Zhao *et al. CABI Agriculture and Bioscience (2023) 4:54*
https://doi.org/10.1186/s43170-023-00196-w

CABI Agriculture and Bioscience

RESEARCH

Open Access

Control of two-spotted spider mite, *Tetranychus urticae*, on strawberry by integrating with cyetpyrafen and *Phytoseiulus persimilis*

Shan Zhao[1,2†], Qiuyu Zhao[1,2,6†], Xiaoyan Dai[1,2†], Bing Lv[1,2], Ruijuan Wang[1,2], Zhenjuan Yin[4], Feng Zhang[5], Yan Liu[1,2], Long Su[1,2], Hao Chen[1,2], Li Zheng[1,2], Hongmei Li[5], Lixia Xie[3*] and Yifan Zhai[1,2*]

Abstract

The two-spotted spider mite (TSSM, *Tetranychus urticae* Koch) is a significant agricultural pest, particularly in strawberries. Management of TSSM has traditionally relied on synthetic acaricides, but to mitigate dependency on these chemicals, the control of TSSM on strawberry is often combined with biological control measures and chemical control strategies. The predatory mite, *Phytoseiulus persimilis,* is a promising biological control agent, preying on all TSSM developmental stages. In this study, we examined the toxicity of six common acaricides on TSSM and *P. persimilis*, and cyetpyrafen was selected due to its highest relative toxicity value. Then, we examined the compatibility of cyetpyrafen with *P. persimilis* for TSSM management on strawberries. The results suggested that cyetpyrafen revealed no substantial differences in prey consumption or longevity when compared to the control, though minor effects on the development durations of protonymphs and deutonymphs were noted in the subsequent generation. Additionally, cyetpyrafen's toxicity on key pollinators, such as *Apis mellifera* and *Bombus terrestris*, was found to be low. Thus, an integrated strategy combining cyetpyrafen (0.83 mg/L) with *P. persimilis* (predator–prey ratio of 1:30) was examined under laboratory and field conditions. Laboratory trials demonstrated a reduction in mites per leaf from 32.72 to 14.50 within 3 days, correlating to a 70.23% control efficiency. This efficacy increased to 96.04% by day 9 and was sustained until the experiment concluded on day 27. Field trials similarly showed a reduction in TSSM from 53.93 to 9.63 mites/leaf by day 6, achieving an 83.64% control efficiency, and culminated in a 98.46% reduction by day 10. These findings suggested that an integrated approach utilizing cyetpyrafen in conjunction with *P. persimilis* can be an effective alternative for TSSM management on strawberry plants.

Keywords TSSM, Cyetpyrafen, *Phytoseiulus persimilis*, Integrated strategy, Strawberry

---

†Shan Zhao, Qiuyu Zhao and Xiaoyan Dai have contributed equally to this study.

*Correspondence:
Lixia Xie
xielixia2006@163.com
Yifan Zhai
zyifan@tom.com

[1] Shandong-CABI Joint Laboratory for Bio-Control, Institute of Plant Protection, Shandong Academy of Agricultural Sciences, Jinan 250100, China

[2] Key Laboratory of Natural Enemies Insects, Ministry of Agriculture and Rural Affairs, Jinan 250100, China

[3] College of Plant Protection, Shandong Agricultural University, Tai'an 271000, China

[4] College of Agriculture, Guizhou University, Guiyang 550025, China

[5] MARA-CABI Joint Laboratory for Bio-Safety, Institute of Plant Protection, Chinese Academy of Agricultural Science, Beijing 100193, China

[6] College of Rural Revitalization, Shandong Open University, Jinan 250014, China

Introduction

Spider mites, such as the two-spotted spider mite (TSSM), *Tetranychus urticae* Koch, are one of the most pernicious pests impacting agricultural crops globally (Yin et al. 2022; Pekár and Raspotnig 2022), which feed on plant sap by using their piercing-sucking mouthparts, leading to functional damage in leaves and rendering them more susceptible to pathogens and viruses (Beavers et al. 1972; Bensoussan et al. 2016; De Lillo et al. 2021; Nieberding et al. 2022). TSSM has a wide host range and is notably damaging to greenhouse vegetables and fruits, particularly strawberries (Li and Zhang 2021; Park et al. 2005; Meck et al. 2013; Livinali et al. 2014; Akyazi et al. 2019). In 2016, China was the leading global strawberry producer, with an output of 1,801,865 tons (Wu et al. 2020). However, TSSM jeopardizes the physicochemical and nutritional quality of strawberries, significantly reducing their market value (Livinali et al. 2014). Traditional control methods mainly involve acaricides, but their excessive use has led to TSSM resistance, highlighting the dire need for alternative, eco-friendly control strategies (Desneux et al. 2007; Zhang et al. 2022; Hamdi et al. 2023; Xu et al. 2023; Van Leeuwen et al. 2010).

Biological control measures such as predatory mites and natural acaricides are often effective and eco-friendly (Attia et al. 2013; Iskra et al. 2019; Zélé et al. 2020; Nieberding et al. 2022; Cruz-Miralles et al. 2022). *Phytoseiulus persimilis* Athias-Henriot is a biological agent for the control of tetranychid mite (Basha et al. 2021), which was introduced into China from Chile in 1975 (Takafuji et al. 1976). Adult mites possess the ability to consume all developmental stages of TSSM, whereas their nymphs predominantly prey on TSSM eggs and nymphs (Takafuji et al. 1976). Although *P. persimilis* is being successfully utilized to manage TSSM populations in various greenhouse-grown plants, including cucumbers, tomatoes, bedding plants, strawberries, and even citrus orchards (Cakmak et al. 2009; Opit et al. 2009; Gontijo et al. 2012; Argolo et al. 2013; Bilbo et al. 2020), their field application is limited by environmental factors and high costs (Croft and Jung 2001; Jung and Croft 2001; Bilbo and Walgenbach 2020). The control of two-spotted spider mite on strawberry is often combined with *P. persimilis* and chemical control strategies. Therefore, it is important to identify acaricides that are compatible with *P. persimilis* to develop an integrated control strategy (Ricupero et al. 2022).

In this study, we examined the toxicity of six commonly used acaricides on TSSM and *P. persimilis*. A candidate chemical was selected based on relative toxicity value, and then, its toxicity on pollinators, *Apis mellifera* and *Bombus terrestris,* and impact on *P. persimilis* were assessed. We explored an integrated control strategy through laboratory and field efficacy trials to establish a sustainable TSSM management approach for strawberries.

Materials and methods

Mites, pollinators, plants

The colony of TSSM were obtained from Nanjing Agricultural University (Nanjing, China) and was reared in a climatic chamber at the condition of 25 ± 1 °C, 70 ± 5% relative humidity and a photoperiod of 16L:8D on leaves of kidney bean *Phaseolus vulgaris* L plants (21 day-old). The bean plants were cultivated on plastic pots (15 cm in diameter and 12 cm in height). Symptoms of TSSM attack were observed in bean leaves 7–10 days after the infestation, and then, leaves with mites were collected for use in the experiment. Additionally, the colony of mites used in the field trials was naturally infested on strawberry leaves on farm.

The colony of *P. persimilis* was acquired from Shandong Lubao Technology Co. Ltd (Jinan, China) and was kept in a climatic chamber as described before. The predatory mites were reared in plastic trays (10 cm in length, 5 cm in width and 5 cm in height) covered with insect-proof net (200 mesh), and were fed with TSSM four times per week with each tray received three bean leaves infested with TSSM.

