AGRICULTURE & HORTICULTURE DEVELOPMENT BOARD

SCEPTREPLUS

Final Review Report

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Target	Spotted wing drosophila, *Drosophila suzukii* (SWD)
Lead researcher:	Dr Bethan Shaw
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I the undersigned, hereby declare that the work was performed according to the procedures herein described and that this report is an accurate and faithful record of the results obtained

30/03/2021	B. Shaw
Date	Authors signature

Review Summary

Introduction

Drosophila suzukii, spotted wing *Drosophila* (SWD), is one of the most problematic pests that soft- and stone-fruit growers face globally. There are several cultural control options that help reduce SWD populations however growers depend on a handful of chemical control products to reduce fruit infestation. In this review, we have focused on control options which can be applied or deployed in crops to reduced yield loss due to SWD. These products may cause direct mortality on SWD life stages or act as deterrents to egg laying females. We have included a brief overview of best practice cultural control, which should be incorporated into SWD IPM programs, but the primary focus is on chemical and biological control interventions. The aim of this review is to identify conventional and novel chemistry and other control strategies which may be used to target SWD in the UK. Many of the strategies come from overseas research or current practice or may be currently used to target other pests.

Summary

Cultural control

- Crop hygiene is key in reducing SWD re-infestation in crops. This includes removing unmarketable waste and dropped fruit.
- Waste fruit should be sterilised (e.g. anaerobically treated) and disposed of correctly (e.g. buried) to prevent re-inoculation.
- Crop canopy can be thinned to increase light penetration and reduce humidity, therefore making it less favorable for SWD. In addition, this will also increase spray penetration.
- Insect proof netting (mesh), although initially costly, can prevent SWD entering the crop. It can be used for several seasons if correctly cared for.
- Monitoring traps should be used to detect the adult flies around crops and larval extraction should be used to check the fruit for infestation through the ripening process.

Biological control

- Entomopathogenic fungi (EPFs) have been found to reduce populations over time and have both direct and residual activity against SWD. There are several commercial products approved for use in the UK which are unlikely to disrupt IPM for other pests.

- Longer term assessments may be needed to appropriately assess efficacy of biological control options as they reduce populations over longer periods compared to fast knock-down.
- *Entomophthora muscae* could be a promising new fungal product if production issues can be overcome.
- Commercial formulations of *Steinernema* and *Heterorhabditis* sp. entomopathogenic nematodes are effective in laboratory studies against some juvenile stages of SWD.
- An entomopathogenic nematode *Oscheius onirici* is a promising 'new' species identified in the USA with a significant impact on SWD as it can reduce survival of larvae within fruit.
- Bacteria *Chromobaterium subtsuage* (Grandevo) can reduce larval survival when incorporated with a feeding stimulant and this is effective when used in a spray rotation. However, it has not been effective as a standalone product to date.
- *Bacillus thuringiensis* sp. and *Photorhabdus luminescens* bacteria have variable impacts on SWD larvae when incorporated into diet media with, typically, the youngest larvae having higher mortality.
- *B. thuringiensis* sp., *C. subtsuage* and *P. luminescens* bacteria have not been tested with commercial adjuvants against SWD, which would form a valuable investigation for use in the field.
- Promising repellents identified within a BBSRC CTP studentship project will be investigated in field crops within the AHDB TF/SF145a project.
- Baits, in combination with approved plant protection products, will be evaluated in the field in cherry in 2021, however this will only include spinosad and cyantraniliprole, which are known to be effective.
- Through a confidential IUK project, some strains of *Metarhizium* have also been shown to be effective for SWD control and could be pursued as part of further SCEPTRE plus trials for comparisons with the EPFs mentioned above.

Chemical control

- Rigel-G (silicon) has been found to reduce numbers of SWD larvae in fruit in dipping trials and would be worth further investigation of efficacy in the field.
- Several products are approved for use in the UK in fruit crops which have not been tested against SWD.

- Several highly effective products are used for SWD control in the USA including Zeta-cypermethrin, phosmet and spinetoram.
- A new active ingredient, GS-omega/kappa HXTXHv1a peptide from spider venom, has been found to have excellent efficacy and falls under a new IRAC group (32).
- *Urtica* showed variable results in laboratory trials as a dipping solution against SWD in blueberry and blackberry fruit. *Urtica* would benefit from further evaluation against SWD to confirm its efficacy.
- Phagostimulant baits, Combi-protec or molasses, could help improve the efficacy of approved products found to have minimal or low impact, such as abamectin.

Next Steps

Several control options have been highlighted within the review that could be investigated for their ability to control SWD in fruit. From the review it is clear there is a great variation in the efficacy of products tested in the laboratory and subsequent field trials. For this reason, we would suggest a semi-field trial that would demonstrate real crop growing systems and environmental factors. Table 1 contains a summary of suggested active ingredients that could be tested in the field for their ability to reduce SWD egg laying in fruit. Products and active ingredients that are known to be toxic to SWD that are currently used only overseas are not included in this review, as their efficacy has been proven (i.e Malathion). For these products it is the approval status in the UK that prevent their use in the UK.

Table 1: Summary list of suggested active ingredients or products to test for control of SWD

Type	Active ingredient	Comments
Entomopathogenic fungi	*Beauveria bassiana*	Naturalis-L (oil formulation) found to be effective in the laboratory against SWD. Would benefit from field trial testing on fruit crops as a direct spray*
Entomopathogenic fungi	*Beauveria bassiana*	Bp-Protect (wettable powder) found to be effective in the laboratory against SWD. Would benefit from field trial testing on fruit crops as a drench to growing substrate*
Entomopathogenic fungi	*Metarhizium* strains	Commercial strains under development
Bacteria	*Chromobaterium subtsuage*	Grandevo found to be effective against SWD when combined with a phagostimulant but not efficient as a ‘standalone’ product*
Bacteria	*Bacillus thuringiensis*	Found to be effective against larvae when incorporated into media. Minimal bioassays against adults. Would benefit evaluation in combination with a phagostimulant.
Bioinsecticide	Silicon	Evidence from manufacturer that it protects fruit from oviposition
Urtica	Plant extract	Previous SCEPTRE plus studies gave inconclusive results related to reduced egg laying/ egg development.
Insecticide	Fatty acids C7-C20	Untested against SWD but approved/EAMU in the UK on some fruit
Insecticide	Flonicamid	Untested against SWD but approved/EAMU in the UK on some fruit
Insecticide	Indoxacarb	Untested against SWD but approved/EAMU in the UK on some fruit
Insecticide	Acetamiprid	Short efficacy in previous toxicity trials. Would benefit evaluation in combination with a phagostimulant.

* Suggest testing these products in combination in the same plots. They have all been shown to have some level of efficacy in the laboratory but need to be part of a long-term strategy causing population reduction over time rather than quick knockdown.

Take home message(s)

- Control of SWD should focus on cultural control practices initially.
- There are several biological control options that have an impact on SWD populations, but they would benefit from further investigation in the field. It may be that a program or combinations of these products would have greater impact on SWD control. Longer term assessments may be needed as they seem to show a reduction in populations over time rather than a fast knock-down.
- There are several approved products for UK soft and stone fruit that have not been tested against SWD.
- The efficacy of some of the biological and chemical control options could be improved by combining them with approved adjuvants.
- Many effective products are used to control SWD in the USA but are not approved for use in the UK.

