



ORIGINAL RESEARCH ARTICLE

Efficacy evaluation of particle films as oviposition deterrent against *Drosophila suzukii* in Austrian vineyards

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ABSTRACT

Drosophila suzukii Matsumura (Diptera: Drosophilidae) is a polyphagous invasive vinegar fly. Females can penetrate certain soft-skinned grapevine varieties with their strong serrated ovipositor to lay their eggs within berries, which eventually leads to the decay and collapse of grapes. Alternative pest control options were tested in practically oriented field trials set up in two vineyards in Styria. The effect of the mineral particle films diatomaceous earth, kaolin and muscovite mica was compared to an untreated control. All products were complemented with wetting agents to increase the efficacy and/or the rain resistance of the film. Due to the long waiting times after application in organic production, only some of the trials also comprised a comparable insecticide variant (Spinosad). Treatments were applied from the beginning of infestations until harvest, and berries were sampled once to twice a week, depending on pest pressure. Evaluation of treatment effects was based on a microscopic analysis of berries for oviposition and a visual evaluation of the clusters. Both kaolin and diatomaceous earth led to a statistically significant reduction in oviposition and to a significantly improved macroscopic appearance of clusters compared to the control, whereas the effect of muscovite mica was negligible. A direct comparison of particle film and spinosad treatment was only expedient in one experiment, and in this case, the effect of kaolin on oviposition was significantly superior. Kaolin and diatomaceous earth might complement established integrated pest management practices against *Drosophila suzukii* and contribute to the reduction of chemical plant protection agents in the future.

KEYWORDS: Spotted wing drosophila, field trial, diatomaceous earth, kaolin, Muscovite mica

INTRODUCTION

Drosophila suzukii Matsumura (Diptera: Drosophilidae) is a polyphagous pest of soft-skinned fruits such as strawberries, raspberries, elderberries, cherries and grapes. A dark pigmented spot on the lateral end of their males' wings becomes visible shortly after eclosion, hence the name "spotted wing drosophila" (SWD). Pest pressure is highly dependent on climatic conditions during the vegetation period, with SWD and its developmental stages thriving in moderate temperatures. Studies have shown high oviposition rates between 18 °C and 30 °C and high egg-to-adult development rates between 19 °C–25 °C, whereas temperatures above 30 °C increase the mortality of adult flies and decrease egg development (Kinjo *et al.*, 2014; Eben *et al.*, 2018; Winkler *et al.*, 2020). The female adult fly can pierce healthy host fruits with its serrated ovipositor to deposit its eggs under the skin and lay up to 380 eggs throughout its lifetime (Walsh *et al.*, 2011). Under optimal environmental conditions, 10–15 generations per year are possible underlining the reproductive potential of the species.

Larvae feed on fruit flesh beneath the skin entailing sap leakage and even collapse of the fruit. Studies on grapes (Ferrari *et al.*, 2017; Ioriatti *et al.*, 2018) showed an increased concentration of acetic acid bacteria in sound and incised berries exposed to SWD, which indicates that this vinegar fly is capable of vectoring microbial communities. Volatiles produced by acetic acid bacteria promote additional decay by attracting further SWD and other Drosophilids. Moreover, damage to the berries and sap leakage lead to the colonisation of grapes by other phytopathogens, such as *Botrytis cinerea*. Overall, SWD contributes to grape spoilage and sour rot and seriously compromises wine quality. SWD does not infest all grapevine cultivars equally, the susceptibility of grapes to oviposition greatly depends on fruit colour, pH, skin firmness and sugar levels (Atallah *et al.*, 2014; Ioriatti *et al.*, 2015; Lee *et al.*, 2011). Vulnerable cultivars in Austria are for example 'Rotburger (Zweigelt)', 'Blauer Portugieser' and 'St. Laurent' (Riedle-Bauer *et al.* 2020).

Options for a preventative control of SWD include cultural practices reducing humidity, and an interruption of fly development by removing infested or rotten fruits. Possible biocontrol strategies comprise the use of larval or pupal parasitoids (Wang *et al.*, 2020) and entomopathogenic nematodes (Matheis *et al.*, 2023). Chemical control options are limited. At the beginning of 2024, only spinosad (SpinTor) was registered in Austrian vineyards against SWD (Pflanzenschutzmittel Database, 2024). Austrian legislation limits spinosad to two applications per vegetation period and it is mandatory to stop spraying grapes two weeks prior to their harvest. The regulations of BIO AUSTRIA, the largest Austrian organic association prescribe a doubling of this waiting period (BIO AUSTRIA, 2024).

Fruits become more susceptible to SWD as they ripen (Lee *et al.*, 2016) and in studies in Austria most ovipositions on

grapes happened a few days before harvest (Riedle-Bauer *et al.*, 2020). At this point in time, registered insecticides can no longer be applied. The small number of active substances registered against SWD in Austria increases the risk of resistance development, as has already been observed for spinosad and SWD in California (Gress and Zalom, 2019). In addition, insecticides negatively affect beneficial insects and bees and can have a generally negative impact on biodiversity. Overall, the control of SWD in grapes by insecticides has several shortcomings and limitations and alternative control options are urgently needed.

Particle films have been successfully applied for decades to control insect pests in various agricultural crops. Sprayed in a suspension in water they form a mineral particle film on the plant surface. These films act as physical barriers to infestation, impede insect movement and alter the visual, olfactory and tactile characteristics of the fruits, which can thereby disrupt insects to find their host plant (Glenn and Puterka, 2004). They are nontoxic to humans and animals (Fields and Korunic, 2000). A frequently used compound is kaolin, containing kaolinite, a white, hydrous aluminosilicate. Originally it has been used as a grain protectant (Golob, 1997) and to protect grapes and apples from solar damage (Glenn *et al.*, 2002; Lobos *et al.*, 2015). Kaolin has also been used to control SWD in vineyards, where it significantly reduced oviposition rates (Linder *et al.*, 2020; Dam *et al.*, 2022), and neither affected the fermentation nor the sensory attributes of the processed wines (Linder *et al.*, 2020). Another particle film used as an insect deterrent is diatomaceous earth, an amorphous silicon dioxide derived from fossilised algae (Round *et al.*, 1992; Korunic, 1998). The particles, which are mainly between 10 and 50 µm in size, have an abrasive effect and adsorb the cuticular waxes of insects (Ebeling, 1971; Korunic, 1998; Glenn and Puterka, 2004). Films based on diatomaceous earth have been successfully used to control SWD in elderberry (Krutzler *et al.*, 2022). Their application combined with an alcohol ethoxylate-based wetting agent significantly reduced oviposition and improved the macroscopical appearance of the umbels compared to an untreated control. In addition, this study has indicated that the choice of the wetting agent might have a direct impact on the efficacy of the treatment, on one side by its role for the stabilisation of the particle films and on the other side by its potential side effects on adult flies (Krutzler *et al.*, 2022). Due to its low price, another mineral, the product Mica G, is often used in Austria to combat sunburn damage. This product contains fine muscovite, consisting of hydrated phyllosilicate of aluminium and potassium with a median diameter of 12.5 µm (Aspanger Bergbau und Mineralwerke, 2020).