Apis mellifera and *Bombus terrestris*, the common pollinators for strawberry, were used in this study. Both colonies were obtained from Shandong Lubao Technology Co. Ltd (Jinan, China) and maintained in plastic box (30 cm in length, 10 cm in width and 20 cm in height) surrounded with carton under control conditions of 30 ± 2 °C with 65 ± 5% relative humidity, fed with sucrose solution (50% w/v) ad libitum and kept in darkness until the experiments were carried out.

Akihime strawberry was used in this experiment. Seedlings of strawberry individually grown in 1-L plastic pots (17 cm in diameter and 20 cm in height) were used in laboratory trials. The potted strawberry plants were kept in a greenhouse at the condition of 25 ± 1 °C, 70 ± 5% relative humidity under natural lighting. Field trials were carried out in a greenhouse at a strawberry farm in Jiyang District (Jinan, Shandong Province, China). The strawberry plants were established on September 5, and the experiments were conducted on November 28 during the flowering phase of strawberries. No acaricides were used in experiment areas.

All mites, pollinators and plants were not exposed to acaricides prior to the experiments.

Acaricides

Six commonly used acaricides were chosen in this study, including cyetpyrafen (30%; Shenyang Sciencreat

Chemical Co. Ltd), cyflumetofen (20%; Suzhou FMS Plant Protective Agent Co. Ltd), bifenazate (43%; Modern Mind Agricultural Solutions Co. Ltd), spirodiclofen (24%; Bayer Crop Science Co. Ltd), diafenthiuron (50%; Shanghai Hulian Biological Pharmaceutical Co. Ltd) and etoxazole (11%; Sumitomo Chemical Co. Ltd). The detailed information about the six acaricides was shown in Additional file 1: Table S1.

Toxicity of the six acaricides on TSSM and *P. persimilis*

The toxicity of acaricides on TSSM and *P. persimilis* was assessed using the dip method (Luo et al. 2018). The acaricides were diluted to multiple concentrations and tested separately (Table 1). The acaricide solution (40 mL) was poured into a Petri dish (90 mm in diameter and 15 mm in height). Adult females of TSSM were glued backside to glass slides with double-sided sticky tape, keeping their legs free. The glass slides were dipped into the acaricide solution for 5 s. Adult females of *P. persimilis* were dipped into the solution using a fine-bristle brush for 5 s and kept in acrylic chambers (Su et al. 2019) for observation. TSSMs on glass slides and *P. persimilis* in acrylic chambers were placed in incubators with the same condition mentioned before, and mortality was assessed 24 h later. Mites in the control group were dipped in distilled water. The mites were considered dead if their feet failed to move upon a light touch. 30 mites with uniform individual size were used for each acaricide concentration, and three replicates were conducted for each treatment and control. The results were considered to be acceptable when mortality in the control group was less than 10%.

The relative toxicity value was used to evaluate the selectivity of acaricides and calculated using the formula: LC_{50} of *P. persimilis*/LC_{50} of TSSM (Yohzi and Keizi 1973). The results, including LC_{50} with corresponding 95% confidence limits (CL), regression equation, chi-square ($\chi2$) and correlation coefficient, were calculated using the data processing software, DPS v. 19.05 (Tang et al. 2013).

Toxicity of cyetpyrafen on pollinators

The toxicity of cyetpyrafen on *A. mellifera* and *B. terrestris* was assessed by acute oral toxicity bioassay and acute contact toxicity bioassay. In acute oral toxicity bioassay, five gradient concentrations (from 0.5 to 5000 mg a.i./L) of cyetpyrafen solution were prepared by diluting cyetpyrafen stock with sucrose water. Worker bees emerged for 3 days were caged individually in containers (7.5 cm in length, 5 cm in width and 9 cm in height). After deprived food for 4 h, different concentrations of cyetpyrafen suspension diluted in 20 μl sucrose water (50%, v/v) were supplied to bees in 2 mL Eppendorf tubes inserted into plastic cages. After the cyetpyrafen solution was consumed, sufficient sucrose water was supplied to the bees. For acute contact toxicity bioassay, the cyetpyrafen suspension was diluted with distilled water to five gradient concentrations (from 0.005 to 50 g a.i./L). Worker bees emerged for 3 days were anesthetized with carbon dioxide, and 2 μl of cyetpyrafen solution was dropped onto the mid-chest of each bee. When the solution evaporated, the bees were removed to the container and fed sucrose water. For both bioassays, bees in the control group were treated with distilled water. 20 worker bees were used for each concentration and three replicates were conducted respectively. The mortality was recorded 48 h later. The results were evaluated according to the Environmental Safety Assessment Test Criteria for Chemical Pesticides. Part 10: Acute Toxicity Test for Bees, published in China, the pesticide was judged as low toxicity when the $LD_{50} > 11.0$ μg a. i./bee (Yuan et al. 2014).

Prey consumption of *P. persimilis*

Three experimental groups were conducted to assess the prey consumption of *P. persimilis*. In the cyetpyrafen-treated *P. persimilis* and cyetpyrafen-treated TSSM (TPTT) group, both *P. persimilis* and TSSM were treated with cyetpyrafen. In the untreated *P. persimilis* and cyetpyrafen-treated TSSM (UPTT) group, the TSSM was treated with cyetpyrafen, while *P. persimilis* was treated with distilled water. In the untreated *P. persimilis* and

Table 1 The gradient concentrations of six acaricides for bioassays (mg/L)

Acaricide	TSSM					*P. persimilis*				
Cyetpyrafen	0.30	0.60	1.20	2.40	4.80	2	20	200	2000	20,000
Cyflumetofen	0.16	0.80	4	20	100	166.67	500	1500	4500	13,500
Bifenazate	2.56	6.40	16	40	100	2000	3000	4500	6750	10,125
Spirodiclofen	1500	3000	6000	12,000	24,000	1563.50	3125	6250	12,500	25,000
Diafenthiuron	39.06	156.25	625	2500	10,000	1250	2500	5000	10,000	20,000
Etoxazole	1250	2500	5000	10,000	20,000	5000	7500	11,250	16,875	25,312.50

untreated TSSM (UPUT) group, both *P. persimilis* and TSSM were treated with distilled water. For cyetpyrafen-treated *P. persimilis* or TSSM, cyetpyrafen was sprayed on the body of mites gathered on bean leaves using a sprayer at a concentration of 0.83 mg/L (LC_{50} for TSSM determined in the 24 h acute toxicity test) with a usage of 5 mL. 30 min after the treatment, the surviving mites were picked and kept in separate chambers for 24 h, and then removed to a new chamber with a *P. persimilis*/TSSM ratio of 1:20. The number of TSSM ingested by *P. persimilis* in all three groups was counted and recorded 24 h later. 20 *P. persimilis* with uniform individual size were used for each treatment, and three replicates were performed. Data were analyzed with one-way ANOVA, followed by separation of means using Student–Newman–Keuls post hoc test ($P < 0.05$).

Life history traits of *P. persimilis*

TSSMs kept on kidney bean plants were sprayed with cyetpyrafen at a concentration of 0.83 mg/L with a usage of 5 mL per leaf. After 24 h, newly emerged *P. persimilis* (F_0) female adults were removed to the acrylic chambers individually, and surviving TSSMs from the treated plants were used to feed F_0 until it died (each F_0 was fed with 10 TSSMs per day). The F_0 was mated with adult males on the second day after emergence, and the eggs (F_1) were collected and reared to adults. F_1 adult females were fed the same way as F_0, and eggs (F_2) were counted and recorded daily until F_1 females died. The longevity of F_0, as well as the egg duration, larva duration, protonymph duration, deutonymph duration, adult duration, preadult, adult preoviposition period (APOP) and total preoviposition period (TPOP) of $F_{1,}$ were recorded. 20 F_0 females and 50 F_1 females were used in this experiment. For control, adult females of *P. persimilis* were fed with untreated TSSM. All data for *P. persimilis* were analyzed based on the two-sex age-stage life table with the TWOSEX-MSChart program (Chi et al. 2013) and data were considered as significantly different if $P < 0.05$.

