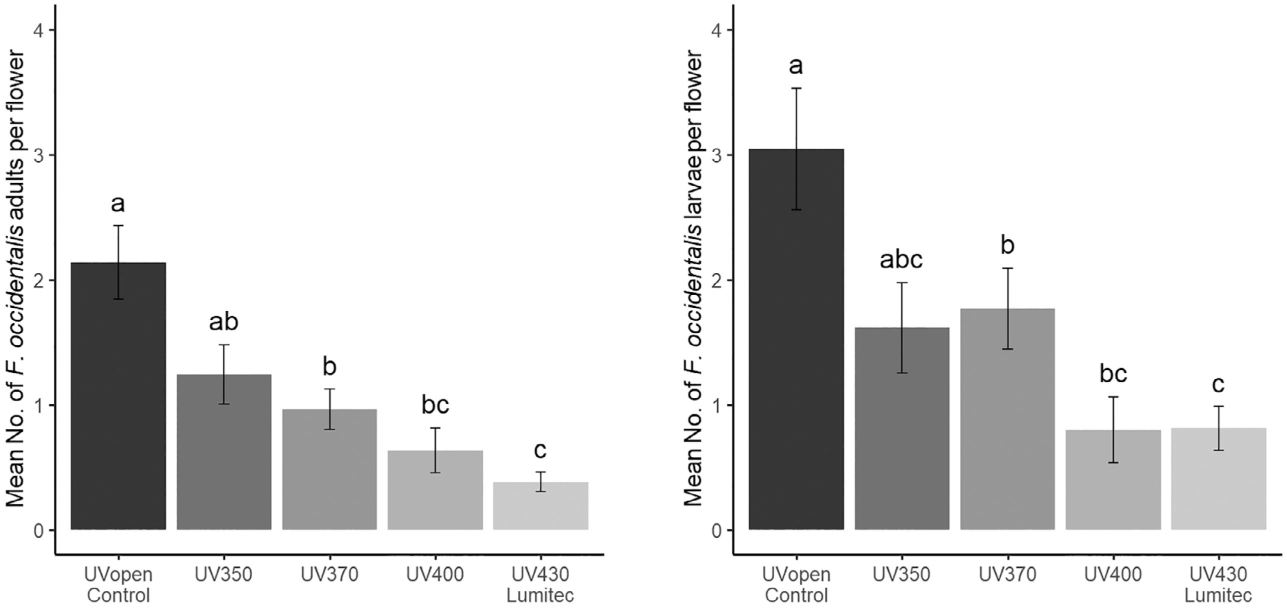

FIGURE 2 Overall, mean (±S.E) numbers of adult (left) and larval (right) Frankliniella occidentalis per strawberry flower from tunnels clad with UV-attenuating films compared with a UV open control across all timepoints; combined data from all three field experiments (2016, 2017, 2018). Different letters denote significant differences in thrips numbers between films (Tukey's HSD, $\alpha = 0.05$)

interaction between date and treatment (χ^2 [df $= 6$] $= 16.53$, $p = 0.011$). The numbers of thrips in flowers grown under the UV370 film were around a third compared with the open (control) film. There were also fewer adult *F. occidentalis* in strawberry flowers grown under the UV430 film compared with the UV370 film and open film (Table 1).

Analyses of the three-year combined dataset revealed significant differences between the UV-attenuating films for both the number of *F. occidentalis* adults (χ^2 [df $= 4$] $= 46.043$, $p < 0.001$, Figure 2) and larvae (χ^2 [df $= 4$] $= 39.203$, $p < 0.001$, Figure 2) per flower. The number of adult *F. occidentalis* per flower was reduced up to 42% (1.24 ± 0.24), 54% (0.96 ± 0.16), 70% (0.63 ± 0.18), and 82% (0.38 ± 0.08) for UV350, UV370, UV400, and UV430 (Lumitec) films, respectively, compared with the UVopen film (2.13 ± 0.29). Furthermore, the numbers of larvae per flower were reduced by 41% (1.77 ± 0.32) and 47% (1.61 ± 0.36) for UV370 and UV350, respectively, and 73% for both UV400 (0.8 ± 0.27) and UV430 (Lumitec) (0.81 ± 0.18) compared with the UVopen film (3.04 ± 0.49) (Figure 2).

