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Interactive Lethal Effects of Common Strawberry Fungicides and Adjuvants on *Phytoseiulus persimilis* (Mesostigmata: Phytoseiidae)

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Abstract. **Integrated pest management (IPM) programs in California strawberry production depend on repeated fungicide applications and augmentative releases of predatory mites, yet the compatibility of fungicide-adjuvant mixtures with predatory mites remains insufficiently understood. We evaluated the lethal effects of commonly used strawberry fungicides, spray adjuvants recommended by pest control advisers, and their combinations on nymph mortality of the predatory mite *Phytoseiulus persimilis* Athias-Henriot under controlled laboratory exposure. Nymphs were subjected to direct spray delivered with a Potter spray tower at field-equivalent concentrations, and mortality was assessed 48 h after exposure. Mortality responses were analyzed using bias-reduced logistic regression to determine the influence of fungicide, adjuvant, and their interaction. All model factors affected mortality significantly, demonstrating that adjuvant toxicity depended strongly on the associated fungicide. Fungicides alone demonstrated low toxicity. Silwet L-77 alone and in combination with most fungicides caused high *P. persimilis* mortality. In contrast, the adjuvants Broadspred and Widespread® Max were generally compatible with *P. persimilis* and only differed significantly from the control in one of the fungicide combinations for each. These results indicate that adjuvants can be a primary driver of nontarget mortality in strawberry spray programs and emphasize the importance of evaluating complete tank mixtures rather than individual active ingredients when assessing compatibility with biological controls. Careful adjuvant selection may improve the integration of chemical disease management with predatory mite use in strawberry IPM programs.**

Introduction

California strawberry production relies on integrated pest management (IPM) to control pathogens and arthropod pests (Holmes 2024; Lahiri et al. 2022; Strand 2008). Major pathogens such as *Botrytis cinerea* Pers. (the causal agent of Botrytis fruit rot) and *Podosphaera aphanis* (Wallr.) U. Braun & S. Takam (the causal agent of powdery mildew) require intensive management to maintain yield and fruit quality (Holmes 2024; Palmer and Holmes 2021). Although nonchemical approaches such as ultraviolet-C applications (Mello et al. 2022) and resistant cultivars (Palmer and Holmes 2022) are used in certain situations, fungicides remain a primary disease management tool and are applied repeatedly throughout the production season in both organic and conventional systems. Fungicide applications often contain a spray adjuvant to improve coverage, retention, and penetration (Gent et al. 2003; Ryckaert et al. 2008). Spider mites such as *Tetranychus urticae* Koch and *Eotetranychus lewisi* McGregor can cause substantial yield loss in strawberries and are managed using a combination of chemical control and augmentative biological control with predatory mites (Howell and Daugovish 2013; Nyoike and Liburd 2013). Biological control is used simultaneously with chemical disease management programs and thus it is crucial to understand how fungicides and adjuvants interact against beneficial arthropods.

The strawberry industry relies on predatory mites such as *Phytoseiulus persimilis* Athias-Henriot and *Neoseiulus californicus* McGregor to control *T. urticae* (Holmes 2024; Lahiri et al. 2022). *Phytoseiulus persimilis* is a specialist predator that feeds only on mites in the *Tetranychus* genus and do not prey on *E. lewisi* (Howell and Daugovish 2013; Seiedy et al. 2012). Augmentative application rates are ~61,000 predatory mites/ha (Howell and Daugovish 2016). Predator survival can be influenced by exposure to insecticides, miticides, and fungicides (Duso et al. 2008, 2020).

Substantial research has been conducted to evaluate the compatibility of insecticides and miticides with *P. persimilis* (Bilbo and Walgenbach 2020; Bilbo et al. 2022; Cloyd et al. 2006; Cote et al. 2002; Duso et al. 2008; Zhang and Sanderson 1990). Commonly used miticide active ingredients such as bifenazate and cyflumetofen are reported to have a low impact on *P. persimilis* (Abdel-Rahman and Ahmed 2018; Bilbo and Walgenbach 2020; Liburd et al. 2007), whereas others such as abamectin, acequinocyl, and spiromesifen have deleterious effects such as direct mortality, shortening life span, and reducing reproductive rates (Cloyd et al. 2006; Rezaei et al. 2025; Zhang and Sanderson 1990). In contrast, fewer studies have investigated the effects of fungicides on predatory mites. Busuulwa et al. (2024) reported that fungicide effects on three predatory mites differed by species. Laboratory application of the fungicides azoxystrobin, chlorothalonil, boscalid, and cyazofamid showed no direct toxicity to *P. persimilis* (Ditillo et al. 2016). Compatibility assessments often evaluate fungicides or miticides in isolation, even though commercial spray programs almost always include an adjuvant. Adjuvants can alter pesticide toxicity and can affect arthropod survival independently. Organosilicone surfactants combined with insecticides increased mortality in honeybees (Chen et al. 2019; Mullin et al. 2016; Wernecke et al. 2022). The compatibility of fungicide-adjuvant mixtures with *P. persimilis* remains insufficiently understood.