Review

Introduction

Spotted Wing Drosophila, *Drosophila suzukii* (Matsumura) (SWD) has been at the forefront of horticultural research for the past decade as its global invasion continues to progress. At the time of writing the Ladakh region of India, located in the North-western Himalayan Mountains, was the most recently invaded area and is classed as "the second coldest inhabited place in the world" (Hussain et al., 2020). Originally from South-East Asia, the migration of this pest is believed to have been aided by international trade of contaminated fruit (see Cini et al. (2014) for further details of the European invasion). One of the reasons this pest has received so much research attention is due to the extremely diverse host range which spans cultivated soft- and stone-fruit (Lee et al., 2011, Bellamy et al., 2013) to wild hosts (Briem et al., 2016, Castro-Sosa et al., 2017, Knipp, 2018, Bal et al., 2017). Control options have been a large part of this research due to the difficulty of controlling the pests as part of Integrated Pest Management programs. Due to the volume of research, this review primarily focuses on sprayable control options and only briefly on cultural and physical methods.

Target Description and Life-cycle

Spotted Wing Drosophila are on average 2.5 mm in body length (Kanzawa, 1935). They have red eyes, and their antennae are tipped with spindly hairs called arista, characteristic of *Drosophila* species. During the summer, the overall body colour is yellow to light brown, but turns dark brown in the winter months when the flies develop during colder temperatures. The segments of the abdomen ('tergites') alternate from light to dark giving the appearance of banding. For SWD this banding is continuous and does not show any pattern, typical of other closely related *Drosophila* species.

Female SWD are slightly larger than the males overall. They have a serrated ovipositor which can cut into the skin of ripening soft- and stone- fruits to lay eggs (Figure 1). Males have a single wing spot on each forewing, giving rise to the common name (Figure 2). Males can also be distinguished by two sets of sex combs on the front leg. These consist of 5-6 thick black hairs in the first comb and 3-4 in the second.

Female SWD use their ovipositor to cut into the skin of ripening fruit and deposit the egg just beneath the surface of the fruit. Breathing filaments can sometimes be seen protruding from the small entry point which enable respiration to occur. Once the egg hatches the larva progresses through three instars which feed on the fruit flesh. The 3rd instar, also known as wandering larvae, move near or on the surface of the fruit to identify a suitable pupation site before entering the pupal phase. Wandering larvae have also been found to fall to the ground for pupation to occur within the growing substrate. Features of the adult fly can be seen through the pupal case as it develops, starting with the red eyes. Figure 3 shows the juvenile life stages of SWD. Egg laying to adult eclosion (the fly emerging from the pupal case) can occur as quickly as within 10 days at 28°C (Tochen et al., 2014). Based on average UK temperature data, it can be estimated that between 9-13 generations occur a year. Mating can occur within 3 days of eclosion and adults live up to 30 days in mild conditions. When pupation occurs at temperatures below 10°C the emerging adult fly is darker and larger than the summer morph and have been recorded to live over 100 days (Dalton et al., 2011). These winter morph flies enter a reproductive diapause while temperatures are low, but in the spring, with warming temperatures, become reproductively active and deposit eggs of the first generation of the year (Shearer et al., 2016, Stockton et al., 2018).

Due to the life cycle, SWD adults are the primary life stage at which control options are conventionally aimed, as the juvenile stages are either protected within the fruit or in the growing substrate.

Figure 1. Female SWD. Left- Female with egg protruding from ovipositor. Right- Detail of female ovipositor. Images Bethan Shaw

Figure 2. Male SWD. Left- Characteristic wing spot on each wing. Right- The two sex combs on the first leg, from male caught on a yellow sticky trap. Images Bethan Shaw

Figure 3. Juvenile life stages of SWD. From left to right: egg, 1st instar larva, 2nd instar larva, 3rd instar larva (also known as a wandering larva), fresh pupa with no distinguishable adult fly features, developing pupa with red eyes visible through skin of case, mature pupa with red eyes and body features visible through the pupal case. Image credit: Nicolas Gompel. Image use is licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License.

Symptoms and Identification

Without monitoring, growers would typically be unaware of the presence of SWD until harvest, when damage caused by female oviposition and subsequent larval feeding is observed. The action of the larvae feeding on the fruit from within results in the collapse of the fruit structure and growers may notice fruit juice dripping from the crop. The entry point made by the female can expose the fruit to pathogens and other pests which would generally be unable to pierce the fruit skin. An increase in numbers of *Drosophila melanogaster* Meigen, and sour rot bacteria contamination of wine grapes has been associated with the incursion of SWD to vineyards in many areas of Europe (Ioriatti et al., 2018). For this reason, SWD may not necessarily be identified as the cause of yield loss, which may be attributed to molds and rots.

Contamination of fruit by SWD can be identified by taking regular flotation samples to detect the larvae in the crop. To do this, ripe and ripening fruit are submerged in a sugar/water solution (180 g/L) forcing the larvae to exit the fruit when they can then be seen in the solution (Shaw et al., 2019). Samples should be taken from white fruit stages in soft- and stone-fruit, prior to colour development, which is when the fruit is vulnerable to oviposition.

Monitoring with traps can give early warning of pest presence in a crop by attracting adult SWD to a drowning solution or a dry or liquid attractant (Frewin et al., 2017) and traps should be in place prior to flowering. More information about trapping and identification can be found on the AHDB website (https://ahdb.org.uk/knowledge-library/spotted-wing-drosophila-swd).

Cultural and Physical Control

As the focus of this review is sprayable/deployable protection products, only the most efficacious cultural and physical control methods will be mentioned in the section below. Please see the references included for further reading. In addition, the methods discussed in the section below complement sprayable protection products as part of an IPM strategy.

Hygiene and waste disposal

Hygiene practices are known to be highly effective at preventing or suppressing SWD populations in crops. Leach et al. (2017) demonstrated that picking fruit every 1-2 days, removing all waste and unmarketable fruit at each pick, significantly reduced SWD damage in marketable fruit. This method is successful as it removes possible sources of re-inoculation, which would otherwise be left in the crop. Frequent picking also reduced reliance on insecticide applications. Removing dropped fruit from the floor within the crop is also encouraged as this could be harboring juvenile SWD.

The treatment of waste fruit is also essential as, if untreated, it can also result in the re-inoculation of SWD. To prevent this re-inoculation, waste fruit should be anaerobically treated to kill any eggs and larvae that may be within the fruit. This can be performed on a large scale by the transferal of waste into sealed pallet bins, which results in the build-up of CO_2 killing the eggs and larvae (Noble et al., 2017) (Also see AHDB communication https://ahdb.org.uk/knowledge-library/containing-the-spread-of-spotted-wing-drosophila-swd). On a smaller scale, waste can be transferred to black bags, tied closed and left in a sunny location for several days when the heat in the bags kills any SWD within the fruit (Haye et al., 2016). The latter method is more appropriate in summer while the former method can be used at milder temperatures of below 14°C.

Once treated, the waste fruit needs to be disposed of. This can be done by burial, incorporation into soil or spent growing media, bio digestion (for bio digestion the fruit waste must be combined with a high dry matter content) or even through use as animal feed (Noble et al., 2017).

Canopy management

SWD thrive in high humidity and growers should ensure humidity is reduced in the crop. Low humidity encourages desiccation of SWD adults and juveniles (Fanning et al., 2019). Pruning of crop canopies can reduce humidity and increase light penetration into the crop, both of which were found to reduce SWD oviposition (Evans et al., 2017, Schöneberg et al., 2020). Humidity can also be altered by the management of ground cover in the crop with regular mowing of vegetation (Santoiemma et al., 2020) or the use of ground covers/Mypex (Rendon et al., 2020), both of which disrupt pupation behaviour. Pruning the crop canopy can also improve spray coverage of the fruit, which is vital to gain control of SWD (Lewis and Hamby, 2020, Mermer et al., 2020). Having a sparser canopy can also increase visibility for pickers removing waste and marketable fruit. Increased visibility reduces the chance fruit will be missed, which would provide feeding and oviposition resources for SWD.