The current study aimed to determine the efficacy of different mineral particle films complemented by varying wetting agents on SWD infestation in grapes. In a four-year study, treatment effects were assessed weekly or twice weekly by microscopic analyses of the berries and by visual assessment of grape quality.

MATERIAL AND METHODS

Field trials were conducted in two vineyards situated in Schloßberg bei Leutschach (GPS: 46°38'50.3"N 15°26'53.0"E), planted in 2006, and Kaindorf an der Sulm (GPS: 46°47'58.1"N 15°31'02.7"E), planted in 1990, both in southern Styria, Austria in four consecutive years (2019–2022; Supplementary Figures A1–A6). The organically managed vineyard Schloßberg was included in all experiments throughout the experimental period. The vineyard in Kaindorf, cultivated according to the principles of integrated viticulture, was included from 2021 onwards. Rotburger (Zweigelt), an early ripening red variety, widespread in Austria, identified as susceptible to SWD (Riedle-Bauer *et al.*, 2020) was chosen as the test variety in the current experiments.

Both vineyards are maintained by the winery Silberberg of the Austrian Province of Styria (Steirisches Landesweingut Silberberg). The study aimed to test the effect of the particle films under the most practical conditions possible. In consequence, the applications were carried out using standard application devices. A randomised block design was waived and the trial was designed as a strip trial involving two repetitions per treatment, vineyard and year. Each plot included four adjacent rows and measured approximately 0.2 ha. Sampling was restricted to the centre of the inner rows of each plot to minimise border effects (Supplementary Figures A1–A6).

In total, eight different treatments were studied, consisting of five treatments combining particle films with wetting agents, two different spinosad treatments and an untreated control (Table 1). The treatments consisted of the following:

- SilicoSec-Wetcit (Sil):** Combines SilicoSec (diatomaceous earth, Biohelp, Vienna, Austria) at a concentration of 25 kg/ha combined with Wetcit (orange oil/alcohol ethoxylate, Biohelp, Vienna, Austria) at a concentration of 0.4 % (v/v).
- SilicoSec-Helioterpen-Vitisan (Silvit):** Includes SilicoSec at a concentration of 25 kg/ha combined with Helioterpen Film (terpene oligomere, Biohelp, Vienna, Austria) at a concentration of 1 % (v/v) and Vitisan (potassium bicarbonate, Biohelp, Vienna, Austria) at a concentration of 4 % (v/v).
- Surround-Wetcit (Sur):** Comprises Surround (kaolinit, Kwizda, Vienna, Austria) at a concentration of 24 kg/ha and Wetcit at a concentration of 0.4 % (v/v).
- Surround-Designer-Nu Film (Surdes):** Includes Surround at a concentration of 24 kg/ha, Designer (latex/trisiloxane, Kwizda, Vienna, Austria) at a concentration of 0.1 % (v/v) and Nu Film (pinolene, Kwizda, Vienna, Austria) at a concentration of 0.15 % (v/v).
- Mica G-Designer-Nu film (Micades):** Combines Mica G (muscovite mica, Aspanger Mineralwerke, Aspang, Austria) at concentration of 30 kg/ha, Designer at a concentration of 0.1 % (v/v) and Nu Film at a concentration of 0.15 % (v/v).
- SpinTor (Spin):** Consists of SpinTor (spinosad, Kwizda, Vienna, Austria) at a concentration of 0.16 l/ha.
- SilicoSec-Helioterpen-Vitisan + SpinTor (Spin+Silvit):** Combines SilicoSec-Helioterpen-Vitisan with concentrations of 25 kg/ha, 1 % (v/v) and 4 % (v/v) with a subsequent treatment of SpinTor with a concentration of 0.16 l/ha.
- Untreated control (Contr):** No treatment applied.

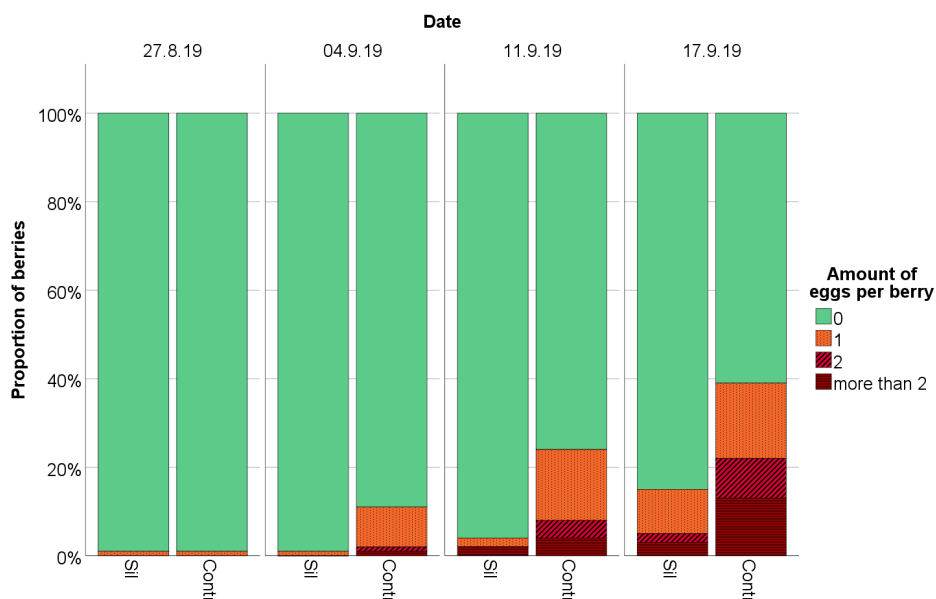


FIGURE 1. Effects of treatments on egg infestation of berries in Schloßberg 2019.

Sil: SilicoSec-Wetcit; Contr: untreated control.

TABLE 1. Overview of vineyard treatments.