To implement IPM effectively, each component of the program must not reduce the efficacy of another. Despite the widespread use of fungicides, adjuvants, and predatory mites in strawberry production, the interactive effects of fungicide–adjuvant mixtures on *P. persimilis* are poorly characterized. Compatibility studies have focused on individual pesticide active ingredients or single adjuvants, limiting their ability to assess biological outcomes under practical spray conditions. The objective of our study was to quantify the lethal effects of six commonly used strawberry fungicides, five adjuvants, and their combinations on *P. persimilis* mortality under controlled laboratory direct exposure.

Materials and Methods

Source of P. persimilis *and* T. urticae. *Phytoseiulus persimilis* used in the experiment was sourced from Bioline Agrosciences (Phytoline; plastic bottle with vermiculite carrier; 2000 individuals; Camarillo, CA, USA). Transfer of *P. persimilis* nymphs into experimental arenas occurred on the same day that a shipment was received. Nymphs were used in our study because they represent the majority of *P. persimilis* in commercial bottles, making this choice more representative of the population after a grower release. All *T. urticae* used as a food source in the study were obtained from a colony in the entomology laboratory at the Strawberry Center. Green bean plants (*Phaseolus vulgaris* cv. Bush Lima, Fordhook No. 242; Burpee Seeds, Warminster, PA, USA) were grown under light-emitting diode lights in a controlled environment and were watered twice weekly. Three-week-old bean plants were placed into 60- × 60- × 60-cm rearing cages (BugDorm-2120F; MegaView Science, Taichung, Taiwan) containing infested bean plants to maintain colonies of

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Table 1. Number of applications for fungicide active ingredients (a.i.) used in our study of California strawberries from 2021 to 2023.

	No. of applications/yr to California strawberries		
Fungicide a.i.	2021	2022	2023
Captan	7495	7171	7983
Sulfur	4582	3990	3841
Fludioxonil	1752	1811	2040
Cyprodinil	1695	1655	1893
Trifloxystrobin	1674	1762	1851
Fluopyram	1555	1630	1764
Thiram	1491	1556	1751
Thiophanate-methyl	491	502	516

T. urticae. The initial *T. urticae* colony originated from infested strawberry foliage collected in Field 25 at Cal Poly State University (lat. 35°18′19″N, long. 120°40′36″W).

Fungicides and adjuvants. The six fungicides used in our study were selected based on their high use in the California strawberry industry, with the exception of thiophanate-methyl, as determined from California Department of Pesticide Regulation pesticide use reports (Table 1) (California Department of Pesticide Regulation 2021, 2022, 2023). The five adjuvants were chosen for their frequent use in the industry, based on consultations with pest control advisors. Each adjuvant and fungicide was tested individually, as well as in all possible fungicide-adjuvant combinations. Fungicides (Table 2) and adjuvants (Table 3) were applied at selected rates.

Experimental arenas. Cylinders of floral foam (Artesia WetFōM Brick–Green, Ludington, MI, USA) were punched with a 2.2-cm-diameter cork borer (Humboldt Mfg Co, Elgin, IL, USA) before being cut into 2.5-cm-long sections. Floral foam was then wrapped with 2.5-cm blue Scotch® tape (3M, St. Paul, MN, USA) to prevent *P. persimilis* mortality from drowning on the floral foam. The foam was then hot-glued to the middle of a 29.6-mL soufflé cup (First Street, Commerce, CA, USA). After letting the glue dry, 25 mL of tap water was added to the soufflé cup. Clean bean plants, grown using the same methods described previously, were used for leaf disks. The same 2.2-cm borer was used to punch out the leaf disks before placing them abaxial side up on top of the floral foam. More than 20 *T. urticae* were transferred onto the leaf disk to provide food for the *P. persimilis*. Five *P. persimilis* nymphs were placed on the leaf disk using a paint brush. Treatments were assigned randomly to a soufflé cup and had 10 replicates.