Laboratory and field trials

72 potted strawberry plants with 5 or 6 leaves were used in laboratory trials. The plants were divided into 12 groups with 6 in each group. For each group, plants were covered with insect-proof net (59 cm in length, 58 cm in width and 60 cm in height, 200 mesh). 100 adult TSSMs were released into each group evenly on leaves to build the mite population, and the number of mites on each leaf was surveyed 5 days later. The experiments would be carried out when the average number of per leaf over 10 (Strong and Croft 1993). Four treatments were settled including biological, chemical, integrated and untreated groups, with each group containing 3 repetitions. For biological treatment, *P. persimilis* was released evenly on leaves of plants with a predator–prey ratio of 1:15 (referenced by Gong et al. 2015). For chemical treatment, cyetpyrafen was diluted to obtain a concentration of 60 mg/L (the recommended concentration in the field, Chen et al. 2019) with distilled water using 500 mL and sprayed evenly on the back and top sides of the leaves. For integrated treatment, the concentration of cyetpyrafen was 0.83 mg/L with a usage of 500 mL, and 24 h after the solution was sprayed, *P. persimilis* were released on leaves with a predator–prey ratio of 1:30 (based on pre-assays results). Plants in untreated group were sprayed with 500 mL distilled water. All treatments were performed only once in this experiment. The surviving TSSM population was sampled by selecting one leaf from each plant (six leaves from each group) and the number of mites was counted using a professional eye loop (10×) on days 3, 6, 9, 12, 15, 18, 21, 24 and 27. The results in each group were expressed as an average of the six leaves.

In the field trials, 12 cultivated plots were marked and covered with insect-proof net (3 m in length, 1 m in width and 2.3 m in height, 200 mesh), and were randomly divided into 4 groups with each group containing 3 plots. A distance of 3 m was kept between the plots. The number of TSSM in each plot was counted before the experiments. The same treatment as in the laboratory was conducted, except that the usage of cyetpyrafen was changed to 3 L. The population of TSSM survivors was sampled by selecting five plants in each plot and three leaflets were selected in each plant (45 leaves from each group). The number of mites was counted on days 3, 10, 17, 24, and 30. The results in each group were expressed as an average of the 45 leaves.

The control efficiency (%) in different groups was calculated by the rate of population reduction using the formula of $(PT - PC)/(100 - PC) \times 100\%$, where PT represents the population reduction rate of the treated group and PC represents the population reduction rate of the control group (Chen et al. 2022). The control efficiency of TSSM under different treatments in the same day was analyzed with one-way ANOVA. If significant differences were detected among treatments, means were separated using Student–Newman–Keuls as post hoc test ($P < 0.05$).

Results

Toxicity of six acaricides on TSSM and *P. persimilis*

To select an effective acaricide, the 24 h acute toxicity of six acaricides was tested. LC_{50} of the six acaricides for TSSM was 3.53 mg/L (cyflumetofen), 0.83 mg/L (cyetpyrafen), 18.26 mg/L (bifenazate), 582.41 mg/L (diafenthiuron), 5108.31 mg/L (etoxazole) and 4436.07 mg/L (spirodiclofen), while LC_{50} for *P. persimilis* was 1676.49 mg/L (cyflumetofen), 2696.81 (cyetpyrafen), 28,034.62 mg/L (bifenazate), 52,540 mg/L (diafenthiuron), 22,424.00 mg/L (etoxazole) and 31,811.78 mg/L (spirodiclofen) (Table 2). The results showed that all the acaricides were significantly more toxic to TSSM than to *P. persimilis*, indicating that all six acaricides had positive selectivity for pest mites.

The relative toxicity value of each acaricide was calculated, and the results showed that cyetpyrafen had the maximum relative toxicity value of 3264.91 in the 24 h bioassay (Table 2). Based on the above results, cyetpyrafen was selected for further study.

Toxicity of cyetpyrafen on pollinators

Due to the significant role of bee pollination in strawberry production, the toxicity of cyetpyrafen on *A. mellifera* and *B. terrestris* was assessed using acute oral and contact bioassays. No bees were dead after 48 h with the highest dose of 100 μg a.i./bee in both assays. According to the relevant standard in China (Yuan et al. 2014), if no bees died with an acaricide dose of 100 μg a.i./bee, there is no need to test higher concentration, and the acaricide was considered as safe to bees. The results indicated that cyetpyrafen has a low toxicity to both pollinators.

Effect on prey consumption of *P. persimilis*

The influence of cyetpyrafen on prey consumption of *P. persimilis* was detected. In TPTT group, the number (4.05) of TSSM consumed by *P. persimilis* was significantly lower than that in UPUT group (5.45) ($P < 0.05$) (Fig. 1). In UPTT group, an average of 5.20 TSSM was consumed by *P. persimilis*, which was similar to that of UPUT group (Fig. 1). The results indicated that the consumption of *P. persimilis* was unaffected as long as the predator mites were not treated directly with cyetpyrafen.

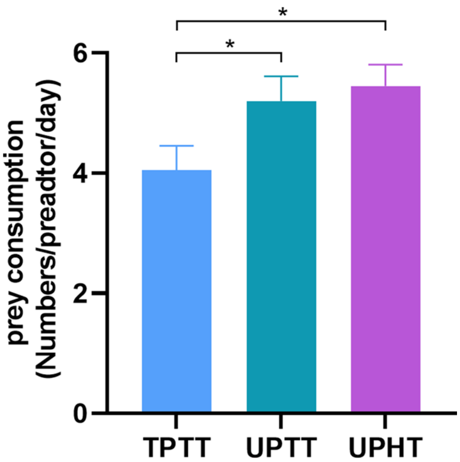

Fig. 1 Consumption of *P. persimilis* on TSSM with different treatments. The results were expressed as means ± SD, *$P < 0.05$. TPTT, treated *P. persimilis* and treated TSSM. UPTT, untreated *P. persimilis* and treated TSSM. UPUT, untreated *P. persimilis* and untreated TSSM

Effects on life history traits of *P. persimilis*

To assess whether the life history traits of *P. persimilis* was affected when fed on cyetpyrafen-treated TSSM, we detected the longevity of F_0 and the developmental progression of F_1. The results showed that the average longevity of F_0 was 15.65 days, which was similar to that of control (13.75 days) (Table 3). In F_1, the duration of egg and deutonymph stages were 1.78 days and 1.43 days, respectively, which were both significantly longer than that in the control group (1.64 and 0.97 days, respectively) ($P < 0.05$), while the protonymph stage was 1.28 days, which was significantly shorter than that in the control group (1.51 days) ($P < 0.05$) (Table 3). However, there was no difference between the two groups in adult

Table 2 The 24 h acute toxicity and relative toxicity value of six acaricides to *P. persimilis* and TSSM