Netting

Exclusion netting (mesh) is an effective control strategy when deployed at the correct time. Deploying netting too late may trap SWD within the crop, but when used correctly netting can delay onset of SWD in the crop (Leach et al., 2016). This needs to be balanced with allowing ingress of pollinators and other beneficial insects for the control of other pests. To ensure the crop is protected, netting should be erected as soon as possible, without interfering with pollination. In systems provisioned with managed pollinators (honeybees or bumblebees), the crop can be netted in the spring. Netting is an initial expense (Del Fava et al., 2017, Ebbenga et al., 2019), but this system can be used for several years if maintained correctly. Correct maintenance includes ensuring the nets are free from holes, careful deployment and removal at the beginning and end of each season, ensuring it is securely attached to structures to prevent tearing, and ensuring doors are closed after operations such as spraying and fruit picking.

Trapping/monitoring

Monitoring traps can be used to indicate the presence of the pest in an area and can consist of homemade or commercial products. Generally they include a liquid attractant but they can also consist of a dry lure and a drowning solution (Tonina et al., 2018). The design of the trap has some effect on trap catch and sensitivity but overall, those with a greater entry area catch greater numbers of SWD, but are less selective (Iglesias et al., 2014, Renkema et al., 2014, Whitener and Beers, 2014).

At high densities, monitoring traps can also be used as precision monitoring devices which are deployed around the perimeter of a crop, intercepting migrating SWD between fields (Spies and Liburd, 2019). These are typically deployed at 2 m intervals but this can vary between products and manufacturers' recommendations should be observed. A combination of trap catches, information on onset of egg laying, larval numbers through extraction tests, crop stage, environmental conditions and surrounding habitat should be used alongside experience to dictate the timing of plant protection product (PPP) applications.

The following sections focus on control products that can be applied or deployed in the cropping area to target SWD and which may act as preventative or curative treatments.

Biological control

Studies focused on biological options to control SWD are extensive due to increasing pressure for more sustainable crop management strategies. In addition, conventional insecticides are associated with negative impacts on natural enemies, secondary pest outbreaks, resistance development, prolonged pre-harvest intervals and increasing legislation restrictions (Wang et al., 2020).

For many of the biological control agents (BCA) discussed in the following section, products rely on living organisms to induce SWD mortality. The use of BCAs to control a target pest comes with its own issues in that parameters that impact the control organism itself must be considered for them to be effective. This includes factors such as optimum temperature and humidity and the method of application or exposure to the target pest. If conditions are not optimum or application not appropriate, it is likely that the BCA will be unsuccessful in its efficacy. This has led to a negative perception from growers who are expecting instantaneous impacts, as they do with most conventional insecticides (Moser et al., 2008). Many strategies in this section exploit naturally occurring organisms readily found in the environment that have been formulated into commercially available products. For entomopathogenic fungi (EPFs), nematodes and bacteria, products have been developed which can be mass produced and formulated to improve their longevity or persistence in the crop. They often have a narrow invertebrate host range resulting in no detrimental impacts on non-target vertebrates and can be used in conjunction with many other IPM practices (Kaya and Gaugler, 1993). Generally, the uptake of these organisms in horticulture has been minimal (Litwin et al., 2020), probably due to the lag between application and control. A review by Wang et al. (2020) thoroughly summarises recent research surrounding all aspects of biological control of SWD, along with the methods and outcomes described by each paper. From the reviewed literature it is clear that there is great variation in the efficacy of biological control options, even those of the same species. Below, we will highlight some of these variations, focusing on commercially available and approved formulations.

Entomopathogenic fungi

To date, 750 species of entomopathogenic fungi (EPF) have been documented worldwide, able to infest hosts from virtually all insect orders (Mantzoukas and Eliopoulos, 2020). One of the benefits of EPFs in pest control is their ability to persist in the environment, even when hosts are absent. They are also capable of providing season-long inoculum in the correct conditions, as the result of the synchronicity with a hosts life cycle (Shah and Pell, 2003). The limitations of EPFs are that they may take several days to cause death due to the delay between exposure, inoculation, sporulation and then infection of the target host. This time period varies between species, strains and fomulations but generally takes 7-14 days (Litwin et al., 2020). Due to the rapid life cycle of SWD and the number of eggs a single female can lay in one day (average 25 eggs per female per day at 25°C within the laboratory (Kinjo et al., 2014)), female SWD may be able to lay eggs prior to the EPFs causing mortality. However, EPFs could play a role in supressing SWD populations over time, as a season-long strategy, and have been found to reduce reproductive fitness with lower offspring survival from females treated with some strains (Cossentine et al., 2016).

There are a handful of commercially available (and currently approved for use in the UK) EPF products (Table 2) which have been tested in an array of bioassays against SWD. Naturalis – L® (Fargro), Botanigard® (Myotech Europe Ltd) and Bb-Protect (Andermatt Biocontrol AG) are formulations of living spores from the fungus *Beauveria bassiana* (Bals. -Criv.) Vuilleum that occur naturally in soil (Gargani et al., 2013). These three formulations are applied as a foliar spray or a drench. Met52® Granular (Fargro) is a formulation of *Metarhizium anisopliae* var. *anisopliae* which is applied by being incorporated into the growing substrate and has historically been applied to control vine weevil (*Otiorhynchus sulcatus* (F.)). EPF spores germinate once they encounter the insect's cuticle and are dormant until this time. The germination of the spores breaks through the insect's cuticle and produces toxins in the blood stream, resulting in mortality. In most cases, the spores on the insect cadaver act as inoculum for the next host.

Table 2. Details of commercial EPFs approved for use in the UK (March 2021).

Species	Strain	Commercial formulations/ manufacture	Colony Forming Units (CFU)	Method of application	Dose/recommended rate	Crops approved	On label target sp.	Parameters/ optimum application
Beauveria bassiana	ATCC 74040	Naturalis-L Oil formulation. Intracem Bio Italia	2.3 x 10^{7} ml^{-1}	Fine spray	0.3 % v/v (3 litres in 1000 l water). Max. 5 treatments	Protected edibles	Adult & larval stages thrips, aphids & whitefly	Naturalis-L optimum range of 20-30°C and over 60% RH.
Beauveria bassiana	GHA	Botanigard. Wettable powder. Myotech Europe Ltd.	4.4 x 10^{10} CFU/g MPCA Min.3.7 x 10^{10} Max. 5.2 x 10^{10}	Fine spray	0.63 – 0.94 kg/Ha. dependent on crops Max. concentration g/100L. Max. water volume L/Ha 1000-1500. Max. 5 treatments	Protected edibles, ornamentals & fruit trees	Whitefly	Evening application as spores are inactivated by sunlight, avoid other fungicides and temperatures of below -0^{o}C and above 30^{o}C.
Beauveria Bassiana	R444	Bb-Protect Wettable powder. Andermatt Biocontrol	>2 x 109 CFU/g	Full spray or drench every 3-14 days	300-900 g/Ha (1 g/litre water for full cover or drench into soil	Wide range	Whitefly, spider mite and other agricultural pests and mites	High humidity, low UV, avoid other fungicides 3 days before and after application
Metarhizium anisopliae var. *ansiopliae*	F52	Met52 Granular. Novozymes Biologicals FR	Min. 9 x 10^{11} CFU/kg	Incorporate into soil or growing media	Met52 granular is incorporated into soil or growing media at a rate of 0.5 kg/m3. 122 kg/Ha open ground usage	Ornamentals & berry fruit	Black vine weevil larvae in un/protected soft fruit and ornamentals	Optimum temperature 15 – 30^{o}C and not excessively wet conditions. Control of larvae is likely to be greatest in peat-based growing media.