Year	Vineyard	Start of treatments	First sampling	Harvest	Treatments
2019	Schloßberg	August 27	August 27	September 18	Sil, Contr
2020	Schloßberg	August 19	August 31	September 30	Sil, Silvit, Spin+Silvit, Contr
2021	Schloßberg	August 31	September 13	October 4	Sil, Sur, Contr
	Kaindorf	August 20	September 13	October 4	Sil, Surdes, Spin, Contr
2022	Schloßberg	August 29	August 29	September 23	Sil, Sur, Contr
	Kaindorf	August 30	September 5	September 23	Micades, Surdes, Spin, Contr

*Sil: SilicoSec-Wetcit; Silvit: SilicoSec-Helioterpen-Vitisan; Spin: SpinTor; Spin+Silvit: SpinTor + SilicoSec-Helioterpen-Vitisan; Sur: Surround-Wetcit; Surdes: Surround-Designer-Nu Film; Micades: Mica G-Designer-Nu film Contr: untreated control.

The mineral products were initially suspended in water and subsequently added to the tank with the agitator running. All treatments were applied at a total of 400 l/ha of spray liquid at an approximate speed of 5 km/h with the Zupan ZM300HKA sprayer (2016), utilising five Albus green nozzles, each with an output of 80 l/ha. Treatments commenced immediately following the identification of the first eggs in grape berries, with inspections of infestation occurring at 2–3 day intervals (Supplementary Table 1). The position of the plots on the vineyards are shown in Supplementary Figures A1–A6.

Assessment

For the assessment of treatment effects, 20 grape clusters were randomly collected from every plot once to twice a week. Two to three berries per cluster, a total of 50 berries, were randomly taken and analysed for oviposition. As each treatment was repeated twice, this resulted in a total of 100 berries per treatment and sampling date. The number of eggs present was determined by counting the respiratory filaments located on the surface of each berry with the aid of a stereomicroscope. At harvest, the efficacy of the treatments was expressed in accordance to Abbott's formula (Abbott, 1925):

$$\text{efficacy}(\%) = \left(1 - \frac{\text{number of eggs in treatment}}{\text{number of eggs in untreated control}}\right) * 100$$

Moreover, the physical conditions of 20 sampled grape clusters per repetition were visually determined in the years 2020 and 2022. Based on the consultation with growers, clusters were classified either as “acceptable” if not more than 10 % of total berries were damaged or as “unacceptable” if more than 10 % of total berries were damaged. To accurately evaluate the damage as a result of SWD infestation, clusters were categorised into one of the four following subcategories:

1. Acceptable

- Berries are intact; the surface of the grape is dry
- Up to 10 % of the total berries are damaged due to larval activity; no or nearly no leaking of sap due to larval activity

2. Unacceptable

- 10 %–50 % of total berries are damaged; leakage of sap due to larval activity
- More than 50 % of the total berries are damaged; a large quantity of leaked sap due to larval activity

Production of must and determination of volatile acidity

At harvest in 2020 and 2021, 10 kg of grapes of each treatment were first destemmed (Fuhrmann, Steinebrunn) and berries were then pressed (Wine press Velo; Fuhrmann, Steinebrunn) to extract the must. The volatile acids found in the must underwent a steam distillation (Gibertini Super DEE) alongside tartaric acid to separate them, followed by titration using a sodium hydroxide solution in the presence of phenolphthalein to measure the concentrations of volatile acids (Jaulmes, 1991), which mainly consisted of acetic acid (Table 3).

Recording of weather data

Temperature and precipitation data were collected by two weather stations (Adcon A733, Firmware 3.3; Supplementary Figures B1 and B2). The stations are located in Kitzeck (GPS: 46°46'47.2"N 15°27'59.1"E), 4.4 km away from the Kaindorf trial location, and in Haidegg (46°38'54.8"N 15°30'17.0"E), 4.5 km away from the Schloßberg trial location. In July 2022, there was a technical malfunction at the Kitzeck weather station, resulting in unusually high precipitation levels and maximum temperatures.

Statistical analysis

Data evaluation and statistical analyses were conducted separately for each vineyard and trial year using the SPSS Statistics 26 software (IBM, Vienna, Austria). We computed generalised linear models (GLM) for the response variables i) number of eggs per berry and ii) visual classification of clusters in classes 1 and 2 as defined by the visual classification scheme. For the former, we treated every berry

as a biological replicate and utilised the ‘Poisson loglinear’ model type. For the latter, each grape cluster was considered a replicate and the calculation used the ‘binary logit’ model type. The models comprised the categorical explanatory variables i) ‘treatment’, ii) ‘position’ (two repetitions per treatment at distinct positions in the vineyard) and the continuous covariate iii) ‘days after start of treatment’ (Table 2). If significant, pairwise contrasts were calculated (least significant differences (LSD), $\alpha < 0.05$).

RESULTS

Field test in 2019

At the first sampling date on August 27, rates of infested berries were only 1 % in both treatments. (Figure 1). Starting on September 4, the rate of infested berries rose continuously and by the last sampling date on September 17, the proportion of infested berries reached 39 % in the untreated control and 15 % in SilicoSec-Wetcit plots.

TABLE 2. Summary of the generalised linear models explaining the treatment effects 2019–2022.

Year	Response variable	Explanatory variables/covariate	Wald χ^2	p	df	Pairwise comparison (LSD) of treatments (estimated marginal means)
2019	N° of eggs per berry Schloßberg	Treatment	50.2	0	1	
		Position	0.3	0.599	1	Sil(0.05) ^a Contr(0.18) ^b
		Days	107.2	0	1	
2020	N° of eggs per berry Schloßberg	Treatment	138.1	0	3	
		Position	2.2	0.136	1	Silvit(0.14) ^a Sil(0.15) ^a Spin+Silvit(0.15) ^a Contr(0.36) ^b
		Days	169.2	0	1	
2020	Visual classification of clusters Schloßberg	Treatment	71.0	0	3	
		Position	0.008	0.927	1	Sil(0.02) ^a Silvit(0.04) ^a Spin+Silvit(0.06) ^a Contr(0.3) ^b
		Days	0.1	0.719	1	
2021	N° of eggs per berry Kaindorf	Treatment	170.1	0	2	
		Position	2.5	0.111	1	Surdes(0.01) ^a Sil(0.02) ^a Contr(0.14) ^b
		Days	145.7	0	1	
2021	N° of eggs per berry Schloßberg	Treatment	97.0	0	2	
		Position	17.4	0	1	Sil(0.00) ^a Sur(0.03) ^b Contr(0.14) ^c
		Days	102.6	0	1	
2021	N° of eggs per berry Schloßberg	Treatment	40.9	0	2	
		Position	1.4	0.234	1	Sil(0.01) ^a Sur(0.02) ^b Contr(0.10) ^c
		Days	28.4	0	1	
2022	N° of eggs per berry Kaindorf	Treatment	30.9	0	3	
		Position	2.3	0.121	1	Surdes(0.04) ^a Spin(0.15) ^b Micades(0.18) ^{b,c} Contr(0.22) ^c
		Days	8.3	0.004	1	
2022	Visual classification of clusters Schloßberg	Treatment	6.3	0.042	2	
		Position	5.3	0.022	1	Sur(0.02) ^a Sil(0.03) ^{ab} Contr(0.07) ^b
		Days	13.9	0	1	
2022	Visual classification of clusters Kaindorf	Treatment	8.4	0.039	3	
		Position	3.4	0.065	1	Surdes(0.02) ^a Spin(0.11) ^b Micades(0.11) ^b Contr(0.12) ^b
		Days	6.8	0.009	1	