Acaricides	Mites	Acute toxicity regression equation	LC$_{50}$ (mg/L)	95% confidence interval (mg/L)	χ^2	Correlation coefficient	Relative toxicity value
Cyflumetofen	TSSM	y = 1.32 x + 4.28	3.53	2.68–4.63	22.37	0.9098	474.79
	P. persimilis	y = 0.84 x + 2.28	1676.49	1139.43–2503.48	14.84	0.8940	
Cyetpyrafen	TSSM	y = 2.99 x + 5.25	0.83	0.64–1.01	38.67	0.9217	3264.91
	P. persimilis	y = 0.52 x + 3.22	2696.81	1299.33–7196.37	8.75	0.9697	
Bifenazate	TSSM	y = 2.52 x + 1.82	18.26	15.74–21.33	10.05	0.9231	1535.08
	P. persimilis	y = 1.62 x – 2.22	28,034.62	15,151.64–142,137.20	9.44	0.7269	
Diafenthiuron	TSSM	y = 1.37 x + 1.22	582.41	451.63–748.33	17.00	0.9131	90.21
	P. persimilis	y = 1.02 x + 0.18	52,540.56	26,550.79–208,612.30	7.26	0.7174	
Etoxazole	TSSM	y = 3.08 x – 6.42	5108.31	4497.43–5808.78	9.22	0.9241	4.39
	P. persimilis	y = 2.40 x – 5.44	22,424.00	18,637.66–29,620.21	21.81	0.8503	
Spirodiclofen	TSSM	y = 2.04 x – 2.45	4436.07	3701.96–5209.52	7.13	0.9758	7.17
	P. persimilis	y = 1.31 x – 0.91	31,811.78	20,694.30–65535.53	16.04	0.7781	

Table 3 Longevity, development time and fertility of *P. persimilis* fed on cyetpyrafen-treated TSSM

Parameters	Control	Cyetpyrafen-treated
Longevity (day)^{a}	15.65 ± 2.64^{a}	13.75 ± 2.39^{a}
Egg duration (day)	1.64 ± 0.06^{b}	1.78 ± 0.04^{a}
Larva duration (day)	0.62 ± 0.04^{a}	0.60 ± 0.03^{a}
Protonymph duration (day)	1.51 ± 0.06^{a}	1.28 ± 0.09^{b}
Deutonymph duration (day)	0.97 ± 0.03^{b}	1.43 ± 0.07^{a}
Adult duration (day)	12.53 ± 1.76^{a}	12.33 ± 1.65^{a}
Preadult (day)	4.72 ± 0.08^{a}	5.11 ± 0.08^{a}
APOP	1.11 ± 0.06^{a}	1.02 ± 0.07^{a}
TPOP	5.88 ± 0.11^{b}	6.21 ± 0.12^{a}
Fecundity (eggs/adult female/day)	7.04 ± 0.84^{a}	7.65 ± 1.09^{a}
Number of eggs/adult female	23.59 ± 3.083^{a}	21.61 ± 3.598^{a}

APOP, adult preoviposition period, TPOP, total preoviposition period

^{a} The longevity was detected in F_0. Values are shown as means ± SE. Different lowercase letters in a row indicate significant differences between different groups ($P < 0.05$)

preoviposition period (APOP) (Table 3). In addition, the total preoviposition period (TPOP) of F_1 in the treated group (6.21 days) was significantly longer than that in the control group (5.88 days) ($P < 0.05$). The average number of eggs produced per day (7.65) and the total number of eggs produced (21.61) were similar to those in the control group (Table 3). The results showed that, when *P. persimilis* was fed with cyetpyrafen-treated TSSM, no effects were found on other detected parameters other than the development duration on egg and nymph of F_1.

Control efficacy in laboratory and field trials

The control efficacy was assessed in laboratory and field trials. In laboratory trials, the number of TSSM in untreated group increased continuously from 20.44 to 122.11 mites/leaf. The population increased rapidly between day 15 and 18, and till day 21, the population remained stable at a high level (Fig. 2). Typical indicators, such as mature TSSM colonies, faded leaves and development of a silk net, were observed on day 27. In contrast, the TSSM population was suppressed in the other three groups with different control efficacy. The number of TSSMs with chemical treatment decreased rapidly in the first 3 days (from 21.72 to 0.67 mites/leaf), resulting in a control efficiency of 97.95% on day 3 and over 99% thereafter (Fig. 2, Table 4). In the biological treated group, TSSM density increased slightly during the first 3 days (from 29.28 to 33.94 mites/leaf), and then, the density decreased slowly and consistently, resulting in 99.64%

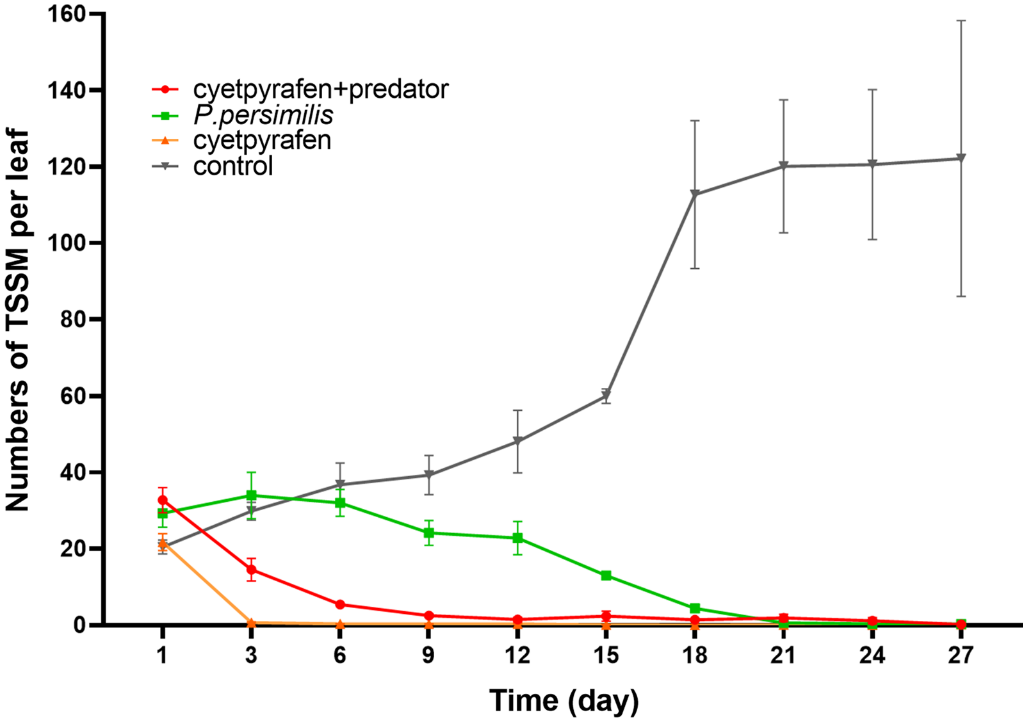

Fig. 2 TSSM populations on strawberry leaves with different treatments in laboratory experiment. The chemical treated group was sprayed with 500 mL cyetpyrafen solution at concentration of 60 mg/L; the biological treated group was released with *P. persimilis* with a predator–prey ratio of 1:15; the integrated treated group was sprayed with 500 mL cyetpyrafen solution at concentration of 0.83 mg/L, and *P. persimilis* was released 24 h later with a predator–prey ratio of 1:30; the control group was sprayed with 500 mL distilled water

Table 4 The TSSM control efficiency with different treatments in laboratory experiment

Groups	**Control efficiency during the experiment (%)**								
	3 d	**6 d**	**9 d**	**12 d**	**15 d**	**18 d**	**21 d**	**24 d**	**27 d**
Integrated	70.23 ± 0.03^b	87.53 ± 0.03^b	96.04 ± 0.01^a	98.15 ± 0.01^a	97.78 ± 0.01^a	99.24 ± 0.01^a	99.02 ± 0.01^a	99.48 ± 0.02^a	99.92 ± 0.01^a
Biological	21.39 ± 0.05^c	38.90 ± 0.03^c	56.94 ± 0.04^b	67.20 ± 0.05^b	84.53 ± 0.02^b	97.34 ± 0.01^b	99.64 ± 0.01^a	99.81 ± 0.01^a	99.87 ± 0.02^a
Chemical	97.95 ± 0.02^a	99.32 ± 0.01^a	99.32 ± 0.01^a	99.36 ± 0.01^a	99.84 ± 0.01^a	99.95 ± 0.01^a	99.91 ± 0.01^a	99.96 ± 0.01^a	99.85 ± 0.01^a