Cahenzli et al. (2018) tested the effects Bb-Protec and Naturalis-L on adult mortality of SWD using three different application methods, direct, indirect and exposure to treated fruits. With the direct application method, flies were sprayed with the recommended label rate of several 'microorganisms' and mortality was assessed after 72 hours. For indirect residue activity, flies were exposed to the recommended field rates for 72 hours once the solutions were dry on the surface of a glass vial. Finally, mortality as a result of the residual activity of treated fruit was assessed. Direct and indirect exposure to *B. bassiana* in the Naturalis-L formulation resulted in significantly higher mortality than the control, however this was not seen with the Bb-Protec treatments. In addition, and a promising outcome, Naturalis-L performed as well as the positive control, Spinosad (Audienz (Omya), 44.2% Spinosad) from both direct and indirect exposure. In contrast there was no significant difference in mortality between the control and Naturalis-L when female SWD were exposed to dried residues on the surface of treated fruit. However, it is suggested by the authors that the oils released from the surface of glass vials may have caused suffocation, resulting in higher mortality in the direct and indirect exposure bioassays (Cahenzli et al., 2018). It would be interesting to see if this response is seen using Naturalis-L in a more ventilated arena, in which mortality would not be caused by suffocation.

Cossentine et al. (2016) exposed male and female SWD to Met52 spores on the surface of a velvet cloth in laboratory-based bioassays. Flies were exposed to spores for 48 hours before the treatment was removed from the arena. Mortality diverged from the control after 6 days with 36% mortality at the higher doses (1 x 10^9 CFU), rising to 87% after 8 days and 100% after 14 days. In a following trial where fecundity was assessed, the development of the next generation of pupae was significantly impacted in comparison to an untreated control. Males and females were exposed to the EPF for 48 hours before being transferred to a clean arena. Mortality of the treated adults and subsequent pupal development was assessed. Although significant differences in mortality were not observed until 7 days post exposure, there was a significant reduction in the development of pupae from 5 days post exposure. By the end of the assessment the cumulative total number of pupa that developed was 555 pupae from the EPF exposed cohort compared to 1643 pupae in the control treatment.

Gargani et al. (2013) conducted laboratory-based trials using Naturalis-L and Botanigard to test their performance as a preventative (residue) and a curative (direct) treatment against SWD. Curative treatment of SWD is generally difficult since eggs and larvae are well protected within the fruit. Curative trials were conducted by initially exposing blueberries to SWD for 72 hours for egg laying to take place. Inoculated fruits were then immersed in 100 ml of the *B.*

bassiana based solutions at the recommended label dose (Botanigard at 125 ml/100 L & Naturalis-L at 75 cc/100 L) for 30 seconds. Fruit was then incubated for 10 days as 25°C. The number of adults that emerged from the fruit were then counted. Preventative (residue) toxicity was assessed by dipping fruit into the same solutions, leaving them to dry and then offering them to SWD adults for 72 hours to lay eggs. After this time, the adults were removed and the number of eggs counted. For both Botanigard and Naturalis-L in both the contact and residue bioassays, there was a significant reduction in the number of offspring in comparison to an untreated control. As a curative treatment, Botanigard and Naturalis-L reduced the emergence of the following generation by 84% and 53% and as a preventative treatment by 80% and 76% respectively. However, in contrast, another study (Cahenzli et al., 2018), found that when used as a preventative control strategy, Naturalis-L did not reduce oviposition rates within a 24-hour period in comparison to a control. In addition, there was no impact on mortality of the egg laying females within 5.5 days. It may be that the duration of assessments was not long enough to detect an impact on SWD, as typically infection takes 7-14 days (Litwin et al., 2020).

Cossentine et al. (2016) found reduced reproductive fitness, with lower offspring survival, from females treated with *M. ansiopliae*. In addition, Ibouh et al. (2019) demonstrated an 80% reduction in oviposition following application of *M. ansiopliae* and Alnajjar et al. (2017) found high mortality rates when SWD were exposed to different strains of EPF (*B. bassiana, Isaria fumosorosea* Wize*, M. anisopliae var anisopliae* and *M. robertsii*) in laboratory studies. This effect did not transfer into field based experiments, in which a half life of 3.5 hours was identified for *B. bassiana.* It may be that short persistence or low spore pick-up in the field explains the ineffectivity of EPFs in crops. However, advances in formulation such as microencapsulation, should result in increased longevity. Alnajjar et al. (2017) suggested incorporating EPFs into irrigation systems to accelerate the effectiveness of pathogens in the soil and this would offer protection from harmful conditions such as UV radiation and extreme heat (Usman et al., 2020). This approach requires further investigation, as it is clear that not all EPFs can be used with a standard application protocol. As stated by Cahenzli et al. (2018), the large variation in efficacy between EPF products in different bioassays highlights the importance of using appropriate application methods based on the requirements of the individual product.

Entomophthora muscae (Cohn) is a parasitic fungus that infects and kills many insects including the common house fly (*Musca domestica*) (Becher et al., 2018). At the time of writing there were no patented products based on *E. muscae,* indicating there are no current commercialisation plans. Tests by Becher et al. (2018) have shown *E. muscae* to be highly infectious to SWD, reducing the survival rate by 27%, with most flies dying 4-8 days after exposure, and a significantly quicker kill than the formulated products discussed above. However, Dara et al. (2017) stated that entomophthoralean fungi (which rely on insects to survive) are difficult to culture in vitro, which is likely to be the reason no commercial products are available. It would be worth further investigation as Becher et al. (2018), found a mortality rate of 62.9% when SWD were exposed to dead house flies infected with *E. muscae*. It may be that for this particular fungus, a different application method is required i.e. distributing infected insect cadavers within the crop.

Entomopathogenic nematodes

Entomopathogenic nematodes (EPNs), like EPFs, occur naturally in the soil and are parasitic on a wide range of insects (Brivio and Mastore, 2020). Nematodes have a symbiotic relationship with bacteria from the genera *Xenorhabdus* and *Photorhabdus* which are found in the gut of the nematode (Hübner et al., 2017) and kill the target insect (Brivio and Mastore, 2020) (see bacteria section below). EPNs infect the target host by entering the insect through natural openings found along the abdomen or penetrating the cuticle and can be used against a variety of insects as a biological control. Infective juveniles are the free-living stage of the nematodes and occur in the soil, enabling them to be efficacious against insects that undergo part of their life cycle in the ground (Hübner et al., 2017). Nematode performance can be impacted by soil properties including soil moisture, texture, and composition. Koppenhöfer and Fuzy (2007) found that nematode infectivity was highest at moderate soil moistures (−10 to −100 kPa), but lower in wet (−1 kPa) and moderately dry (−1000 kPa) soils. While foliar application can be used, desiccation and UV radiation are known to reduce the efficacy of EPN’s (Beck et al., 2013). Although these negative impacts can be alleviated by the addition of surfactants and humectants (which help retain moisture) to the formulation to increase nematode survival (Beck et al., 2013), the use of foliar applications is still minimal in crop protection.

