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Assessing the Efficacy of Sodium Alginate and Polyacrylamide as Spray Adjuvants Combined with Bifenthrin and Imidacloprid against *Lygus lineolaris* and *Piezodorus guildinii*

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Abstract: The tarnished plant bug, *Lygus lineolaris*, and the red-banded stink bug, *Piezodorus guildinii*, pose significant economic threats to cotton and soybean crops in the mid-southern USA. However, the efficacy of insecticide spraying is comparatively low, and adjuvants play a crucial role in optimizing insecticide performance. This study evaluated the impact of two adjuvants, sodium alginate (SA) and polyacrylamide (PAM), on enhancing the efficacy of bifenthrin and imidacloprid via laboratory spray bioassays. Both SA and PAM demonstrated insignificant variation in LC_{50} values with formulated bifenthrin and imidacloprid. However, SA and PAM exhibited synergistic effects with two technical-grade insecticides. High concentrations of PAM increased the efficacy of bifenthrin by 1.50- and 1.70-fold for *L. lineolaris* and *P. guildinii*, respectively. Conversely, no enhancement effect was observed for the SA–technical-grade bifenthrin combination against either insect pests. Additionally, both SA and PAM enhanced the effectiveness of imidacloprid in *P. guildinii* by up to 2.68- and 2.73-fold, respectively. While a high concentration of PAM had a 1.45-fold synergistic effect on technical-grade imidacloprid, no enhancement effect was observed for the SA/imidacloprid combination in *L. lineolaris*. This study explored the synergistic impact of SA and PAM on the efficacy of technical-grade and formulated bifenthrin and imidacloprid, providing valuable insights into optimizing pest control strategies in agriculture.

Keywords: two hydrocolloid adjuvants; technical-grade and formulated insecticides; spray bioassay; tarnished plant bug; red-banded stink bug; pesticide efficacy assessment; pest management

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1. Introduction

The tarnished plant bug, *Lygus lineolaris* (Palisot de Beauvois) (Hemiptera: Miridae), and the red-banded stink bug, *Piezodorus guildinii* (Westwood) (Hemiptera: Pentatomidae), are significant threats to cotton and soybeans, respectively, in the mid-southern United States. *L. lineolaris* causes serious damage to cotton by feeding on squares and bolls, resulting in yield losses [1–3]. In recent years, *P. guildinii* has expanded its range, establishing itself as an economically significant pest and causing substantial yield losses in soybean fields in Mississippi and Arkansas [4]. The stink bug complex, with *P. guildinii* as the most abundant species, has contributed to these losses [5]. Chemical control is widely used for managing *L. lineolaris* and *P. guildinii* infestations, and insecticides, including organophosphate, pyrethroids, and neonicotinoids, are key components of control tactics against these pests [6,7]. However, the repeated use of pyrethroids and neonicotinoids against *L. lineolaris* favors the selection of resistant populations, amplifies the economic impact, and complicates management strategies [3].

Insecticide resistance poses a significant challenge and requires higher insecticide application concentrations, which may impact beneficial insects such as bees. An increase in the concentration of neonicotinoid foliar sprays in Mississippi presents a potential direct contact risk to foraging bees [7]. Moreover, the use of conventional pesticides is considered unsustainable, as excessive or improper pesticide application results in unintended contamination of pesticides and their residues in the environment, posing risks to organisms and human health [8]. The intensive use of insecticides in agriculture, homes, and gardens has led to high-level residual accumulations in the soil, surface, groundwater, and food chain [8]. These chemicals may cause serious problems, such as fetal health hazards, birth defects, and even death [9]. However, the utilization efficacy of conventional insecticides is comparatively low in agricultural production, contributing to their excessive application and environmental pollution. Research indicates that the world's annual pesticide output has reached 4.6 million tons, with over 90% of the applied pesticides flowing into the environment and remaining in agricultural products, while the actual utilization rate for targeted pests is less than 0.1% [10]. Spray drift from pesticide applications is a major challenge that affects the efficiency of these applications [11]. The U.S. Environmental Protection Agency (EPA) defines drift as the "movement of pesticide dust or droplets through the air at the time of application or soon after, to any site other than the area intended" [12]. Environmental conditions and operational parameters can influence pesticide spray drift, and modifying the spray solution through tank mix additives and product formulation is an important drift reduction strategy. Incorporating specific spray adjuvants has been reported to result in up to 63% drift reduction, depending on the formulation/adjuvant combination [11]. Different adjuvant products, such as surfactants, drift retardants, mineral oil, and vegetable oil, have shown potential for reducing drift in agricultural spray applications [13].