Values are shown as means ± SE. Different lowercase letters in a row indicate significant differences between different groups ($P < 0.05$)

control efficiency on day 21 (Fig. 2, Table 4). In the integrated treatment group, the number of TSSMs decreased slower than in the chemical treated group, but apparently faster than that in biological treated group. The number of TSSM decreased from 32.72 to 14.50 mites/leaf in 3 days, resulting in a mite control efficiency of 70.23% (Fig. 2, Table 4). At day 6, the control efficiency of the integrated treatment group reached 87.53%, which was lower than that of the chemical treated group (99.32%) but higher than biological treated group (38.90%), and the control efficiency reached 96.04% on day 9, which was similar to that of the chemical treated group, and the control efficiency remained above 96% until the end of the experiment (Table 4). Overall, chemical treatment with cyetpyrafen was the most rapid method to suppress TSSM, and integrated treatment with cyetpyrafen and *P. persimilis* was the second rapid method, while biological treatment with the release of *P. persimilis* required the longest time to achieve the same efficacy.

Similar results were observed in field trials. The number of TSSMs in untreated group increased gradually from day 1 to 19 (from 47.30 to 139.81 mites/leaf, Fig. 3), and the density of TSSM increased slightly thereafter. The number of TSSM in the chemical treated group decreased from 50.32 mites/leaf on day 1 to 0.95 mites/leaf in 3 days, resulting in a control efficiency of 98.23% (Fig. 3, Table 5). In the biological treated group, 19 days were cost to suppress the TSSM density from 58.55

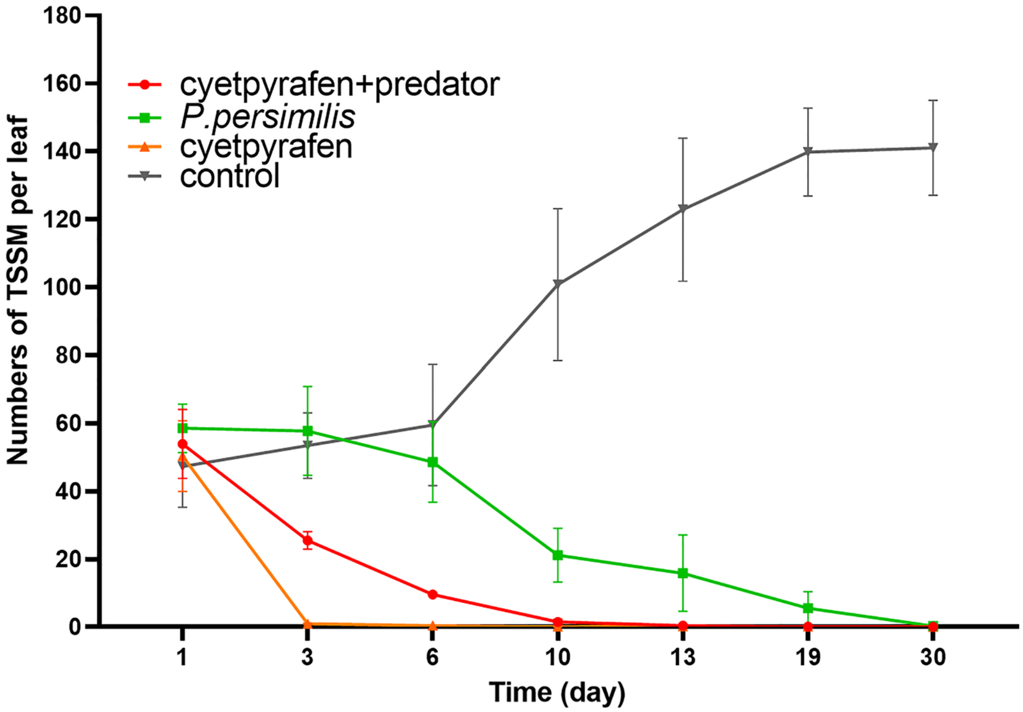

Fig. 3 TSSM populations on strawberry leaves with different treatments in field experiment. The chemical treated group was sprayed with 3 L cyetpyrafen solution at concentration of 60 mg/L; the biological treated group was released with *P. persimilis* with a predator–prey ratio of 1:15; the integrated treated group was sprayed with 3 L cyetpyrafen solution at concentration of 0.83 mg/L, and *P. persimilis* was released 24 h later with a predator–prey ratio of 1:30; the control group was sprayed with distilled water

Table 5 The TSSM control efficiency with different treatments in field experiment

Groups	Control efficiency during the experiment (%)					
	3 d	**6 d**	**10 d**	**13 d**	**19 d**	**30 d**
Integrated	54.99 ± 0.07^{b}	83.64 ± 0.04^{b}	98.46 ± 0.01^{a}	99.69 ± 0.01^{a}	99.91 ± 0.01^{a}	99.97 ± 0.01^{a}
Biological	15.36 ± 0.11^{c}	36.23 ± 0.08^{b}	80.81 ± 0.90^{b}	86.81 ± 0.10^{a}	95.73 ± 0.04^{a}	99.84 ± 0.01^{a}
Chemical	98.23 ± 0.01^{a}	99.28 ± 0.01^{a}	99.86 ± 0.01^{a}	99.80 ± 0.01^{a}	99.90 ± 0.01^{a}	99.94 ± 0.01^{a}

Values are shown as means ± SE. Different lowercase letters in a row indicate significant differences between different groups ($P < 0.05$)

mites/leaf to 5.55 mites/leaf, resulting in 95.73% control efficiency (Fig. 3, Table 5). In the integrated treated group, TSSM density decreased from 53.93 to 9.63 mites/leaf in 6 days, with 83.64% control efficiency, and the density reached a relatively low level on day 10 when density reached 1.08 mites/leaf with 98.46% control efficiency (Fig. 3, Table 5).

Discussion

Controlling pests through integrated strategies is gaining popularity recently due to its lower impact during the process (Mateos Fernández et al. 2022; Misango et al. 2022). Several novel approaches have been identified as effective integrated strategies to control TSSM. For example, Hata et al. (2016) suggested that intercropping garlic plants between strawberry rows could reduce mite populations, with the results providing insights for developing alternative control methods using plant extracts. Lime sulfur inhibited oviposition and egg viability of TSSM while favoring predatory mites, suggesting that it could be a potential tool for integrated mite pest management (Ajila et al. 2020). Typically, to effectively control pests and reduce economic and environmental costs, integrated strategies often incorporate both biological and chemical agents (Lacey et al. 2015; Ghidiu et al. 2012), and acceptable achievements have been reported before (Rhodes et al. 2006; Iwassaki et al. 2015; Lin et al. 2021). In the present study, we aimed to develop an integrated strategy with predatory mite and acaricide to control TSSM on strawberries.