While the majority of the SWD life cycle occurs within fruit where the larvae are protected, pupation may occur in the soil which offers an opportunity for growing substrates to be treated with EPN drenches to target 3rd instar larvae and pupae. *Heterorhabditis* and *Steinernema* are the most widely used EPN species in soil treatments and have different 'hunting' techniques; *Steinnerma* species are usually static parasites waiting for the host whereas *Heterorhabditis* species actively approach a host (Brivio and Mastore, 2018).

Cuthbertson and Audsley (2016) investigated using nematode species *Steinernema feltiae, S. carpocapsae, S. kraussei* and *Heterorhabditis bacteriophora* in drench treatments (160 IJ (infective juveniles) /cm²) against SWD pupae in laboratory trials, with varying degrees of efficacy. Nematode solutions were applied to 3-day old pupae held within fine sterile sand (to remove other possible hosts) and the numbers of adults to emerge were assessed after 10 days. All four EPFs significantly reduced adult survival in comparison to the untreated control, with mortality ranging from 52% in the *S. kraussei* treatments, 83% for *S. feltiae* and *S. carpocapsae* and 95% mortality in the *H. bacteriophora* treatment. Brida et al. (2019) also found high mortality of SWD when solutions of isolates from *Heterorhabditis amazonensis* (100%), S. *carpocapsae* (96%) and *S. feltiae* (96%) were applied to pupae (166.66 IJs/cm²). However, in trials by Garriga et al. (2019) there was no reduction in adult survival when 6 day-old pupae were treated with *S. carpocapsae* (100 IJ/ cm²), although infection rates of young adults were high (89%). Peabody and White (2013) state that newly emerged *Drosophila* adults go through a critical period of expansion and hardening of the cuticle and wings, making them less mobile during this process, which may be when nematode infection is able to occur. It may be that although the infection rate of newly emerged adults is high, mortality assessments may not be undertaken over a long enough period to observe an impact of the infection on survival.

In trials focusing on infecting larvae, there have also been varying results. One study (Woltz et al., 2015) concluded that only 2% of larvae were infected when nematode solutions were pipetted onto the surface of fruit and that there was no impact on mortality in comparison to the control. This included *Steinernema* and *Heterorhabditis* species. Foye and Steffan (2020) explored the efficacy of *Oscheius onirici,* a rare species of nematode identified in Wisconsin USA, against juvenile SWD in laboratory trials. When directly applied to 2nd and 3rd instar SWD larvae (157 IJ/cm²), only 8.9% survived in the *O. onirici* treatment compared with 88.9% in the untreated control. In further bioassays, Foye and Steffan (2020) explored the efficacy of *O. onirici* on blueberries infested with *D. suzukii* larvae. Blueberries were exposed to adults for 72 hours for egg laying and egg hatch to occur, before 1 ml of treatment was applied per berry

(10,000 IJ per ml). Fourteen days post treatment the numbers of emerged adults were counted, and a 76% reduction was found from the nematode-treated fruit compared to the water control. *Oscheius onirici* appears to be effective against SWD due to its ability to actively 'hunt' the larvae within the fruit (Foye and Steffan, 2020). This was also demonstrated by Hübner et al. (2017) in bioassays where fruit containing SWD larvae was placed on sand treated with a solution of *S. carpocapsae* (to mimic dropped fruit in a commercial crop), an average of 39, 32 and 38% mortality occurred in 1st, 2nd, and 3rd instar larvae respectively.

Bacteria

Chromobaterium subtsuage is a violet pigment bacterium that was first isolated from under an eastern hemlock tree (*Tsuga canandensis*) in a region of central Maryland, USA (Martin et al., 2007a). *Chromobaterium subtsuage* is found to be toxic to Colorado potato beetle (*Leptinotarsa decemlineata* Say) resulting in 78% mortality in 2nd instar larvae when incorporated into an artificial diet of corn roots with 90% mortality after 7 days in 2nd instar Diamondback moth (*Plutella xylostella*) larvae when fed re-hydrated freeze-dry pellets (Martin et al., 2007b).

Grandevo® (Marrone Bio Innovations) is a formulated product containing *C. subtsuage* (strain PRAA4-1T) registered for use in the USA to target aphids, mites, psyllids, thrips, whitefly and SWD. Several research groups have investigated the efficacy of *C. subtsuage* on SWD, with varying levels of success in the laboratory and in the field. In January 2021 it was approved for use in New Zealand vineyards and glasshouses to control a range of pests. To date it is not approved for use in the UK or the EU.

Rhagoletis indifferens Curran, 1932 (western cherry fruit fly) is a pest in the North West of the United States, similar in behaviour to SWD, with females depositing eggs in fruit and the subsequent larval feeding resulting in yield loss. Yee (2020) conducted laboratory tests to assess the efficacy of Grandevo on mortality and oviposition of *R. indifferens*. In these bioassays, *C. subtsugae* was used as a stand alone insecticide or in combination with a bait, by adding it to sucrose yeast extract. Flies were exposed to the residues of both treatments and mortality and subsequent egg laying assessed. Yee (2020) found that *C. subtsuage* was toxic to *R. indifferens* when used alone but was not toxic when used in combination with bait, and it was ineffective in reducing oviposition.

Gullickson et al. (2019) tested Grandevo against SWD in conjunction with a feeding stimulant (erythritol) and with an organic adjuvant (Oroboost®, Oro Agri, Inc.) and compared efficacy to other insecticidal products by assessing direct mortality and impacts on the following generation. In the laboratory, *C. substugae* combined with the feeding stimulant resulted in higher mortality than the water control, but not when compared with spinosad and zeta-cypermethrin. There was no significant effect on mortality when it was used in combination with the adjuvant. In addition, *C. substage* did not reduce subsequent oviposition, numbers of larvae or pupa, or emergence of the following generation when combined with either the feeding stimulant or adjuvant. In contrast, in field trials, *C. substugae* was effective when used as part of a spray program in cherry (Wise et al., 2017), blueberry (Wise et al., 2014) and raspberry crops (Fanning et al., 2018a). In these trials SWD larval counts were reduced when *C. substugae* was used in rotation with conventional insecticides. It may be that as a standalone product it is ineffective, but that it enhances the efficacy of other products and could be used within a season-long spray program.

Photorhabdus luminescens is a gut bacterium of *Heterorhabditis spp*. nematodes that are highly toxic to numerous insect species (Duchaud et al., 2003). While the nematodes themselves contribute to inducing mortality in a host, *P. luminescens* is often solely responsible for death (Guo et al., 1999). Shawer et al. (2018) tested *P. luminescens* against third instar SWD larvae and pupae in several bioassays. In oral consumption bioassays larvae that were fed a diet containing *P. luminescens* had significantly higher mortality than the control 4 days post feeding. There was also fewer developed pupa after 10 days and 50% mortality in those that emerged as adults. In larval dipping bioassays there was no significant difference between the treatments and the untreated control in larval survival 4 days post dipping. However, there was 60% pupal mortality, 9 days post dipping with the *P. luminescens* treatment and 30% in the control. When pupae were dipped in treatment solutions, there was higher adult mortality compared to the control. In contrast to the juvenile stages, the bacterium had no effect on adult flies and increased survival compared to the control. Shawer et al. (2018) suggested this may be due to the growing bacteria providing a nutrient rich food source, resulting in increased survival.