The primary goal of adjuvant products is to enhance the effectiveness of agrochemicals by facilitating the spreading and sticking of spray droplets and improving the penetration of active ingredients through the leaf cuticle or targeted pests, thereby reducing the amount of pesticide required for effective pest control [14]. Adjuvants fulfill various roles; they are used as surfactants to enhance insecticide coverage and penetration, emulsifiers in stabilizing formulations, compatibility agents to improve the interaction of insecticides with other ingredients, tools for enhancing insecticide retention on plant foliage [15], off-target drift reducers [11], products to improve wetting and spreading of insecticide formulations [16], and rainfastness providers [17]. The Council of Producers and Distributors of Agrotechnology (CPDA) has certified 221 adjuvants as approved tank-mix products [18]. Additionally, many adjuvant products not certified by the CPDA are widely used by commercial-scale producers, although their effectiveness remains uncertain. Studies on pollinator safety indicate that some adjuvants can be as or more toxic to pollinators than pesticide active ingredients [14,19–24]. Therefore, there is an urgent need to develop and utilize adjuvants that are less toxic to insect pollinators. Challenges such as insecticide resistance also highlight the importance of testing new adjuvants for pesticide applications.

The main chemical classes of principal functional agents listed on spray adjuvant labels include non-ionic surfactants, crop oil concentrates, modified seed oils, organosilicone surfactants, and hydrocolloid polymers [25]. In this study, we focused on two hydrocolloid polymers: sodium alginate (SA) and polyacrylamide (PAM). Sodium alginate (SA) $(C_6H_7\,O_6Na)_n$ is nontoxic, biocompatible, and biodegradable [26]. It is nearly odorless and tasteless [27]. Upon dissolving in water, it forms a thick colloidal solution of higher pH and concentration, exhibiting significantly increased viscosity. However, it does not cause substantial reductions in surface tension at higher doses. SA solutions effectively endure freeze and thaw cycles. It is recognized by the United States Food and Drug Administration [28] as a "generally recognized as safe" (GRAS). Additionally, SA is registered as a food improvement agent in the European Union (EU) [29]. The United States Environmental Protection Agency (U.S. EPA) rates SA as a safer chemical [30]. SA is applied in the medical and food industries [31–34], water and wastewater treatment practices, oil and gas production, and a variety of other industries. Polyacrylamide (PAM) [–$CH_2CH(CONH_2)$–]n is a non-ionic [34], water-soluble, and biocompatible polymer. Upon dissolving in water, it forms a thick colloidal solution with increasing pH and concentration, leading to a significant decrease in surface tension. However, it does not exhibit appreciable increases in viscosity at higher doses. PAM is used in the water and wastewater treatment industry as a flocculant [35,36], soil conditioning and erosion control agent [37–39], and in the oil and gas industry [40]. However, high levels of acrylamide in PAM have been associated with cancer in laboratory animals and are reasonably anticipated to be a human carcinogen [41,42]. The risk posed by acrylamide compounds to humans is not fully understood. This reiterates the importance of the current research to identify pesticide adjuvants that are safer for humans and other animals (e.g., pollinators) important in our food production system.