P. persimilis is widely recognized as one of the most effective predators and has been extensively used to control TSSM on various plants (Argolo et al. 2013; Bilbo et al. 2020). Therefore, *P. persimilis* was considered as the primary choice as the biological agent for this study. When selecting a chemical agent for the integrated strategy, the acaricides needed to be highly effective in suppressing the pests without harming the predators (Gentz et al. 2010). Adhering to this principle, the toxicity of six acaricides to TSSM and *P. persimilis* was detected in our study, and the results were evaluated with relative toxicity. Of the six acaricides, cyetpyrafen was found to be the most harmful to TSSM based on 24 h acute toxicity, while diafenthiuron had the least impact on *P. persimilis*. Based on the relative toxicity value, cyetpyrafen exhibited the highest value among the six acaricides (Table 2). As a result, cyetpyrafen was chosen as the chemical agent for this study.

The life table is an important tool for studying population ecology (Nika et al. 2021; Leroy et al. 2022), as it provides a clear overview of parameters such as survival rate, development time, longevity and fecundity (Chi et al. 2022a; b). The impact of cyetpyrafen on the life history traits of *P. persimilis* is a key aspect of the combined strategy. Because less acaricide was used in a combined strategy, predators play an important role in maintaining the pest density at a low level. Therefore, the acaricides selected for the combined strategy should be harmless to predators. In this study, we examined the effect of cyetpyrafen on the life history traits of *P. persimilis*, and the results indicated that when *P. persimilis* was fed with cyetpyrafen-treated TSSM, only the development duration of egg and nymph in the first generation were affected, with no impact on other detected parameters (Table 3). This indicated that cyetpyrafen showed negligible influence on the life history traits of *P. persimilis*. The results provided further support for the application of the combined strategy using cyetpyrafen and *P. persimilis*.

As biological agent plays an important role in the long-term control of pest mites, more attention should be paid to the compatibility between predators and acaricides (Duso et al. 2020). Additionally, to meet the demand for safe and healthy foods, fruits pollinated by insects have the potential to yield significant economic benefits (Klatt et al. 2013). Therefore, a thorough examination of the risks posed by chemical agents used in integrated strategies for predators and pollinators is essential (Gentz et al. 2010). In a previous study, *P. persimilis* showed tolerance to many acaricides (Schmidt-Jeffris et al. 2021). Similarly, our study revealed that when fed with cyetpyrafen-treated TSSM, *P. persimilis* showed no change in consumption (Fig. 1), and only minor effects occurred in the next generation of *P. persimilis* (Table 3). Furthermore, it was observed that neither *A. mellifera* nor *B. terrestris* suffered any mortality when exposed to the highest concentration of cyetpyrafen. These results, therefore, indicated that cyetpyrafen was compatible with *P. persimilis* and could serve as an environmentally friendly option.

The control efficacy of the integrated strategy was evaluated through laboratory and field experiments in our study, and consistent results were observed. In both experiments, the TSSM population decreased rapidly when controlled with recommend concentration of cyetpyrafen (Figs. 2 and 3), suggesting that chemical control had advantages over other methods to some extent (Van Leeuwen et al. 2015; Zhang et al. 2022; Xu et al. 2023). In contrast, it took more than 20 days in both experiments by releasing *P. persimilis* to achieve the same level of control efficiency as chemical control methods (Figs. 2 and 3, Tables 4 and 5). These results were consistent with previous studies (Fraulo et al. 2007) and indicated that biological control should be considered as a supplementary method when managing pest mites. In the group using an integrated strategy with cyetpyrafen and *P. persimilis,* the control efficiency reached that in the cyetpyrafen groups 5 days later in both trials (Tables 4 and 5). However, considering the low concentration of cyetpyrafen and the low predator–prey ratio, these results were acceptable, and a greater control efficacy might be achieved with the optimization of cyetpyrafen concentration and predator–prey ratio. Additionally, the integrated strategy contributed to a reduction in acaricides usage, balancing the food safety and the environmental compatibility. Our findings, as well as assessments in various plants, suggested that integrated strategies for controlling TSSM may present a promising alternative for the future (Lacey et al. 2015; Ghidiu et al. 2012). Further evaluations are needed to refine integrated pest management for strawberries.

In present study, we developed an integrated strategy with cyetpyrafen and *P. persimilis* to control TSSM on strawberries. The selection of cyetpyrafen as the chemical agent in the integrated strategy was based on relative toxicity value and a thorough safety assessment. The control efficacy of this integrated strategy was assessed through both laboratory and field trials, with results indicating that the integrated strategy with cyetpyrafen and *P. persimilis* was effective in controlling TSSM on strawberries. These findings could potentially provide an alternative method for managing TSSM infestations in the future.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s43170-023-00196-w.

Additional file 1. Table S1: The detailed information of the six acaricides.

Acknowledgements

This research was funded by the National Natural Science Foundation of China (31972273); Shandong Provincial Natural Science Foundation (ZR2021YQ21 and ZR2021QC218); the Shandong Provincial Agriculture Research System (SDAIT-24) and Jinan Agricultural Application Technology Innovation Program (CX202201).

Author contributions

YZ and LX performed conceptualization; YZ and LS performed date curation; LZ and YZ acquired funding; SZ, QZ, DX and BL performed research; RW and YL performed methodology; SZ, QZ and XD wrote the paper; FZ, HC and HL reviewed the paper. All authors have read and agreed to the published version of the manuscript.

Data availability

No data was used for the research described in the article.

Declarations

Competing interests

The authors declare no competing interests.

Received: 18 September 2023 Accepted: 19 November 2023
Published: 27 November 2023

References

Ajila HEV, Oliveira EE, Lemos F, Haddi K, Colares F, Gonçalves PHM, Venzon M, Pallini A. Effects of lime sulfur on *Neoseiulus californicus* and *Phytoseiulus macropilis*, two naturally occurring enemies of the two-spotted spider mite *Tetranychus urticae*. Pest Manag Sci. 2020;76(3):996–1003. https://doi.org/10.1002/ps.5608.

Akyazi R, Liburd OE. Biological control of the twospotted spider mite (*Trombidiformes: Tetranychidae*) with the predatory mite *Neoseiulus californicus* (Mesostigmata: *Phytoseiidae*) in blackberries. Fla Entomol. 2019;102:373–81. https://doi.org/10.1653/024.102.0217.

Argolo PS, Banyuls N, Santiago S, Molla O, Jacas JA. Compatibility of *Phytoseiulus persimilis* and *Neoseiulus californicus* (Acari: *Phytoseiidae*) with imidacloprid to manage clementine nursery pests. Crop Prot. 2013;43:175–82. https://doi.org/10.1016/j.cropro.2012.09.018.

Attia S, Grissa KL, Lognay G, Bitume E, Hance T, Mailleux AC. A review of the major biological approaches to control the worldwide pest *Tetranychus urticae* (Acari: *Tetranychidae*) with special reference to natural pesticides. J Pest Sci. 2013;86:361–86. https://doi.org/10.1007/s10340-013-0503-0.

Basha HA, Mostafa EM, El-Deeb A. Mite pests and their predators on seven vegetable crops (Arachnida: *Acari*). Saudi J Biol Sci. 2021;28:3414–7. https://doi.org/10.1016/j.sjbs.2021.03.004.

Beavers JB, Reed DK. Susceptibility of seven tetranychids to the nonoccluded virus of the citrus red mite and the correlation of the carmine spider mite as a vector. J Invertebr Pathol. 1972;20:279–83. https://doi.org/10.1016/0022-2011(72)90157-7.

Bensoussan N, Santamaria ME, Zhurov V, Diaz I, Grbić M, Grbić V. Plant–herbivore interaction: dissection of the cellular pattern of *Tetranychus urticae* feeding on the host plant. Front Plant Sci. 2016;7(1105):1105. https://doi.org/10.3389/fpls.2016.01105.