Bacillus thuringiensis Berliner is a bacterium that synthesise several toxins with different modes of action on infected hosts (Babin et al., 2020). The different strains or variants are known to have specific target species and are exploited in organic farming to target pests

(Babin et al., 2020). *Bacillus thuringiensis* has insecticidal properties against Lepidoptera, Diptera, and Coleoptera and a range of commercial biopesticide products are available (Cossentine et al., 2016), with several currently approved for use in the UK. Insect death is caused when the bacterium is ingested, inducing a toxin that causes the rupturing of gut cells resulting in internal infection or starvation (Federici et al., 2006). Twenty-two variants of *B. thuringiensis* have been tested to assess their efficacy against SWD adults, larvae, pupae, and oviposition (Wang et al., 2020).

Cossentine et al. (2016) found that when *B. thuringiensis* toxins were incorporated into media, SWD 1st instar larval mortality was greater than 75% from *Bacillus thuringiensis* var. *thuringiensis*, *kurstaki*, *thompsoni*, *pakistani*, and *bolivia* variants. For *B. thuringiensis* var. *kurstaki*, 1st instar SWD larvae were the most susceptible juvenile stage, followed by the 2nd instar and 3rd instar (100%, ~95% and ~28% mortality, respectively), but once pupae had formed there was no significant impact on mortality. Babin et al. (2020) also reported that the youngest larvae were more susceptible to *B. thuringiensis* variants and that there was a male bias in emerging adults when development occurred on treated media. However, the studies by Babin et al. (2020) also evaluated the impact this treatment had on other *Drosophila* species and found similar reductions in emergence of *D. melanogaster, D. subobscura, D. immigrans, D. hydei* and *D. simulans,* which are commonly found in the environments *D. suzukii* inhabit. For *B. thuringiensis,* combining the bacteria with a known SWD phagostimulant would be the most promising approach for use in a commercial setting as the toxin needs to be ingested to have an effect (see attract and kill).

Viruses

While there have been investigations into viruses that could control SWD, there are no 'products' available commercially that could be considered for current use. Several naturally occurring viruses have been identified from wild populations of SWD in Europe (Medd et al., 2018, Carrau et al., 2018) and the UK (Medd et al., 2018), which could be considered for future development but are unlikely to be available in the medium-term. The benefit of exploiting naturally occurring viruses identified in wild SWD populations is that they are likely to be species specific and have minimal impacts on non-targets (Medd et al., 2018).

Essential oils/plant extracts and repellents

Essential oils and volatile organic compounds (VOCs) are successfully used as repellents for a variety of pest insects in relation to human, livestock and plant health (Renkema et al., 2016). They can also have insecticidal effects on pests, as well as disrupting insect development, suppressing population growth (Regnault-Roger et al., 2012). Many VOCs are regulated as flavorings in food products or as components in perfumes, which are seen as lower risk to the environment and receive less negativity from the general public than other synthetic compounds (Isman, 2006). Although there are many benefits associated with using VOCs in horticulture, the regulatory process is regarded as the main obstacle, preventing more products reaching approval for use in this capacity (Regnault-Roger et al., 2012).

Park et al. (2017) investigated plants from the Myrtaceae family (which include Eucalyptus and tea-tree species), for their insecticidal properties on SWD adults when applied directly to the fly. In laboratory based bioassays, droplets of Kanuka (white tea-tree, *Leptospermum ericoides* A.Rich.) and Manuka (New Zealand tea-tree, *Leptospermum scoparium* J.R.Forst. & G.Forst) VOCs at 2.5 µg/fly were applied to the abdomen of male and female SWD adults. This resulted in 97.9-100% and 100% mortality within 24 hours of males and females respectively.

While these results are promising in that the extracts kill SWD, VOCs need to be efficacious in protecting fruit, but not negatively impact the fruit (e.g. flavor) for human consumption. Bedini et al. (2020) found VOCs from mandarin and tea tree were effective at repelling SWD from fruit treated with the extracts. The organoleptic profiles (the factors that stimulate the sensory organs) of fruit treated with mandarin extract were not negatively impacted by the application of the extract. However, the organoleptic profiles of fruit treated with tea tree were, making the fruit unsuitable for consumption. The use of essential oils provides a positive alternative to conventional insecticides, however, investigations of their impacts on the target crop and subsequent human health is required. To overcome negative impacts on host plants caused by direct application, essential oils could be added to a carrier substance or a deployed as point sources, removing the need to apply directly to the fruit. Renkema et al. (2017) reduced the number of larvae in strawberry crops treated with biopolymer flakes impregnated with peppermint oil in comparison to a control but noted that only a few days of efficacy was provided.

In bioassays where SWD were exposed to residues of plant compounds, variable adult mortality has occurred due to their short persistence in the environment (Eben et al., 2020).

As stated by Eben et al. (2020), due to the high mobility of SWD, adult flies are more likely to come into contact with residues on treated fruit rather than direct contact. To induce mortality from residues it is expected that higher concentrations of VOCs would be needed to protect the crop from SWD. Although de Souza et al. (2020) found residues on artificial media resulted in a reduction in oviposition from female SWD, the short persistence of the VOC on the crop would require frequent applications to ensure fruit was protected.

Fumigation methods with essential oils have reduced the emergence of SWD adults from pupae in the soil (Gowton et al., 2020) and caused mortality in adults (Kim et al., 2016); however, it would be difficult to implement this method in the field as vast areas would need to be treated.

Although essential oils and VOCs induce mortality in adult SWD, the results from the published literature indicate they may be better employed as repellents. This would remove any concerns about their impacts on the crop and fruit marketability and subsequent consumer health. Several promising repellents have been identified in the NIAB EMR BBSRC CTP studentship project (C. Conroy) which will be tested in replicated field trials in commercial crops in summer 2021 in SF/TF 145a. In 2020, research by Conroy in semi-field trials identified two coded compounds which significantly reduced oviposition up to 8 m from repellent sachets deployed in a strawberry crop.

Attract and kill

Due to increasing restrictions with chemical Plant Protection Products (cPPP) and limited direct applications, several commercial companies are developing 'attract and kill' or 'lure and kill' strategies. They can take many forms and include the combination of a feeding stimulant (phagostimulant), a bait or attractant with a killing agent which could be an insecticide or trapping agent, like a glue. Several baits increase the efficacy of insecticides as it attracts the adults directly to feed on the spray product. However, in most cases the highest efficacy has been from baits combined with insecticides that are already known to have an impact on SWD (SF 145a). As an example, in research by Noble et al. (2019) the baits (combi-protec® (Dedetec) (an adjuvant), fermented strawberry juice and yeast *Hanseniaspora uvarum*) were combined with reduced doses of approved insecticides (spinosad, cyantraniliprole and lambda-cyhalothrin) and a significant reduction in SWD survival and oviposition were recorded. Likewise, research by Bianchi et al. (2020) used *H. uvarum* combined with spinosad on glasshouse grape and found an impact on mortality and oviposition, even when residues were 7 days old. The use of these baits has resulted in a lower dosage of insecticide needed and up to a 95% reduction in the amount of active ingredient applied to the crop over a season. Currently there are no commercially available attract and kill systems approved for use in the UK although several are in development. Although there are no approved attract and kill systems, the adjuvant Combi-protec® is approved for use with approved insecticides at 50% maximum label rate, up to and including first fruit set (depending on crop) (HSE websitehttps://secure.pesticides.gov.uk/adjuvants/ListEntry.aspx?id=34732). It would be beneficial to investigate the use of this adjuvant with conventional control options that have been found to have minimal or short duration efficacy when used alone (e.g. Acetamiprid). Further work in project SF/TF 145a has shown that insecticides combined with molasses also give equivalent control to Combi-protect, but molasses are not yet approved for this use. Within SF/TF 145a, the use of baits and approved cPPPs will be further investigated in cherry crops in 2021.