This research evaluated the potential of two adjuvants, SA and PAM, to enhance the efficacy of bifenthrin and imidacloprid, shedding light on their practical application in pest management. The combination of technical-grade or formulated bifenthrin or imidacloprid, with or without the adjuvant SA or PAM, is referred to as the spray solution. Bioassays were conducted on *L. lineolaris* and *P. guildinii*, which are the two main economically detrimental pests of cotton and soybean in Mississippi, respectively. The potential synergistic and antagonistic effects of SA (a new adjuvant) were evaluated in two target insect pests, and similar assessments were conducted with the commercial pesticide adjuvant PAM for comparison.

2. Materials and Methods

2.1. Insect Populations

The adult tarnished plant bug (*Lygus lineolaris*) used in this study was obtained from a colony established in 1998 [43]. The colony was maintained on a non-autoclaved semisolid artificial diet following a protocol described by Portilla et al. (2011) without exposure to any pesticide [44]. A population of the red-banded stink bug, *Piezodorus guildinii* (Westwood), was collected from a soybean field at the Southern Insect Management Research Unit Farm, Leland, MI, USA, in October 2023.

2.2. Insecticides and Adjuvant Sources

The formulated insecticides used in this study included Advise Four (imidacloprid, 40.4%, Winfield Solutions LLC, St. Paul, MN, USA) and Tundra ®EC (bifenthrin, 25.1%, Winfield Solutions LLC, St. Paul, MN, USA), which were obtained from local agricultural chemical suppliers near Stoneville, Mississippi. In addition, technical-grade imidacloprid (purity 98.3%) and bifenthrin (purity 98.0%) were purchased from Chem Service, Inc. (West Chester, PA, USA). All pesticides were stored at 4 ± 1 °C prior to use. For the experiments, commercially available sodium alginate (SA) produced by Spectrum Chemical Manufacturing Corporation (Gardena, CA, USA and New Brunswick, NJ, USA) and commercially available polyacrylamide (PAM) made by Precision Laboratories (Kenosha, WI, USA) were purchased.

In all experiments, the adjuvant concentrations were 1.25 or 2.5 g/L for sodium alginate (SA 1.25 and SA 2.5) and 0.08 or 0.31 mg/L for polyacrylamide (PAM 0.08 and PAM 0.31). The concentrations used for the two adjuvants were very different. This is because PAM is a ready-to-use product that has existed on the market for several decades as a proven pesticide adjuvant, and we used the minimum to the maximum recommended label rate. However, SA is only a thickener that was explored in this study as a potential pesticide adjuvant. For SA, we determined the minimum and maximum rates based on limited spray experiments in the laboratory. An insecticide efficacy experiment was conducted to test the differences between technical-grade or formulated insecticides (bifenthrin and imidacloprid) against *P. guildinii* and *L. lineolaris* with or without SA or PAM treatments. Formulated bifenthrin or imidacloprid was dissolved in deionized H_2O, whereas technical-grade insecticide was dissolved in acetone to make a stock solution of 1000 mg/L and then diluted with H_2O, ensuring that the amount of acetone remained below 20%. Each technical-grade or formulated pesticide was combined with/without low or high concentration of the adjuvants (SA 1.25 and SA 2.5; PAM 0.08 and PAM 0.31). Serial dilutions were prepared using deionized water, 1.25 and 2.5 g/L SA, or 0.08 and 0.31 mg/L PAM adjuvant solutions to obtain the four desired test concentrations for each treatment. In total, 20 treatments were applied to either *L. lineolaris* or *P. guildinii*.

2.3. Laboratory Spray Tower Bioassays

Either 20 adult *L. lineolaris* or 15 *P. guildinii* were placed into plastic cups (500 mL round wide-mouth polypropylene cup; D $\times$ H: 9.3 $\times$ 10 cm) with fabric mesh-covered holes (5.0 cm in diameter) cut on both the lid and the bottom. The procedure of the spray bioassays was identical to that described previously [45]. Prior to spraying the insecticide solutions, a control treatment was conducted by spraying 0.5 mL of water, 20% acetone, SA 1.25, SA 2.5, PAM 0.08, or PAM 0.31 only.