Bilbo TR, Walgenbach JF. Compatibility of bifenazate and the *Phytoseiulus persimilis* (Acari: *Phytoseiidae*) for management of two-spotted spider mites (Acari: *Tetranychidae*) in North Carolina staked tomatoes. J Econ Entomol. 2020;113:2096–103. https://doi.org/10.1093/jee/toaa159.

Cakmak I, Janssen A, Sabelis MW, Baspinar H. Biological control of an acarine pest by single and multiple natural enemies. Biol Control. 2009;50:60–5. https://doi.org/10.1016/j.biocontrol.2009.02.006.

Chen JC, Wang ZH, Cao LJ, Wei SJ, Gong YJ. Control efficacy and safety of the new acaricide SYP-9625 against two-spotted spider mite (*Tetranychus urticae* Koch on strawberry). Pestic Sci Adm. 2019;40:48–53.

Chen JC, Ma ZZ, Gong YJ, Cao LJ, Wang JX, Guo SK, Hoffmann AA, Wei SJ. Toxicity and control efficacy of an organosilicone to the two-spotted spider mite *Tetranychus urticae* and its crop hosts. InSects. 2022;13:341. https://doi.org/10.3390/insects13040341.

Chi H. TWO SEX-MSChart: a computer program for age stage, two-sex life table analysis. 2013. Available at http://140.120.197.173/ecology/prod02.htm.

Chi H, Güncan A, Kavousi A, Gharakhani G, Atlihan R, Özgökçe MS. WOSEX-MSChart: the key tool for life table research and education. Entomologia Generalis. 2022a;42(6):845–9. https://doi.org/10.1127/entomologia/2022/1851.

Chi H, Kara H, Özgökçe MS, Atlihan R, Güncan A, Rişvanl MR. Innovative application of set theory, Cartesian product, and multinomial theorem in demographic research. Entomologia Generalis. 2022b;42(6):863–74. https://doi.org/10.1127/entomologia/2022/1653.

Croft B, Jung C. Phytoseiid dispersal at plant to regional levels: a review with emphasis on management of *Neoseiulus fallacis* in diverse agroecosystems. Exp Appl Acarol. 2001;25:763–84. https://doi.org/10.1023/A:1020406404509.

Cruz-Miralles J, Cabedo-López M, Guzzo M, Vacas S, Navarro-Llopis V, Ibáñez-Gual MV, Flors V, Montserrat M, Jaques JA. Host plant scent mediates patterns of attraction/repellence among predatory mites. Entomologia Generalis. 2022;42:217–29. https://doi.org/10.1127/entomologia/2021/1237.

De Lillo E, Freitas-Astúa J, Watanabe KE, Ramos-González PL, Simoni S, Tassi AD, Valenzano D. Phytophagous mites transmitting plant viruses: update and perspectives. Entomologia Generalis. 2021;41:439–62. https://doi.org/10.1127/entomologia/2021/1283.

Desneux N, Decourtye A, Delpuech JM. The sublethal effects of pesticides on beneficial arthropods. Annu Rev Entomol. 2007;52:81–106. https://doi.org/10.1146/annurev.ento.52.110405.091440.

Duso C, Van Leeuwen T, Pozzebon A. Improving the compatibility of pesticides and predatory mites: recent findings on physiological and ecological selectivity. Curr Opin Insect Sci. 2020;39:63–8. https://doi.org/10.1016/j.cois.2020.03.005.

Fraulo AB, Liburd OE. Biological control of twospotted spider mite, *Tetranychus urticae*, with predatory mite, *Neoseiulus californicus*, in strawberries. Exp Appl Acarol. 2007;43(2):109–19. https://doi.org/10.1007/s10493-007-9109-7.

Gentz MC, Murdoch G, King GF. Tandem use of selective insecticides and natural enemies for effective, reduced-risk pest management. Biol Control. 2010;52:208–15. https://doi.org/10.1016/j.biocontrol.2009.07.012.

Ghidiu G, Kuhar T, Palumbo J, Schuster D. Drip chemigation of insecticides as a pest management tool in vegetable production. J Integr Pest Manag. 2012;3(3):1–5. https://doi.org/10.1603/IPM10022.

Gong YJ, Wang ZH, Wang S, Zhu L, Shi YC, Wei SJ. Biological control of the two-spotted spider mite *Tetranychus urticae* (Acari: *Tetranychidae*) by the predatory mite *Phytoseiulus persimilis* (Acari: *Phytoseiidae*) on eggplant. Chin J Appl Entomol. 2015;52:1123–30. https://doi.org/10.7679/j.issn.20951353.2015.133.

Gontijo LM, Nechols JR, Margolies DC, Cloyd RA. Plant architecture and prey distribution influence foraging behavior of the predatory mite *Phytoseiulus persimilis* (Acari: *Phytoseiidae*). Exp Appl Acarol. 2012;56:23–32. https://doi.org/10.1007/s10493-011-9496-7.

Hamdi FA, Kataoka K, Arai Y, Takeda N, Yamamoto M, Mohammad YFO, Ghazy NA, Suzuki T. An octopamine receptor involved in feeding behavior of the two-spotted spider mite, *Tetranychus urticae* Koch: a possible candidate for RNAi-based pest control. Entomologia Generalis. 2023;43(1):89–97. https://doi.org/10.1127/entomologia/2023/1808.

Hata FT, Ventura MU, Carvalho MG, Miguel AL, Souza MS, Paula MT, Zawadneak MA. Intercropping garlic plants reduces *Tetranychus urticae* in strawberry crop. Exp Appl Acarol. 2016;69(3):311–21. https://doi.org/10.1007/s10493-016-0044-3.

Iskra AE, Woods JL, Gent DH. Stability and resiliency of biological control of the two-spotted spider mite (Acari: *Tetranychidae*) in hop. Environ Entomol. 2019;48(4):894–902. https://doi.org/10.1093/ee/nvz071.

Iwassaki LA, Sato ME, Calegario FF, Poletti M, Maia AH. Comparison of conventional and integrated programs for control of *Tetranychus urticae* (Acari: *Tetranychidae*). Exp Appl Acarol. 2015;65(2):205–17. https://doi.org/10.1007/s10493-014-9853-4.

Jung C, Croft BA. Ambulatory and aerial dispersal among specialist and generalist predatory mites (Acari: *Phytoseiidae*). Environ Entomol. 2001;30(6):1112–8. https://doi.org/10.1603/0046-225X-30.6.1112.

Klatt BK, Holzschuh A, Westphal C, Clough Y, Smit I, Pawelzik E, Tscharntke T. Bee pollination improves crop quality, shelf life and commercial value. Proc Biol Sci. 2013;281:20132440. https://doi.org/10.1098/rspb.2013.2440.

Lacey LA, Grzywacz D, Shapiro-Ilan DI, Frutos R, Brownbridge M, Goettel MS. Insect pathogens as biological control agents: back to the future. J Invertebr Pathol. 2015;132:1–41. https://doi.org/10.1016/j.jip.2015.07.009.

Leroy N, Hanciaux N, Cornélis JT, Verheggen F. Silicon accumulation in maize negatively impacts the feeding and life history traits of *Spodoptera exigua* (Hübner). Entomologia Generalis. 2022;42(3):413–20. https://doi.org/10.1127/entomologia/2021/1357.

Li GY, Zhang ZQ. The costs of social interaction on survival and reproduction of arrhenotokous spider mite *Tetranychus urticae*. Entomologia Generalis. 2021;41(1):49–57. https://doi.org/10.1127/entomologia/2020/0911.