DISCUSSION

We demonstrated, for the first time in strawberry, that attenuation of ultraviolet radiation (Figure 1) via spectral filters in polytunnel film materials could significantly reduce the numbers of adult and larval *F. occidentalis* in strawberry flowers. This is a significant finding that could also enable better incorporation and success of other non-chemical approaches to thrips control, which ordinarily work at low *F. occidentalis* numbers (e.g., biocontrol agents including predatory mites and *Orius*).

We did not observe enough thrips feeding damage to assess in this study, which we attribute to fewer than four thrips per flower (Sampson, 2014). Reportedly, two adult *F. occidentalis* females can cause cat-facing on the developing fruitlets (Strzyzewski et al., 2021). However, in our experience, this is more typical of mirid feeding and far more thrips per flower are needed to cause bronzing on strawberry fruits. Indeed, 20 adult thrips were needed to cause 40% surface bronzing of 17.6% of fruits in a study by Nondillo et al. (2010). However, our results indicate that suppressing *F. occidentalis* numbers in strawberry flowers might reduce fruit damage in higher populations.

By limiting the levels of UV able to reach the crop, where *F. occidentalis* were introduced, the number of adult (and larval) *F. occidentalis* per strawberry flower was reduced by 42 (47)%, 54 (41)%, 70 (73)%, and 82 (73)% for UV350, UV370, UV400, and UV430 (Lumitec) films respectively, compared with the UVopen control film. A significant reduction in adults and larvae was observed for films that attenuated light below 430, 400, or 370 nm, with the lowest number of adults and larvae found under the UV400 and UV430 films. The UV350 film, which attenuated light from 350 nm and below, did not significantly reduce pest numbers. It is notable that the films do not block spectra linearly (Figure 1). Indeed, the film blocking below 400 nm has an additional transmission peak at around 310 nm. However, overall, the general trend was that the higher the spectral wavelength attenuation, the fewer *F. occidentalis* were found in strawberry flowers.

Spectral balance is important in insect pest navigation, flight orientation, and food sourcing. Thrips (Thysanoptera) generally have a very restricted range of perception within the UVA (300–400), violet-blue (401–500), and green-yellow (501–560) spectra compared with other insect orders (Fennell et al., 2019; Liu et al., 2019; Matteson et al., 1992). UV is an important cue for take-off flight of thrips

(Mazza et al., 2010); however, it is not clear how the attenuating film in our study affected *F. occidentalis* behaviour. In addition, light intensity can change the response of thrips to spectral wavelengths, as demonstrated in Liu et al. (2019). In our study, potentially constricting the spectral range may reduce flower reflection and hence recognition by the thrips and attraction to flowers, preventing dispersal to new egg-laying sites, but more research is needed to demonstrate this. Thrips seeking a food source may seek locations with increased green reflectance or reduced UV, whereas those in dispersal phases are attracted to areas with higher UV spectra (Fennell et al., 2019; Mazza et al., 1999). However, thrips attraction to host plants tends to be in the green spectral range at over 500 nm (Rőth et al., 2016) and hence would not be expected to be influenced by these films. Also, at 500 nm, the Lumitec film had a transmission of around 60%, so that green plants may have appeared darker and less clear than usual. Alternatively, *F. occidentalis* in our study may have moved away from the strawberry flowers under the light attenuating films.

Fennell et al. (2019) concluded that the main mechanisms of suppression of insect pests by films were (i) positive phototaxis to ultraviolet light sources, and (ii) reduced take-off and flight behaviour when UV was absent, indicating that UV is probably acting as a cue for open sky during take-off and for orientation once in flight (Cronin & Bok, 2016). Suppression of thrips was attributed to both a reduction in pest immigration into the crop, and within crop movement (Fennell et al., 2019), although *F. occidentalis* reportedly moves less than 30 cm per day from release points (Rhainds & Shipp, 2004), and is a relatively a weak flyer (Reitz et al., 2020) relying on dispersal by wind for long-distance transport (Mound, 1983; Nyasani et al., 2017). Hence, in our study, a combination of factors may have been at play, including movement away from plants and non-recognition of egg-laying sites. Both of which would result in fewer *F. occidentalis* larvae and a reduction in population growth. Clearly, more studies are needed to establish the true mechanism of how UV-attenuating films influence *F. occidentalis* behaviour and subsequent populations.