Chemical control

*Please note that the below information regarding approvals was correct at time of writing. Details regarding approval status were taken from the HSE website March 2021. Growers should consult their BASIS qualified agronomist for up-to-date information about SWD control options.

UK

In the UK, growers have relied on a handful, of primarily emergency authorisations, of effective products to control SWD in soft- and stone-fruits. PPPs can cause mortality to the flying adults through direct contact or as a residue. They can act as a deterrent, protecting fruit from female oviposition or driving flies from the crop. Unfortunately, many of these efficacious products are broad-spectrum and have been responsible for the disruption of IPM for other key pests (Haye et al., 2016). Spinosad (Tracer) provided up to 14 days protection against egg laying in cherry orchard field trials and direct mortality when applied to the adults (SF 145). At the time of writing, 2 applications of spinosad can be applied a year in the UK with a 3-day harvest interval (note: this varies between crops). However, wide spread insecticide resistance has been reported for SWD in Californian raspberry crops with tolerance levels up to 11 times higher than previously identified (Gress and Zalom, 2019) which is driving the need for alternative effective products. To date, no resistance has been detected in UK wild populations of SWD (SF/TF 145a) but there are concerns that tolerant populations will establish.

Cyantraniliprole (Verimark, Exirel) also provides up to 14 days protection against SWD oviposition in fruit (SF 145). Approval for cyantraniliprole expired for many crops in November 2020. It is not currently known whether an EAMU will be approved for use of cyantraniliprole in 2021.

Within project SF 145, lambda-cyhalothrin gave 14 days protection in field trials in cherry and strawberry crops, with a slightly reduced persistence in outdoor raspberry accredited to rainfall in unprotected crops. There are several EAMUs in place for lambda-cyhalothrin including strawberry (protected and outdoor), outdoor raspberry, outdoor cherry, outdoor blueberry and outdoor plum.

Acetamiprid and deltamethrin provided 4-7 days protection against egg laying (SF 145) and these products could be used in-between the more effective cPPPs within a spray program to mitigate resistance. Thiacloprid was found to significantly reduce SWD emergence when blueberries, pre-inoculated with eggs and larvae, were dipped into a solution (Cuthbertson et al., 2014). However, this product has been removed from use in the UK.

Pyrethrin has minimal efficacy (SF 145) and is incompatible with predatory mites (Fountain and Medd, 2015) released into the crops to control other pests. Pyrethrin is now no longer approved in most soft and stone fruits.

Table 3 shows the current (March 2021) status in 5 crops of products which are known to be effective for SWD, highlighting products that have not yet been tested.

Table 3. Current approvals in blackberry, blueberry, cherry, raspberry, and strawberry for use in the UK as of March 2021 taken from the HSE website. The outcome of efficacy trials against SWD is also indicated or in cases where it has not been tested this is stated. * indicates actives that are due to be withdrawn within the next 12 months. Those in bold have not yet been tested against SWD.

Active	Blackberry	Blueberry	Cherry	Raspberry	Strawberry	Efficacy against SWD
Abamectin	EAMU (P, PPFE)	365 EAMU (P, PPFE)	365 EAMU (P, PPFE)	EAMU (P, PPFE)	Standard authorisation (PPFE)	Minimal
Acetamiprid	365 EAMU (O&P)	365 EAMU (O&P)	Standard authorisation (O&P)	365 EAMU (O&P)	365 EAMU (O&P)	Moderate
Bacillus thuringiensis Kurstaki SA-11						Moderate
Bacillus Thuringiensis var. Kurstaki	EAMU (O&P)	EAMU (O&P)	EAMU (O&P)	Standard authorisation (O&P)	Standard authorisation (O&P)	Moderate
Beauveria bassiana GHA	EAMU (O&P)	EAMU (O&P)	EAMU (O&P)	EAMU (O&P)	EAMU (O) Standad authorisation (PPFE)	Moderate
Bifenazate					Standard authorisation (P)	Unknown
Chlorantraniliprole		EAMU* (O)				Minimal
Cyantraniliprole	**	**	**	**	**	Excellent
Deltamethrin	EAMU (O)			Standard authorisation (O&P)	EAMU (O&P)	Excellent
Fatty acids C7-C20	EAMU (O&P)	EAMU (O&P)	EAMU (O&P)	EAMU (O&P)	EAMU (O&P)	Unknown
Flonicamid			Standard authorisation (O&P)			Unknown
Indoxacarb	EAMU (O&P)	EAMU (O&P)	EAMU (O) 365 EAMU (P)	EAMU (O&P)	EAMU (O) 365 EAMU (P)	Unknown
Lambda-cyhalothrin	EAMU (O)	EAMU (O)	EAMU (O)	EAMU (O)	EAMU (O&P)	Excellent
Lecanicillium muscarium	EAMU (P)	EAMU (P)	365 EAMU (P)	EAMU (P)	Standard authorisation (P)	Minimal
Metarhizium anisopliae	Standard authorisation (O&P)	Standard authorisation (O&P)	EAMU (O&P)	Standard authorisation (O&P	Standard authorisation (O&P	Moderate
Pyrethrins	EAMU (O)	EAMU* (O)		EAMU (O)		Minimal
Spinosad	EAMU (O&P)	EAMU (O&P)		EAMU (O&P)	EAMU (O) Standard authorisation (P)	Excellent
Spirodiclofen	365 EAMU	365 EAMU	EAMU (O) 365 EAMU (P)	365 EAMU	EAMU (O&P)	Unknown
Spirotetramat		EAMU (O)	Standard authorisation (O)		Standard authorisation (O&P)	Minimal

Sulphur						Minimal/ Moderate

Key

Standard authorisation: Full label approval
EAMU: Extension of authorization minor use
365 EAMU: An EAMU permitting application with a 365 harvest interval (in propagation)
O: Outdoor
P: Protected
PPFE: Permanent protection full enclosure
**Denotes annual applications for emergency authorisation

Current Overseas Practices

Table 4 summarizes research to date from around the world on chemical control options together with their efficacy, primarily against SWD adults (modified from Shawer (2020)). In brief, zeta-cypermethrin**,** diazinon, spinetoram, permethrin, and bifenthrin all resulted in 100% mortality 24 hours after being applied directly in laboratory-based experiments (Bruck et al., 2011). In subsequent field trials, exposure to 2-3 hour old residues resulted in a significant reduction in adult survival for the same products. Several other researchers have also reported high efficacy of these insecticides in both laboratory and field trials (Andika et al., 2020, Andreazza et al., 2018, Beers et al., 2011, Bruck et al., 2011, Rosensteel and Sial, 2017, Schlesener et al., 2017, Spies and Liburd, 2019, Van Timmeren and Isaacs, 2013). In addition, spinetoram, methomyl, spinosad, and phosmet were highly effective against the juvenile stages of SWD (Mermer et al., 2020). When cherry and blueberry fruits containing eggs-3rd instar larvae were sprayed with recommended field rates, there was a significant reduction in adult emergence. While effective against adults, zeta-cypermethrin, cyantraniliprole, fenpropathrin and acetamiprid also provided some efficacy against juvenile SWD within cherry and blueberry (Mermer et al., 2020).

Malathion reportedly gives good control of SWD and is widely used in the USA (see references in Shawer (2020)). However, there are indications of an increased level of tolerance (Van Timmeren et al., 2018) of this broad-spectrum PPP in wild populations and, although approved in some EU member states, it is unlikely to be approved for use in the UK.