Lin QC, Chen H, Babendreier D, Zhang JP, Zhang F, Dai XY, Sun ZW, Shi ZP, Dong XL, Wu GA, Yu Y, Zheng L, Zhai YF. Improved control of *Frankliniella* occidentalis on greenhouse pepper through the integration of *Orius sauteri* and neonicotinoid insecticides. J Pest Sci. 2021;94:101–9. https://doi.org/10.1007/s10340-020-01198-7.

Livinali E, Sperotto RA, Ferla NJ, De Souza CFV. Physicochemical and nutritional alterations induced by two-spotted spider mite infestation on strawberry plants. Electron J Biotechnol. 2014;17:193–8. https://doi.org/10.1016/j.ejbt.2014.06.002.

Luo JX, Lai T, Guo T, Chen F, Zhang LL, Ding W, Zhang YQ. Synthesis and acaricidal activities of scopoletin phenolic ether derivatives: QSAR, molecular docking study and in silico ADME predictions. Molecules. 2018;23:995. https://doi.org/10.3390/molecules23050995.

Mateos Fernández R, Petek M, Gerasymenko I, Juteršek M, Baebler Š, Kallam K, Moreno Giménez E, Gondolf J, Nordmann A, Gruden K, Orzaez D, Patron NJ. Insect pest management in the age of synthetic biology. Plant Biotechnol J. 2022;20(1):25–36. https://doi.org/10.1111/pbi.13685.

Meck ED, Kennedy GG, Walgenbach JF. Effect of *Tetranychus urticae* (Acari: *Tetranychidae*) on yield, quality, and economics of tomato production. Crop Prot. 2013;52:84–90. https://doi.org/10.1016/j.cropro.2013.05.011.

Misango VG, Nzuma JM, Irungu P, Kassie M. Intensity of adoption of integrated pest management practices in Rwanda: a fractional logit approach. Heliyon. 2022;8(1):e08735. https://doi.org/10.1016/j.heliyon.2022.e08735.

Nieberding CM, Kaiser A, Visser B. Inbreeding and learning affect fitness and colonization of new host plants, a behavioral innovation in the spider mite *Tetranychus urticae*. Entomologia Generalis. 2022;42(4):531–8. https://doi.org/10.1101/2021.06.29.450353.

Nika EP, Kavallieratos NG, Papanikolaou NE. Linear and non-linear models to explain influence of temperature on life history traits of *Oryzaephilus surinamensis* (L.) Entomologia Generalis. 2021;41(2):157–67. https://doi.org/10.1127/entomologia/2020/1088.

Opit GP, Perret J, Holt K, Nechols JR, Margolies DC, Williams KA. Comparing chemical and biological control strategies for two-spotted spider mites (Acari: *Tetranychidae*) in commercial greenhouse production of bedding plants. J Econ Entomol. 2009;102:336–46. https://doi.org/10.1603/029.102.0144.

Park YL, Lee JH. Impact of two-spotted spider mite (Acari: *Tetranychidae*) on growth and productivity of glasshouse cucumbers. J Econ Entomol. 2005;98:457–63. https://doi.org/10.1093/jee/98.2.457.

Pekár S, Raspotnig G. Defences of Arachnids: diversified arsenal used against range of enemies. Entomologia Generails. 2022;42:663–79. https://doi.org/10.1127/entomologia/2022/1531.

Rhodes EM, Liburd OE, Kelts C, Rondon SI, Francis RR. Comparison of single and combination treatments of *Phytoseiulus persimilis*, *Neoseiulus californicus*, and Acramite (bifenazate) for control of two-spotted spider mites in strawberries. Exp Appl Acarol. 2006;39(3–4):213–25. https://doi.org/10.1007/s10493-006-9005-6.

Ricupero M, Biondi A, Cincotta F, Condurso C, Palmeri V, Antonella V, Zappalà L, Campolo O. Bioactivity and physico-chemistry of garlic essential oil nanoemulsion in tomato. Entomologia Generalis. 2022;42(6):921–30. https://doi.org/10.1127/entomologia/2022/1553.

Schmidt-Jeffris RA, Beers EH, Sater C. Meta-analysis and review of pesticide non-target effects on phytoseiids, key biological control agents. Pest Manag Sci. 2021;77:4848–62. https://doi.org/10.1002/ps.6531.

Strong WB, Croft BA. Phytoseiid mites associated with spider mites on hops in the Willamette Valley. Oregon J Entomol Soc b c. 1993;90:45–52.

Su J, Dong F, Liu SM, Lu YH, Zhang JP. Productivity of *Neoseiulus bicaudus* (Acari: *Phytoseiidae*) reared on natural prey, alternative prey, and artificial diet. J Econ Entomol. 2019;112:2604–13. https://doi.org/10.1093/jee/toz202.

Takafuji A, Chant DA. Comparative studies of two species of predacious phytoseiid mites (Acarina: *Phytoseiidae*), with special reference to their responses to the density of their prey. Res Popul Ecol. 1976;17:255–310. https://doi.org/10.1007/BF02530777.

Tang QY, Zhang CX. Data Processing System (DPS) software with experimental design, statistical analysis and data mining developed for use in entomological research. Insect Sci. 2013;20:254–60. https://doi.org/10.1111/j.1744-7917.2012.01519.x.

Van Leeuwen T, Vontas J, Tsagkarakou A, Dermauw W, Tirry L. Acaricide resistance mechanisms in the two-spotted spider mite *Tetranychus urticae* and other important Acari: a review. Insect Biochem Mol Biol. 2010;40:563–72. https://doi.org/10.1016/j.ibmb.2010.05.008.

Van Leeuwen T, Tirry L, Yamamoto A, Nauen R, Dermauw W. The economic importance of acaricides in the control of phytophagous mites and an update on recent acaricide mode of action research. Pestic Biochem Physiol. 2015;121:12–21. https://doi.org/10.1016/j.pestbp.2012.05.013.

Wu Y, Li L, Li M, Zhang M, Sun H, Sigrimis N. Optimal fertigation for high yield and fruit quality of greenhouse strawberry. PLoS One. 2020;15(4):e0224588. https://doi.org/10.1371/journal.pone.0224588.

Xu J, Lv M, Fang S, Wang Y, Wen H, Zhang S, Xu H. Exploration of synergistic pesticidal activities, control effects and toxicology study of a monoterpene essential oil with two natural Alkaloids. Toxins (basel). 2023;15:240. https://doi.org/10.3390/toxins15040240.

Yin WD, Hoffmann AA, Bai CM, Ma CS. A conservative oviposition preference in spider mites for complex habitats as a preventive strategy for reducing predation risk. Entomologia Generalis. 2022;42(3):389–401. https://doi.org/10.1127/entomologia/2021/1282.

Yohzi T, Keizi K. The selective toxicity of insecticides against insect pests of rice and their natural enemies. Appl Entomol Zool. 1973;8:220–6. https://doi.org/10.1303/aez.8.220.

Yuan SK, Xu H, Qu WG, Shan ZJ, Bu YQ, Yan QP, Wang HL. GB/T31270.10-2014. Environmental Safety Assessment Test Criteria for Chemical Pesticides. Part 10: Acute Toxicity Test for Bees. China Standard Press. Beijing. 2014.

Zélé F, Altıntaş M, Santos I, Cakmak I, Magalhães S. Inter- and intraspecific variation of spider mite susceptibility to fungal infections: Implications for the long-term success of biological control. Ecol Evol. 2020;10:3209–21. https://doi.org/10.1002/ece3.5958.

Zhang Y, Xu D, Zhang Y, Wu Q, Xie W, Guo Z, Wang S. Frequencies and mechanisms of pesticide resistance in *Tetranychus urticae* field populations in China. Insect Sci. 2022;29:827–39. https://doi.org/10.1111/1744-7917.12957.

Publisher's Note