Other studies have used UV-attenuating films, nets, and UV-reflective mulches to interfere with *F. occidentalis* dispersal, orientation, and host-finding resulting in reduced populations (Ben-Yakir et al., 2008; Kigathi & Poehling, 2012; Reeitz et al., 2003). Thrips orientated movement is also influenced by morphological perception (e.g., shape) (Ren et al., 2020) and chemical cues (Mainali & Lim, 2011; Cao et al., 2014; Kirk, 2017; Cao et al., 2019; Reitz et al., 2020). Aggregation pheromones (Kirk, 2017) and host plant volatiles (Cao et al., 2018) also play a role in *F. occidentalis* dispersal, orientation, and host-finding.

In addition to reducing the numbers of *F. occidentalis* in strawberry films, the UV-attenuating films used in this study also reduced egg laying by *D. suzukii* in strawberry fruit in the same experiment (Fountain et al., 2020). Adult *D. suzukii* emergence from strawberry fruit (a proxy for egg laying) was reduced up to 8%, 22%, 34%, and 73% for UV350, UV370, UV400, and UV430 films, respectively, compared with the UVopen cladding. This offers added benefit to fruit growers through the suppression of two key strawberry pests simultaneously. It is not anticipated that there would be a significant interaction between *D. suzukii* and *F. occidentalis* in this study as the former oviposits in ripening and ripe fruits, and the latter generally inhabits the flowers and early fruitlets. Our approach using UV-attenuating films significantly reduced *F. occidentalis* numbers in strawberry, enabling other methods that work more effectively at low populations to be combined with more success (e.g., biocontrols). If the same effect, as reported in this study, when thrips numbers were low were to be found at higher thrips population densities, then this would have the effect of reducing thrips damage and crop losses.

Further research should focus on the mechanisms of how UV-attending films affect insect pests and natural enemies and the promotion of push–pull approaches for *F. occidentalis* management. A push–pull system for thrips management in tomato was suggested by Tyler-Julian et al. (2018), which incorporated push elements of UV-reflective mulch and foliar applications of kaolin, and a pull component of the companion plant *Bidens alba* (L.). For strawberry, we suggest that UV-attenuating films could be used over the crop to ‘deter’ the pest entering and reproducing. Host volatile attractants coupled with aggregation pheromones and attractive traps (Otieno et al., 2018), which incorporate attractive spectra, could be deployed around the crop perimeter to ‘pull’ *F. occidentalis* away. Spectra in the range of 500–600 nm (yellow) are attractive and are used for trapping (Blumthal et al., 2005). Light-emitting diodes (LEDs) are a promising approach to increase the attractiveness of visual traps, for example, blue LEDs could be used to enhance the capture of mass traps in the ‘pull’ approach (Johansen et al., 2018; Otieno et al., 2018; Stukenberg et al., 2020). It is likely that attractant strategies would vary depending on the target crop and time in the season (Johansen et al., 2018).

Most of our films (except the control) blocked UV-C, UV-B, and UV-A (Lumitech) to some degree. UV-C can be used as a treatment for powdery mildew, *Rhizopus* and *Botrytis* pathogens of strawberry (Forges et al., 2020), and UV-B has future potential application for control of plant diseases but is also important in plant responses such as flowering initiation and photosynthesis (Meyer et al., 2021). Indeed, UV transmitting films are demonstrated to reduce powdery mildew in strawberry (Onofre et al., 2022), hence any benefits from pest reduction (Fountain et al., 2020 and this study) need to be balanced with losses in production caused by plant pathogens.

Finally, our films were tested in 12 m flight cages with 1 × 1 mm insect exclusion mesh on strawberry. To fully test these films, they should be trialled on commercial farms on a range of crops in different geographical regions and incorporated as part of an integrated pest and disease management strategy.

AUTHOR CONTRIBUTIONS

Michelle T. Fountain conceptualized the study. Alvaro Delgado and Sebastian Hemer tested increasing UV-attenuating in protective field claddings. Greg Deakin advised on experimental design and statistics and Frederick Davis supplied the data on film transmission (Figure 1). Michelle T. Fountain and Sebastian Hemer prepared the manuscript.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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