*Days: Days after start of treatment. Sil: SilicoSec-Wetcit; Silvit: SilicoSec-Helioterpen-Vitisan; Spin+silvit: SpinTor + SilicoSec-Helioterpen-Vitisan (consecutive treatment); Sur: Surround-Wetcit; Surdes: Surround-Designer-Nu Film; Contr: untreated control. Distinct superscript letters indicate statistical differences ($p < 0.05$).

The generalised linear model (including data from September 4 until September 17) calculated a significant effect of the factor ‘treatment’ and the covariate ‘days after start of treatment’ on the number of eggs per berry, whereas the factor ‘position’ had no effect (Table 2). The efficacy of the SilicoSec-Wetcit treatment with respect to egg numbers was 68 % at harvest.

Field test in 2020

On August 31, the infestation rate of berries in the control plots was 20 %, and up to 7 % in the SilicoSec-Wetcit, SilicoSec-Helioterpen-Vitisan and SpinTor+SilicoSec-Helioterpen-Vitisan plots (Figure 2A). On September 28, 50 % of the berries in the control plots, 19 % in the SilicoSec-Wetcit and the SilicoSec-Helioterpen-Vitisan plots and 16 % in the SpinTor+SilicoSec-Helioterpen-Vitisan plot were infested. The GLM analysis (including data from August 31 until September 28) showed a significant effect for both the factor ‘treatment’ and the covariate ‘days after start of treatment’, whereas the factor ‘position’ had no significant

effect on egg infestation in berries (Table 2). All treatments resulted in a significant reduction in the number of eggs per berry compared to the untreated control. The efficacies of the treatments with respect to egg numbers were 74 %, 72 % and 76 %, respectively.

Grape samples were visually assessed for damage on September 21. Treatments significantly affected the visual classification of the clusters, whereas ‘days after start of treatment’ and ‘position’ had no significant effect (Table 2). A percentage of 98 % of clusters was recorded in class 1 for SilicoSec-Wetcit, 96 % in SilicoSec-Helioterpen-Vitisan and 92 % in SpinTor+SilicoSec-Helioterpen-Vitisan (Figure 2B). Only grape samples from the untreated control plots reached a lower percentage of 71 % for class 1. All particle film treatments significantly improved the condition of the clusters as compared to the untreated control. On September 28, the concentration of volatile acids was 0.3 g/L and 0.4 g/L in musts from the two untreated control plots, below 0.2 g/L in one Spinosad plot and below the detection limit for the other plot (Table 3).

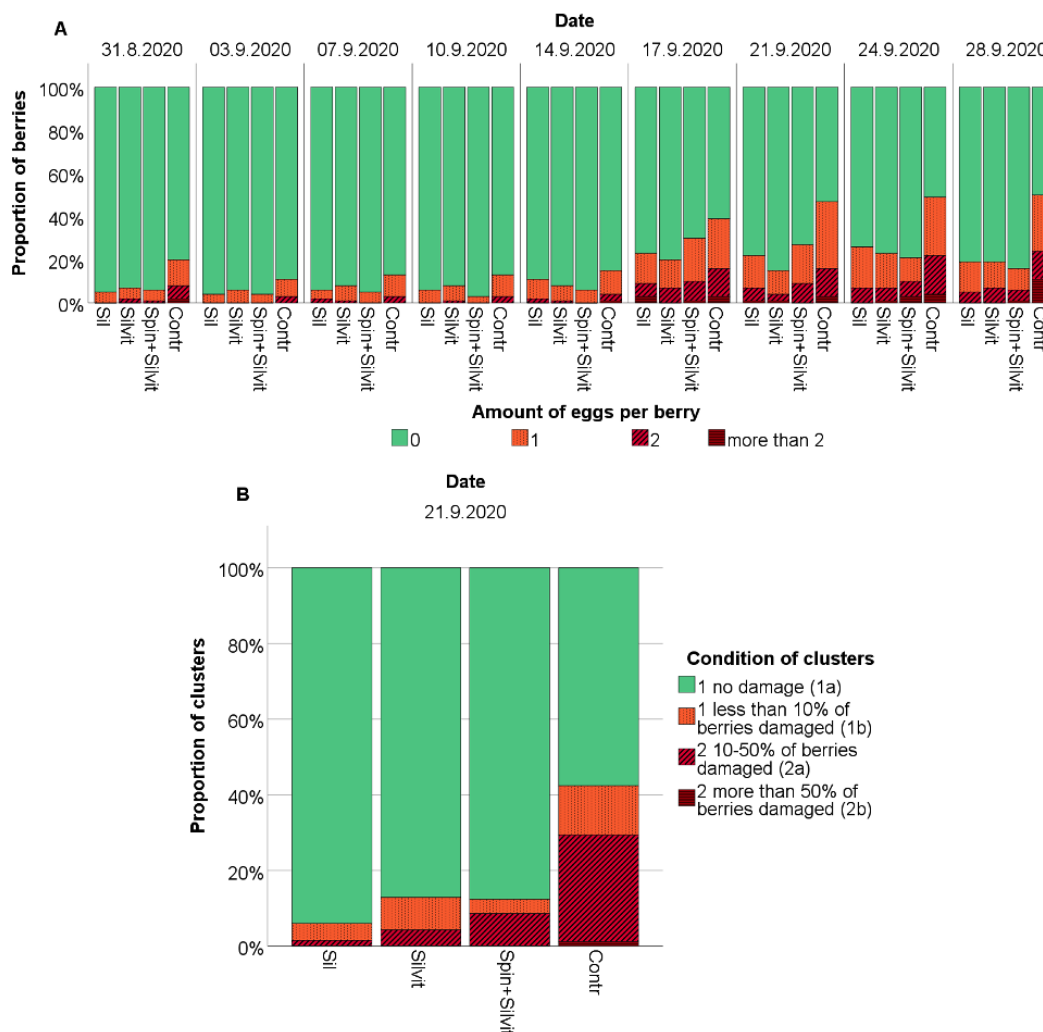


FIGURE 2. Effects of treatments on a) egg infestation of berries and b) grapes based on a classification scheme in Schloßberg 2020.