Applications. Pesticide applications to strawberries on the central coast of California typically use 1402 $L \cdot ha^{-1}$ of water. For the experiment, dilutions equivalent to this rate were prepared in 500-mL volumes, and 2.5 mL was applied per arena. Tap water was used to create each solution. The pH of the water was 7.61 and the electrical conductivity was 0.48 $dS \cdot m^{-1}$. The ideal pH for mixing most pesticides is between 5.5 and 6 (Fishel and Ferrell 2007). Therefore, water was buffered to a pH of 5.5 using Mixwell (JH Biotech, Ventura, CA, USA) before incorporation of the fungicides and adjuvants into solution. Controls were sprayed with buffered water to account for any mortality caused by the water itself. Applications were performed using a Potter tower sprayer (Burkard Manufacturing Co Ltd, Rickmansworth, UK) at 10 psi. After application, arenas were transferred to a growth chamber (model I36VL; Percival Scientific, Perry, IA, USA) set to 20 ± 3 °C, 60% ± 5% relative humidity, and a light/dark photoperiod of 14/10 h, and arranged in a complete randomized design. After 24 h, *T. urticae* was added supplementally to standardize prey density at 20 individuals (combined adults and nymphs) per arena. The number of dead and alive individuals was counted 48 h after application.

Data analysis. Mortality data were analyzed using a bias-reduced logistic regression model. The analysis was conducted in R v. 4.5.0 (R Foundation for Statistical Computing, Vienna, Austria) with the brglm package. The number of dead and alive mites per replicate was modeled using a binomial error distribution with a logit link function as a function of fungicide, adjuvant, and their interaction. The number of mites per treatment served as the binomial denominator.

Type II likelihood ratio tests were conducted using the car package to evaluate the significance of main effects and interactions. Estimated marginal means were computed using the emmeans package on the response scale. Pairwise comparisons of adjuvants within each fungicide level were performed with Tukey's method to adjust for multiple comparisons. Letter displays were generated at $\alpha = 0.05$.

Results

The bias-reduced logistic regression analysis indicated statistically significant effects of fungicide ($\chi^2 = 181.44$, $df = 6$, $P < 0.0001$), adjuvant ($\chi^2 = 468.03$, $df = 5$, $P < 0.0001$), and their interaction ($\chi^2 = 174.05$, $df = 30$, $P < 0.0001$) on *P. persimilis* nymph mortality. Because the fungicide × adjuvant interaction was significant, adjuvant effects were evaluated separately within each fungicide using estimated marginal mean comparisons. Without adjuvants, mortality from fungicides alone was less than 25%.

For captan, mortality was less than 25% when the fungicide was applied alone or combined with Broadspred (Custom Agricultural Formulations, Fresno, CA, USA), Dyne-Amic® (Helena Agri-Enterprises, LLC, Collierville, TN, USA), or Widespread® Max (Loveland Products, Inc., Loveland, CO, USA), and these treatments did not differ statistically from one another. In contrast, Silwet® L-77 (Helena Agri-Enterprises, LLC) and Kinetic® (Helena Agri-Enterprises, LLC) increased mortality to

Table 2. Fungicides evaluated in our study, including trade name, active ingredients, manufacturer, and application rate.

Fungicide trade names	Active ingredient	Manufacturer	Application rate
Switch® 62.5 WG	Cyprodinil + fludioxonil	Syngenta Crop Protection	0.98 $kg \cdot ha^{-1}$
Captan 80 WDG	Captan	Arysta LifeScience North America LLC	4.20 $kg \cdot ha^{-1}$
Topsin® M WSB	Thiophanate-methyl	UPL NA Inc	1.12 $kg \cdot ha^{-1}$
Microthiol® Disperss®	Sulfur	United Phosphorus, Inc	11.20 $kg \cdot ha^{-1}$
Luna Sensation®	Fluopyram + trifloxystrobin	Bayer CropScience	0.56 $L \cdot ha^{-1}$
Thiram SC	Thiram	Taminco US, LLC	5.85 $L \cdot ha^{-1}$

Table 3. Adjuvants evaluated in our study, including trade name, active ingredients, manufacturer, and application rate.