A spider venom peptide tested in both laboratory and field trials showed promising results (Fanning et al., 2018b). The addition of adjuvants improved the efficacy of the peptide in bioassays evaluating contact action when applied directly to adults (98% mortality within 24 hours in combination with Silwet L-77) and as residues (68% mortality) within a laboratory. In field trials, the peptide significantly reduced numbers of larvae in fruit, in comparison to the control, when applied with and without adjuvants, at weekly intervals for 4 weeks. In this trial the number of larvae recovered from fruit treated with the peptide alone was not significantly different to the positive control, phosmet, displaying high efficacy in protecting fruit from damage. The Spear®-T Bioinsecticide (Vestron Corp.) is now commercially available in the USA and falls into IRAC group 32 (Nicotinic Acetylcholine Receptor (nAChR) Allosteric Modulators - Site II).

Table 4. Modified table taken from Shawer et al. (2020) summarising the efficacy of insecticides approved overseas.

IRAC Group	Active Ingredient	Efficacy
Spinosyns	Spinosad	Excellent
	Spinetoram	Excellent
Organophosphates	Malathion	Excellent
	Diazinon	Excellent
	Dimethoate	Excellent
	Phosmet	Excellent
	Fenitrothion	Excellent
	Methidathion	Excellent
Pyrethroids	Bifenthrin	Excellent
	Beta-cyfluthrin	Excellent
	Permethrin	Excellent
	Zeta-cypermethrin	Excellent
	Lambda-cyhalothrin	Excellent
	Deltamethrin	Excellent
	Fenpropathrin	Excellent
Diamides	Cyantraniliprole	Excellent
Neonicotinoids	Thiamethoxam	Moderate
	Thiacloprid	Moderate
	Acetamiprid	Moderate
	Imidacloprid	Moderate
1H- Pyrolle	Chlorfenapyr	Moderate
Spirocyclic tetronic/tetramic acid	Spirotetramat	Minimal
Carbamates	Methomyl	Highly effective against juvenile stages within fruit
IRAC Group 32	GS-omega/kappa HXTXHv1a peptide (Spider venom)	Excellent
Avermectins	Abamectin	Minimal

Related Research from Other Industries in the UK and Overseas

Basic substance' is a term that encompasses a range of by-products and plant extracts that can be used as a plant protection product but is used for other purposes as well (Marchand, 2015). An example of this is 'beer' registered as a basic substance and used as a molluscicide (AHDB https://ahdb.org.uk/knowledge-library/basic-substances). Basic substances are recognized under EU plant protection products regulation and require less stringent evidence to reach approval, such as approval being granted without maximum residue limits (Marchand, 2015). Due to the issues with approvals for 'new' PPP, pursuing basic substances as control options for SWD may alleviate some of the regulatory issues associated with new control options. In the following text, 'other substances' that could fall into one of several categories, including basic substances, plant strengtheners and plant extracts are discussed in the context of SWD control. In some cases, they may be currently used to target other pests or there may be preliminary data on SWD efficacy.

Within the research on biological control options by Gargani et al. (2013), berry dipping trials were undertaken with 'Deffort', an organic fertilizer based on micronutrients including (8%) manganese and zinc with *Sophora flavescens* extracts. These micronutrients are required for many processes and are beneficial to plants during recovery following biotic and abiotic stresses (Waraich et al., 2011). There was a significant reduction in larval emergence from fruit containing SWD eggs and larvae that had been dipped in a Deffort solution, indicating direct toxicity. Unfortunately, the product had no effect as a residue in deterring egg laying females and so appears to have limited persistence once applied.

Sabadilla alkaloids extracted from sabadilla plants (genus *Schoenocaulon*) were originally used to target thrips in the USA on mango and citrus and has recently been given on label approval for use against SWD. It is not approved for use in the UK, nor in any EU member state, and its status on the University of Hertfordshire, BPDB: Bio-Pesticides DataBase, lists it as 'Obsolete'. This is unfortunate as it has shown good promise, resulting in high mortality of adults and subsequent progeny in laboratory trials (Sial et al., 2019) and reducing larval infestations in the field (Fanning et al., 2018a).

Azadirachtin from the Indian Neem tree, *Azadirachta indica* received a great deal of attention post 2000 due to promising investigations on its impact on pests (Mordue and Blackwell, 1993). Its anti-feeding properties were first scientifically recorded on locust (*Schistocerca gregaria* (Forskal)) in 1952 (Butterworth and Morgan, 1971) and it was found to be highly deterrent to Lepidoptera (Nisbet, 2000). Although it has a possible application to control other pests, it has been found to have minimal impact on SWD mortality and offspring survival in several investigations (Sial et al., 2019, Andreazza et al., 2017, Cahenzli et al., 2018). In trials where some efficacy resulted, this was attributed to fumigation due to its oil formulation rather than active toxicity of azadirachtin itself (Erland et al., 2015).

Silicon accumulation in plants is known to aid in combatting biotic and abiotic stresses. Silicon has been found to reduce spider mite (*Tetranychus urticae* Koch) populations in strawberry when plants were fed weekly via irrigation lines (Liu et al., 2020). For this pest, it is likely that an increase in cuticle thickness of the host plants resulted in the subsequent reduction in spider mite population. Regarding SWD, there is preliminary evidence to indicate that silicon provides some protection of fruit against SWD oviposition. Fruit dipped in Rigel-G (a formulated 4% silicon product marketed as an organic feed, Orion) and then offered to SWD for 48 hours showed a 48 and 53% reduction in the numbers of larvae and pupa in comparison to a control (https://www.orionft.com/products/rigel-g). In addition, there have been indications that this product also acts as an oviposition deterrent for SWD; however, this data set is not yet publicly available. In addition, a study on blueberry crops in Oregon, US, by Lee et al. (2015) found that fruit sprayed with Mainstay (calcium silicate 10% calcium, 22% silicon dioxide, Redox Chemicals) had 52% less oviposition than untreated fruit. In following fruit characteristic measurements, they found that fruit treated with calcium silicate was 10% firmer and a 10% greater penetration force required to break the fruit skin than untreated fruit, which could have resulted in lower oviposition as females prefer softer oviposition substrates (Burrack et al., 2013).

Urtica extract (‘stinging nettle’) has been found to be toxic to *Aphis fabae* Scopoli (Black Bean aphid) (Benoufella-Kitous et al., 2014) and to reduced fecundity of *Myzus persicae* (Sulzer) (peach-potato aphid) (Gaspari et al., 2007) in laboratory bioassays. In SP 11 laboratory trials, there was a 53% reduction emergence of progeny when blueberry fruits containing eggs and young larvae were dipped in an *Urtica* solution. However, this reduction was not seen in blackberry fruits using the same protocol. In addition, in a second test there was no significant reduction in emergence when *Urtica* was applied to both fruits prior to exposure to SWD, indicating no efficacy as a residue. This effect was attributed to the higher density of flies applied to the fruit within the second test, which is likely to have resulted in the lack of efficacy. Also, within SP 11, there was no impact of bicarbonate of soda (sodium hydrogen carbonate) treatments post- or pre-inoculation with SWD. In the laboratory in SP 11 and in the field in SF 145, lime (calcium hydroxide) provided no protection against oviposition. Lime-sulphur exhibited minimal efficacy against adults but did have a deterrent effect on oviposition in both no-choice and choice bioassays (Andreazza et al., 2018). The authors of this research point out that lime-sulphur persistence in the environment is short since it degrades quickly and therefore frequent applications would be needed for this treatment to be effective.

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