Sil: SilicoSec-Wetcit; Silvit: SilicoSec-Helioterpen-Vitisan; Spin+Silvit: SpinTor + SilicoSec-Helioterpen-Vitisan; Contr: untreated control.

TABLE 3. Volatile acidity of must produced from treated grapes.

Treatment	Location	Volatile acids [g/L]	
		September 28 2020	October 4 2021
Surround-Designer-Nu Film (1)	Kaindorf	-	0.3
Surround-Designer-Nu Film (2)	Kaindorf	-	0.3
untreated control (1)	Kaindorf	-	1.4
untreated control (2)	Kaindorf	-	0.2
SilicoSec-Wetcit (1)	Kaindorf	-	0.4
SilicoSec-Wetcit (2)	Kaindorf	-	0.2
Surround-Wetcit (1)	Schloßberg	-	0.2
Surround-Wetcit (2)	Schloßberg	-	0.2
untreated control (1)	Schloßberg	0.4	0.2
untreated control (2)	Schloßberg	0.3	0.3
SilicoSec-Wetcit (1)	Schloßberg	below detection limit	0.1
SilicoSec-Wetcit (2)	Schloßberg	below detection limit	0.1

*Numbers within parentheses depict the position of the treatment.

Field tests in 2021

In Schloßberg, oviposition was low at the first two sampling dates (September 13 and 20), with a maximum of 2 % infested berries in the untreated control (Figure 3A). On September 29, berries of the SilicoSec-Wetcit treatment were not infested, whereas on average 9 % of berries treated with Surround-Wetcit and 32 % of berries from the control plots eggs were recorded. On October 4, on average 51 % of the berries in the control plots were infested, whereas infestation rates in the Surround-Wetcit and SilicoSec-Wetcit treatments were 9 % and 3 %, respectively. The GLM analysis (including data from September 20 to October 4) calculated a statistical effect on egg numbers for the factors ‘treatment’, ‘position’ and the covariate ‘days after start of treatment’ (Table 2). According to pairwise comparisons, all treatments significantly reduced egg numbers in berries compared to the untreated control, SilicoSec-Wetcit was most effective followed by Surround-Wetcit. The efficacy for Surround-Wetcit and SilicoSec-Wetcit with respect to egg numbers reached 90 % and 97 % at harvest. On October 4, the concentration of volatile acids in musts produced from all variants ranged between 0.1 g/L and 0.3 g/L (Table 3). All clusters appeared visually intact, therefore the data were not analysed further.

In Kaindorf infestation rates increased steadily from the second sampling date on September 20 (Figure 3B). At the last sampling date on October 4, 71 % of the berries were infested in the untreated control plots, while SilicoSec-Wetcit and Surround-Designer-Nu Film had lower infestation

levels of 23 % and 7 %, respectively. The GLM analysis (including data from September 20 to October 4) calculated a statistical effect on oviposition for the factor ‘treatment’ and the covariate ‘days after start of treatment’, but not for the factor ‘position’ (Table 2). All treatments significantly reduced egg laying compared to the control. The calculated efficacy of treatments with respect to egg numbers was 84 % for SilicoSec-Wetcit and 95 % for the Surround-Designer-Nu Film. On October 4, the concentration of volatile acids in musts produced from all variants ranged from 0.2–0.4 g/L with the notable exception of one of the untreated control plots with an overall 1.4 g/L (Table 3). Macroscopic damage of clusters was not detected and in consequence, the data were not further analysed.

Field tests in 2022

In Schloßberg, at the beginning of the trial on August 29, a maximum infestation rate of 1 % was identified (Figure 4A). The infestation rate increased steadily, reaching an average of 19 % in the untreated control on September 19. In contrast, infestation rates average 2 % at this date both in SilicoSec-Wetcit and Surround-Wetcit plots. According to the GLM model (including data from August 29 onwards) the factors ‘treatment’ and ‘days after start of treatment’ significantly influenced the number of eggs per berry and the factor ‘position’ did not (Table 2). Pairwise comparisons showed a significant effect of both treatments compared to the control with SilicoSec-Wetcit being slightly more effective than Surround-Wetcit.