Adjuvant trade name	Active ingredients	Manufacturer	Application rate ($L \cdot ha^{-1}$)
Broadspred	Blend of polydimethylsiloxane nonionic surfactants	Custom Agricultural Formulations	0.88
Widespread® Max	Polyether-polymethylsiloxane-copolymer, polyether	Loveland Products, Inc	0.58
Dyne-Amic®	Methyl esters of C16–C18 fatty acids, polyalkylene oxide modified polydimethylsiloxane, alkylphenol ethoxylate	Helena Agri-Enterprises, LLC	8.77
Silwet®-L77	Siloxane polyalkyleneoxide copolymer	Helena Agri-Enterprises, LLC	1.43
Kinetic®	Proprietary blend of polyalkyleneoxide modified polydimethylsiloxane and nonionic surfactants	Helena Agri-Enterprises, LLC	4.67

∼82% and 63%, respectively, and both treatments were significantly greater than all other captan combinations (Fig. 1A). In treatments containing cyprodinil + fludioxonil, mortality was at or less than 20% for the fungicide-only treatment and when combined with Broadspred, which did not differ statistically. Mortality ranged from 47% to 69% when mixed with Dyne-Amic®, Kinetic®, and Widespread Max®, and these treatments formed an intermediate statistical group. The addition of Silwet® L-77 produced the greatest mortality at ∼96% and was significantly greater than all other combinations (Fig. 1B).

In treatments containing fluopyram + trifloxystrobin, mortality was less than 30% for the fungicide-only treatment and when combined with Broadspred, Dyne-Amic®, Kinetic®, or Widespread® Max, with no statistical separation among these treatments. The addition of Silwet® L-77 increased mortality to 90% and was significantly greater than all other combinations (Fig. 1C). With sulfur, mortality ranged from 11% to 37% for the fungicide-only treatment and when combined with Broadspred, Kinetic®, or Widespread® Max, and these treatments did not differ statistically. The addition of Dyne-Amic® and Silwet® L-77 increased mortality to ∼79% and 94%, respectively, and both treatments formed a distinct statistical group from the remaining sulfur combinations (Fig. 1D).

Thiophanate-methyl combined with Broadspred, Dyne-Amic®, Silwet® L-77, and Kinetic® resulted in mortality ranging from 85% to 96%, and these treatments formed a statistically distinct group compared the fungicide-only treatment and the Widespread® Max combination, which remained less than 20% (Fig. 1E). In contrast, mortality with thiram ranged from 12% to 39% across the fungicide-only treatment and all adjuvant combinations, and no statistical separation among treatments was detected (Fig. 1F). When adjuvants were evaluated without fungicide, mortality was less than 30% for Broadspred, Kinetic®, and Widespread® Max, which did not differ statistically, whereas Dyne-Amic® and Silwet® L-77 produced significantly greater mortality of 56% and 73%, respectively (Fig. 1G).

Discussion

Our results indicate that the selected fungicides, when applied alone, have relatively low toxicity to *P. persimilis* nymphs when exposed via direct spray. The adjuvant was shown to be the main driver of mortality, but was also highly dependent on the fungicide. Silwet® L-77 (Helena Agri-Enterprises, LLC) consistently displayed high toxicity by itself and in combination with fungicides, except with thiram. Broadspred (Custom Agricultural Formulations), both alone and in combination with fungicides, did not differ from the water-sprayed