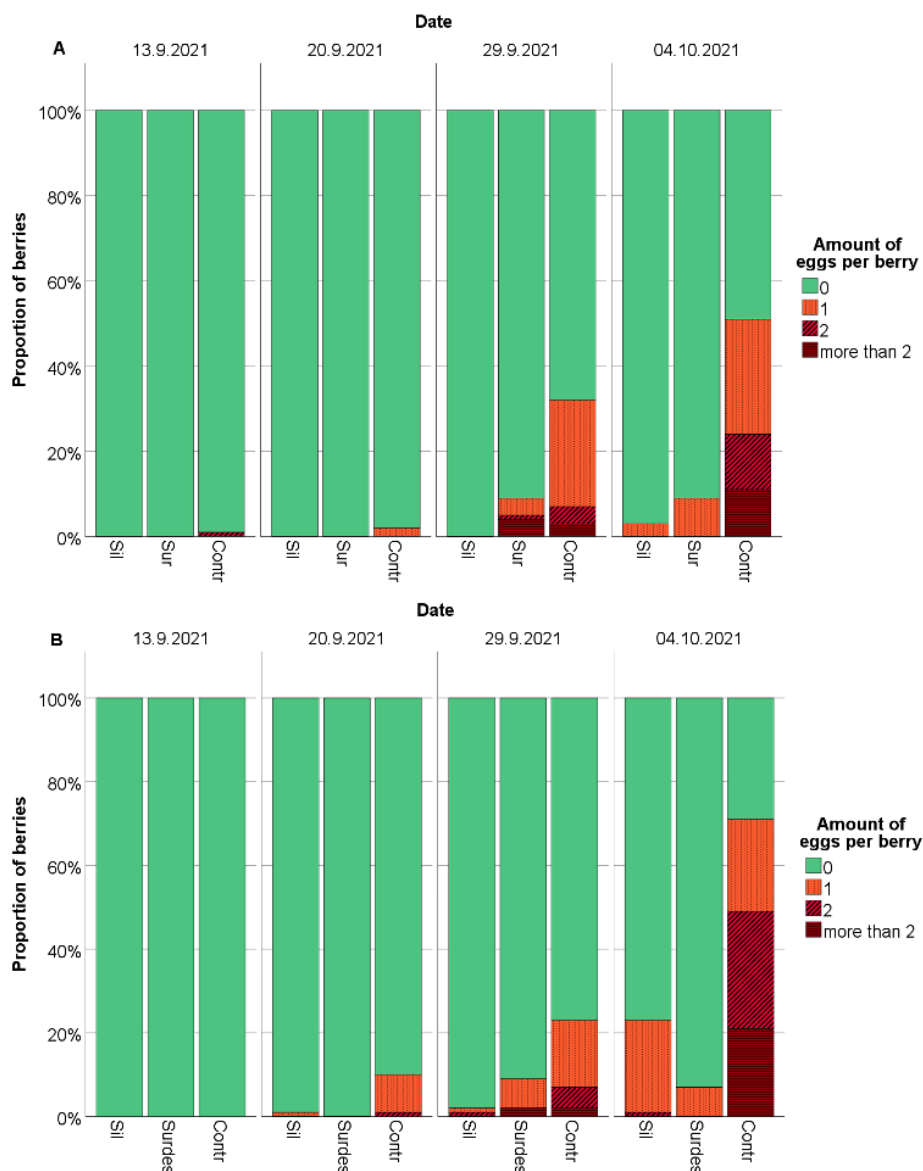


FIGURE 3. Effects of treatments on egg infestation of berries in a) Schloßberg and b) Kaindorf 2021.

Sil: SilicoSec-Wetcit; Sur: Surround-Wetcit; Surdes: Surround-Designer-Nu Film; Contr: untreated control. (Data for the treatment Spin (SpinTor) in Kaindorf is not included in the Figure as there was too much time between treatment on 20.8. and first oviposition on 13.9. to assume any treatment effect.)

The treatment efficacy at harvest with respect to egg numbers was 93 % for SilicoSec-Wetcit and 90 % for Surround-Wetcit. At the beginning of the trial in Schloßberg, clusters of all treatments were visually graded in class 1, whereas at the end of the trial, 90 % of berries treated with Surround-Wetcit, 88 % of berries treated with SilicoSec-Wetcit and 83 % of untreated berries were graded in class 1 (Figure 4B). Statistical analysis revealed a significant treatment effect on the classification of the clusters (Table 2), with clusters from Surround-Wetcit plots being rated significantly better than clusters from the untreated control.

In Kaindorf on September 5, on average 8 % of the berries in the untreated control were infested with eggs, while the infestation rates in the treatments Mica G-Designer-Nu Film, Surround-Designer-Nu Film and SpinTor ranged from 6 % to

13 % (Figure 5A). Shortly before harvest on September 19, the infestation rate in the control plots had reached 18 %, in the Surround-Designer-Nu Film treatment 5 % and in the SpinTor and Mica G-Designer-Nu Film plots up to 16 %. The GLM analysis (including data from September 5 until September 19) calculated a statistical effect for the factor ‘treatment’ and the covariate ‘days after start of treatment’ while the ‘position’ did not significantly affect egg numbers in berries (Table 2). Pairwise comparison revealed a significant effect of the Surround-Designer-Nu Film and SpinTor treatments compared to the untreated control plot with the former being significantly more effective than the latter. The treatment efficacy with respect to egg numbers was 73 % for Surround-Designer-Nu Film, and 18 % for SpinTor, while in Mica G-Designer-Nu Film the efficacy was 23 %.

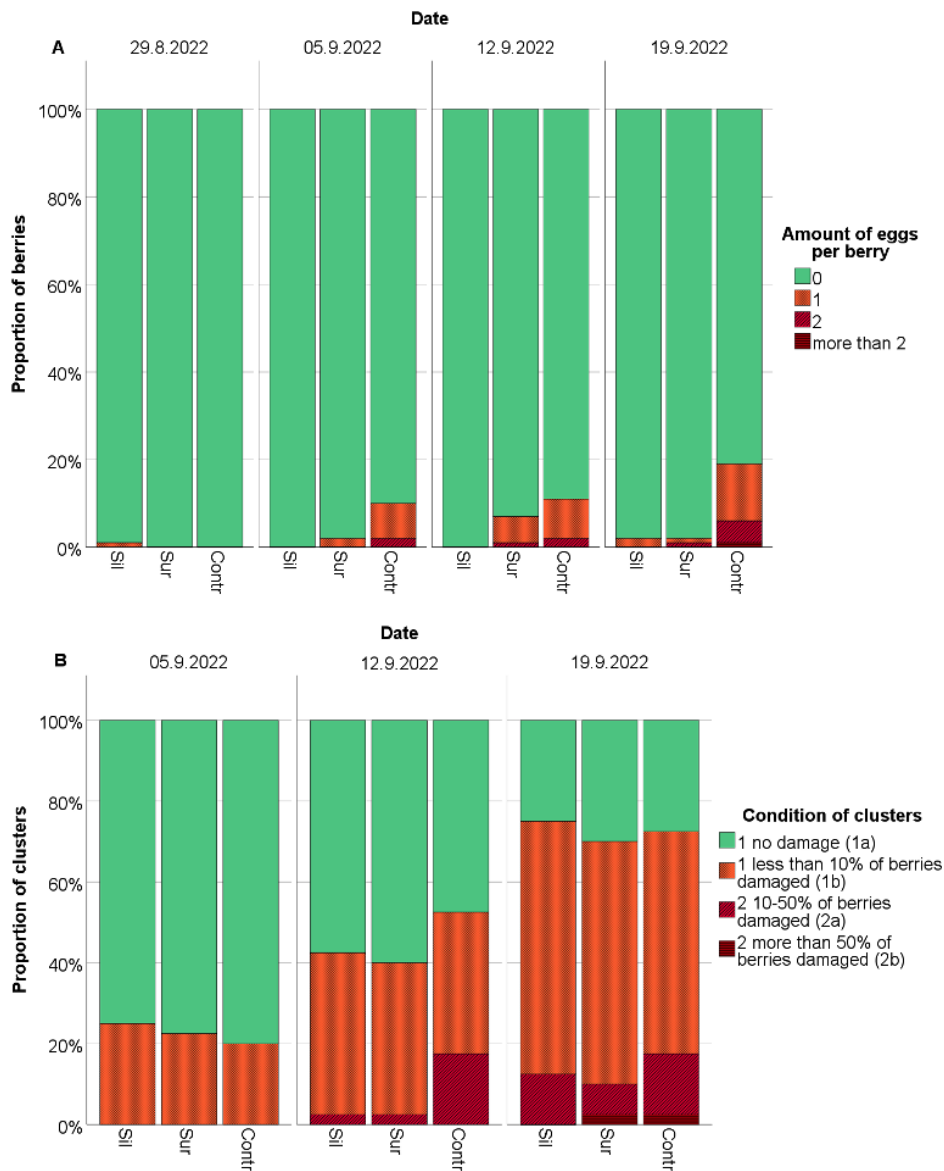


FIGURE 4. Effects of treatments a) on egg infestation of berries and b) on grapes based on a classification scheme in Schloßberg 2022.

Sil: SilicoSec-Wetcit; Sur: Surround-Wetcit; Contr: untreated control.

At the end of the experiment, a proportion of up to 93 % of the clusters in Surround-Designer-Nu film and Mica G-Designer-Nu Film plots were recorded in class 1, 83 % in SpinTor plots, and 88 % in the control plots (Figure 5B). Treatments as well as ‘days after start of treatment’ significantly affected the visual classification of clusters, while the factor ‘position’ did not (Table 2). Clusters treated with Surround-Designer-Nu Film were in significantly better condition than those treated with SpinTor, Mica G-Designer-Nu Film and the untreated control.

DISCUSSION

In the present study, the utilisation of particle films combined with a wetting agent has emerged as a promising strategy to protect grapes from SWD infestation.

In 2019, the treatment of SilicoSec-Wetcit almost completely suppressed oviposition from the end of August until mid-September. Yet, at harvest, the rate of infested eggs in the treated plots rose to 15 %, which still corresponded to an efficacy of 68 % compared to the untreated control. This overall promising outcome is in accordance with our experiments in elderberry (Krutzler *et al.* 2022). We showed that the effect of this treatment is not only based on the particle film but also on the side effect of Wetcit that suffocates flies by penetrating egg spiracles.

In 2020, we included a second diatomaceous earth-based treatment in our trial, namely SilicoSec-Vitsan-Helioterpen. Vitsan is a plant protection product officially registered for use in the control of fungal diseases such as *Botrytis cinerea* and powdery mildew (Pflanzenschutzmittel Database, 2024).

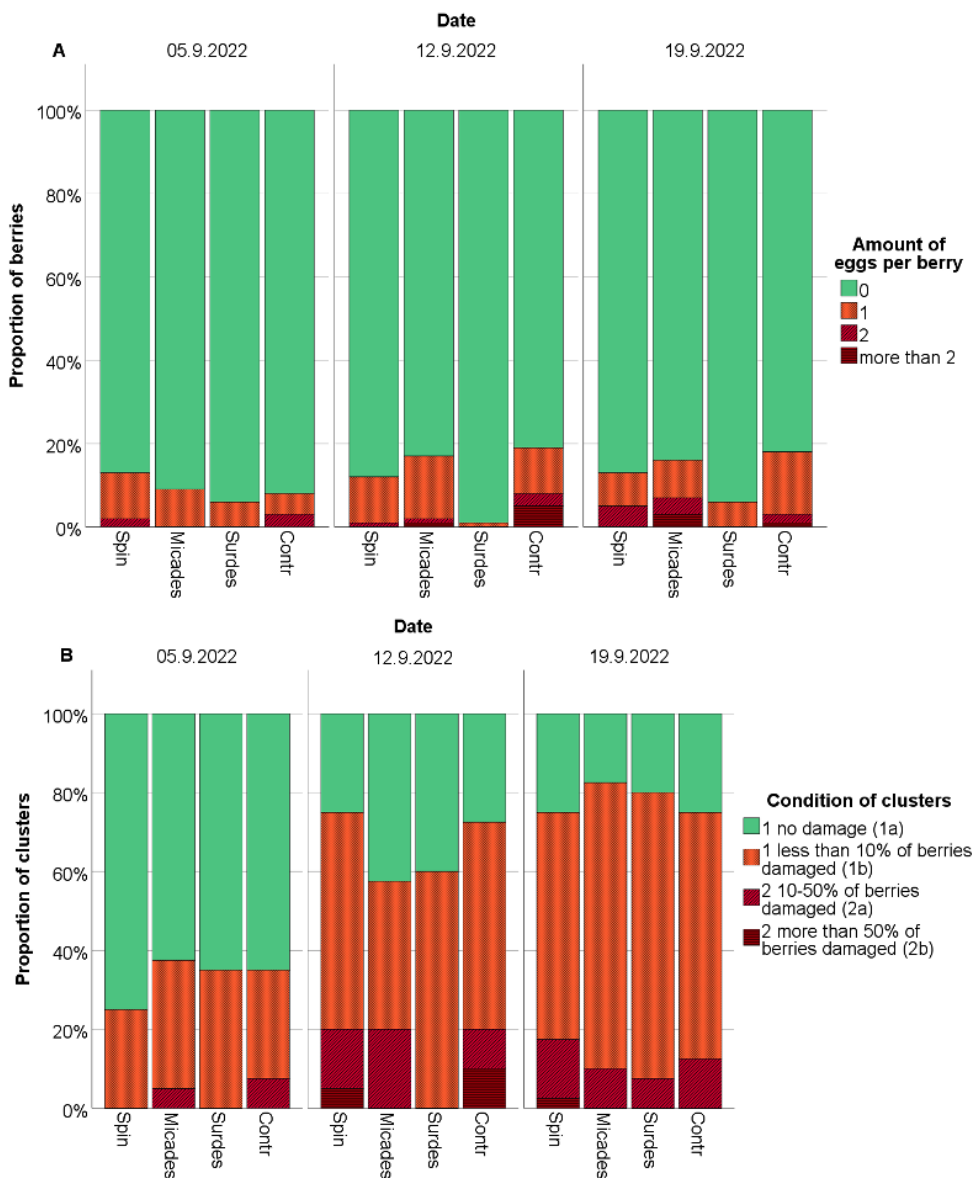


FIGURE 5. Effects of treatments a) on egg infestation of berries and b) on grapes based on a classification scheme in Kaindorf 2022.

Spin: SpinTor; Micades: Mica G-Designer-Nu Film; Surdes: Surround-Designer-Nu Film; Contr: untreated control.