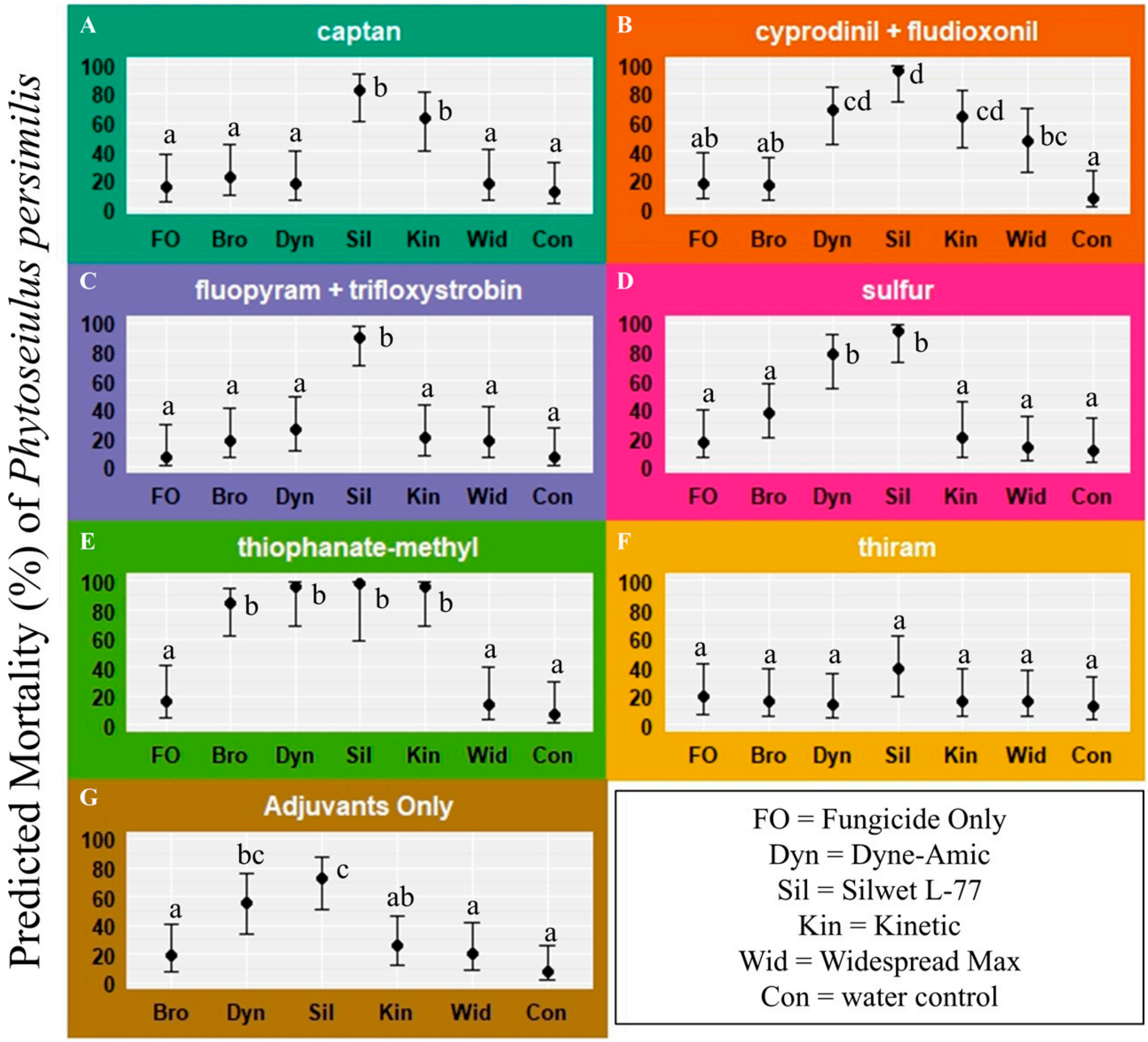

Fig. 1. Model-predicted mortality of *Phytoseiulus persimilis* nymphs 48 h after direct spray exposure to captan (**A**), cyprodinil + fludioxonil (**B**), fluopyram + trifloxystrobin (**C**), sulfur (**D**), thiophanate-methyl (**E**), thiram (**F**), and adjuvants only (**b**) under laboratory conditions (n = 10). Points represent estimated marginal means from a bias-reduced logistic regression model (binomial distribution; logit link). Error bars indicate 95% asymptotic confidence limits. Within each panel, adjuvants were compared using Tukey-adjusted pairwise comparisons (α = 0.05). Treatments sharing a letter are not significantly different.

control, showing that mixing fungicides with Broadspred is generally compatible with *P. persimilis* use. Widespread® Max (Loveland Products, Inc) was also compatible with most fungicides except for cyprodinil + fludioxonil.