It contains potassium bicarbonate and an insecticidal effect might be expected due to its high pH and a potential dehydrating effect. The product Helioterpen Film was added to the mix to stabilise the mineral film, i.e., to increase its rain resistance. However, in our trial, no difference in the number of eggs per berry and in consequence no prominent stabilising effect of the Helioterpen Film was observed compared to the use of SilicoSec-Wetcit only. Likewise, the one-time application of SpinTor in mid of August followed by SilicoSec-Helioterpen-Vitisan did not increase SilicoSec-Helioterpen-Vitisan efficacy against egg-laying nor improve grape quality. This observation, however, was not unexpected as it is well-studied that Spinosad treatments are only effective for a few days (Bruck *et al.*, 2011; Haviland and Beers, 2012). Overall, August and September 2020 were characterised by frequent rainfall, which led to a considerably

higher *D. suzukii* pressure and apparent earlier SWD infestations than in the other three years (e.g., 20 % of berries were infested at the end of August and 50 % at harvest in the untreated control). These unfavourable weather conditions made it necessary to reduce the treatment intervals compared to 2019 to ensure a consistent renewal of the mineral films after rainfall. Despite the challenging weather conditions, the particle film treatments reduced the number of eggs per berry at harvest by more than half and diminished the percentage of damaged clusters in category 2 from 29 % in the untreated control plots to 2–8 % in mineral-treated plots. Consistently, concentrations of volatile acids in the musts of treated berries were lower. Arguably, this prominent improvement in grape quality was due to the consistently lower number of eggs in the particle film-coated berries during the experimental period of one month.

Including the vineyard in Kaindorf in 2021, managed according to integrated viticulture, allowed us to test the wetting agent Designer, a non-organic product based on synthetic latex and siloxanes. According to the manufacturer, Designer not only reduces surface tension and ensures an even distribution of active ingredients but it also protects active ingredients from being washed off by rain. We combined a mineral particle film based on kaolin (i.e., Surround) with Designer and Nu Film, to further increase the rain resistance of the sprayed particle films. Initially, in this experiment infestation pressure was weak and oviposition rates remained low in all plots until mid-September. Therefore, to monitor potential treatment effects longer, the harvest of the experimental plots was delayed for two weeks. At the beginning of October, the calculated treatment efficacy was 84 % for SilicoSec-Wetcit and 95 % for Surround-Designer-Nu Film. This finding suggests a stabilising effect of Designer and Nu Film as two rain events occurred at the end of September, six days after the last treatment (Supplementary Figure B2). The one-time application of spinosad on August 20 had no reducing effect on oviposition, which was not surprising as more than two weeks passed between the treatment and the first detection of eggs in berries on September 13. Since a treatment effect could no longer be expected the insecticide variant was excluded from Figure 3 and the statistical data analysis. The results obtained in the vineyard in Schlossberg once again confirmed the high efficacy of particle film treatments SilicoSec-Wetcit and Surround-Wetcit even though 24 mm of rain were recorded between the last treatment and harvest (Supplementary Figure B1).

The summer of 2022 was hot and dry (Supplementary Figures B1 and B2). However, from the end of August until harvest it rained 1.3 to 3 times more than during the three previous years. Nonetheless, infestation pressure remained lower than in all the other experimental years with infestation rates of berries below 20 % at all sampling dates. Despite the frequent precipitations, the SilicoSec-Wetcit and Surround-Wetcit treatments in Schlossberg and kaolin combined with Designer and Nu Film in Kaindorf reduced egg laying satisfactorily. On the contrary, Mica G treatment in Kaindorf had no effect, the reason for this observation remains unknown. Arguably, the properties of the film depend on the size and geometry of the particles thereby potentially influencing the behaviour of SWD females and consequently oviposition. Spinosad was applied only once, on September 7 and a separate evaluation of the data obtained five days thereafter (on September 12) indicated a significantly lower effect on oviposition as compared to kaolin.

Overall, our results are in accordance with a previous study conducted in Swiss vineyards (Linder *et al.*, 2020). In this study, kaolin had an efficacy of 54 % in over 23 vineyards of different varieties in several areas, with values for individual vineyards varying between 0 and 100 %. In our trials, constant efficacies of 68–97 % for Surround-Wetcit and 90–95 % for SilicoSec-Wetcit were observed. Likely, our high and relatively constant treatment efficacy over the four years

in the two vineyards was related to a consistent experimental design with regular, comparably scheduled treatments, the inclusion of a single cultivar Rotburger (Zweigelt) and at least weekly sampling. However, it is highly likely that not only the mineral particle films but also the applied wetting agents contributed to the treatment efficacy in our study. The effect of compounds reducing surface tension (such as Wetcit and Designer in this study) on the survival of SWD adults has been reported previously (Cahenzli *et al.*, 2018) and has also been observed in field trials in elderberry (Krutzler *et al.*, 2022). In addition, the latex in the wetting agent Designer improved the rain stability of particle films.

CONCLUSION

The current trials have shown that treatments based on mineral particle films together with a suitable wetting agent are a suitable strategy for the management of *D. suzukii* in vineyards. A combination with a suitable wetting agent is recommended i) to achieve an even wetting of the spray liquid on the berries, ii) to increase the effectiveness of the film by combing it with products that might kill flies on contact, and iii) to increase rain resistance, especially during rainy periods. In years with low or moderate infestation pressure as well as in organically maintained vineyards, these applications have the potential to be utilised as stand-alone treatments. In periods of high infestation pressure, they may, at the very least, increase the quality of the harvest. As a result, the use of “classical” insecticides could potentially be reduced. The development of resistances against particle films is unlikely due to their physical mode of action. In addition, particle film treatment might also protect from other insect pests. Recently it has been shown that the application of kaolin also reduces the infestation of ripening grapes with *Forficula auricularia* (Riedle-Bauer *et al.*, 2024). However, the control of SWD in grapevine by particle films and wetting agents has currently one shortcoming, namely the low persistence to rain, which in our trial in 2020 compromised the treatment effect and necessitated dense application intervals. Further studies on strategies for the stabilisation of particle films should therefore be conducted.

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Conflicts of interest/Competing interests

The authors declare no conflicts of interest.

Authors' contributions

Michael Krutzler, Monika Riedle-Bauer, Karl Menhart and Günter Brader conceived and planned the experiments. Karl Menhart supervised the application of plant protection products in the field. Michael Krutzler, Monika Madercic and Monika Riedle-Bauer carried out the entomological studies, evaluated the condition of the clusters, and collected the data. Michael Krutzler and Monika Riedle-Bauer conducted the statistical analyses. Michael Krutzler, Monika Riedle-Bauer and Günter Brader wrote the first version of the paper, and all authors contributed to the final version of the manuscript. All authors read and approved the final manuscript.

Ethical approval

The manuscript is original, has not been published before, and is not considered for publication elsewhere.

Consent to participate

The corresponding author declares that he has the written consent of all authors to publish the manuscript in OENO One should the article be accepted by the editor-in-chief.

Consent for publication

The corresponding author declares that he has the written consent of all responsible authorities at the institutes where the work has been carried out to publish the manuscript in OENO One, should the article be accepted by the editor-in-chief.

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