Adjuvants can be grouped as surfactants, penetrants, spreaders, humectants, and pH modifiers (Sawicka et al. 2025). All the adjuvants used in our study are described as wetter/spreaders on their label and Kinetic® (Helena Agri-Enterprises, LLC), Silwet® L-77, Widespread® Max, and Broadspred are also described as penetrants. Penetrants dissolve the waxy layer of plant cuticles that allow the active ingredient to move into the plant with ease (Sawicka et al. 2025). Although plant and mite cuticles differ substantially in composition (Feng et al. 2025; González-Valenzuela et al. 2023), adjuvants with penetrating properties may disrupt cuticular lipids and increase the uptake of active ingredients into *P. persimilis*, potentially enhancing lethal effects. Several grape pests such as *Frankliniella occidentalis* Pergande, *Tetranychus pacificus* McGregor, and *Pseudococcus maritimus* Ehrhorn have demonstrated high susceptibility to Silwet® L-77, showing that it acts not only as an adjuvant, but also works as an insecticide and miticide (Tipping et al. 2003). The adjuvants Silwet L-77®, Silwet 408, and Dyne-Amic® (Helena Agri-Enterprises, LLC) by themselves are effective at managing populations of *T. urticae* (Chen et al. 2022; Cowles et al. 2000), and were also the adjuvants most lethal to *P. persimilis* when used by themselves in our study (Fig. 1G). Kinetic® and Silwet® L-77 showed 29% and 73% direct mortality, respectively, on *Diaphorina citri* Kuwayama nymphs (Srinivasan et al. 2008), which is consistent with the lesser lethality of Kinetic® on *P. persimilis* as opposed to Silwet® L-77 seen in our study (Fig. 1G). The mechanism of toxicity is unclear, but Cowles et al. (2000) hypothesized that trisiloxane surfactants such as Silwet act like soaps and cause drowning by allowing water to enter the spiracles. The broad-spectrum lethality of Silwet against arthropods is consistent with the results seen in our study (Fig. 1G). When selecting adjuvants for a tank mix, effects on nontarget beneficial insects should be considered.

The formulation of the fungicide may also play a role in lethality on predatory mites when combined with an adjuvant. The powder or granular fungicides used in our study, such as thiophanate-methyl, cyprodinil + fludioxonil, sulfur, and captan, tended to have greater mortality when combined with adjuvants than with the soluble concentrate (SC) formulations such as thiram and fluopyram + trifloxystrobin. Granular fungicides are composed of a mineral component, typically a type of clay, with the pesticide molecule attached (Ohkouchi and Tsuji 2022). In contrast, SC formulations are suspended solid water-insoluble pesticides that lack a mineral component (Ohkouchi and Tsuji 2022). When combining granular-formulated fungicides with an adjuvant, the resulting film will have the mineral particles in suspension, which may be abrasive to the predatory mites or may clog their spiracles, leading to respiratory failure if they do not die from drowning. If this were the case, the lethal effects of certain fungicides coupled with adjuvants may be a physical mode of action (MOA) as opposed to a physiological MOA.

Although few studies have investigated lethal effects of fungicides on *P. persimilis*, there is more research on how they affect other phytoseiid mites. Silva et al. (2019) reported that 48 h after direct spray in the laboratory with sulfur, *N. californicus* McGregor mortality was low and did not differ from the control. Busuulwa et al. (2024) reported survival estimates for *N. californicus* did not differ statistically between thiram and the control, but cyprodinil + fludioxonil and two formulations of captan lowered survival. In our study, *P. persimilis* mortality did not differ from the control with thiram, cyprodinil + fludioxonil, or captan. Predatory mites vary in their sensitivity to fungicides (Busuulwa et al. 2024; Duso et al. 2020), and *P. persimilis* may be less sensitive to these fungicides than *N. californicus*.

Conclusion

Our study gives a framework for considering adjuvant toxicity to *P. persimilis* when tank-mixing. One caveat of laboratory compatibility assays is the potential discrepancy between the laboratory and the field. If drowning is the mechanism of toxicity at play, then coverage will be a source of discrepancy between laboratory and field assays. In the laboratory, there is perfect coverage of the experimental arena, and the adjuvants have no problem creating a film. In the field, *P. persimilis* inhabit the abaxial leaf surface, where coverage is limited and they may be protected from the surfactant film in addition to interference by trichomes. Another limitation of the applicability of our study to field conditions is that mortality was only assessed at 48 h after exposure. Sublethal effects of adjuvants may occur in addition to their direct-spray toxicity, and future research should assess whether adjuvant residues harm *P. persimilis* establishment in any way. The fungicide sensitivity between *P. persimilis* and *N. californicus* should also be compared to assess which species would be most compatible with a conventional spray program. Last, reduced rates of adjuvants should be investigated to determine whether they can provide adequate spreading while minimizing lethal effects on *P. persimilis*. Adjuvants are overlooked components in tank mixes when assessing compatibility with biological controls. This study offers practical insights into how adjuvants can influence fungicide toxicity on *P. persimilis*.

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