2.4. Data Analysis

For the bioassay data, the LC_{50} values and 95% confidence intervals were calculated by Probit analysis using SPSS software (version 19.0, SPSS Inc., Chicago, IL, USA, 2003), and the data are presented as means $\pm$ S.D. The significance of the LC_{50} values among the different treatments was determined when there was no overlap in the 95% confidence intervals. The synergistic ratio (SR) was calculated as the ratio of the lethal concentration (LC_{50}) of *P. guildinii* or *L. lineolaris* treated with bifenthrin or imidacloprid without SA or PAM divided by the LC_{50} of *P. guildinii* and *L. lineolaris* treated with SA or PAM combined with each test pesticide solution.

3. Results

In the spray bioassays of commercially formulated and technical-grade bifenthrin and imidacloprid combined with SA or PAM, applied in *L. lineolaris* populations, the LC_{50} values for formulated bifenthrin alone ranged from 19.28 to 24.78 µg/mL (Table 1), and when bifenthrin was combined with SA, the LC_{50} values slightly increased at a high concentration of 2.5 g/L, while at 0.08 mg/L or 0.31 mg/L PAM, the LC_{50} values slightly decreased but did not significantly differ (Table 1). Formulated imidacloprid alone had LC_{50} values ranging from 17.74 to 27.03 µg/mL (Table 1), and the addition of SA or PAM resulted in slight changes in LC_{50} values, although these values were not significantly different from those of imidacloprid alone. When technical-grade insecticides were used, the bifenthrin LC_{50} ranged from 37.47 to 46.35 µg/mL (Table 2). Bifenthrin with 1.25 g/L or 2.5 g/L SA had an insignificant slightly higher LC_{50} value, while with PAM, the LC_{50} was significantly lower at a higher concentration of 0.31 mg/L, leading to a 1.50-fold increase in toxicity (Figure 1A; Table 2). For technical-grade imidacloprid alone, the LC_{50} ranged from 31.24 to 51.28 µg/mL, and the SA or low-concentration PAM/imidacloprid combination had slightly lower LC_{50} values, while a higher concentration of 0.31 mg/L PAM resulted in a significantly lower LC_{50} value and increased imidacloprid toxicity by 1.45-fold (Figure 1B; Table 2). Overall, the addition of SA or PAM did not consistently enhance the efficacy of formulated bifenthrin or imidacloprid. In contrast, a high concentration of PAM significantly increased the residual activity of technical-grade bifenthrin and imidacloprid, while no enhancement effect was observed for the combination of SA–bifenthrin or imidacloprid against *L. lineolaris*.

The results from *P. guildinii* aligned with those from *L. lineolaris* for formulated bifenthrin and imidacloprid in spray bioassays. Bifenthrin alone had an LC_{50} ranging from 21.28 to 33.71 µg/mL, and imidacloprid alone had an LC_{50} ranging from 18.76 to 38.70 µg/mL for *P. guildinii* (Table 3). When bifenthrin was combined with SA or PAM, its LC_{50} slightly increased with SA and slightly decreased with PAM at both low and high concentrations, but the difference was not significant (Table 3). The addition of SA or PAM also did not significantly affect the efficacy of formulated imidacloprid in *P. guildinii*, regardless of whether the LC_{50} value slightly increased or decreased. However, significant enhancements were observed when SA or PAM was paired with technical-grade bifenthrin or imidacloprid, with the exception of the SA–bifenthrin combination. The LC_{50} values of technical-grade bifenthrin alone ranged from 42.53 to 56.72 µg/mL, which were slightly lower with 1.25 g/L SA and 0.31 mg/L PAM but significantly lower (22.35 to 35.29 µg/mL) at a high concentration of PAM (0.31 mg/L). Correspondingly, a high concentration of PAM increased the efficacy of technical-grade bifenthrin by 1.70-fold (Figure 2A; Table 4). Both SA and PAM significantly reduced the LC_{50} value of imidacloprid at lower and higher concentrations, especially at higher concentrations, effectively enhancing the efficacy by 2.68-fold and 2.73-fold, respectively, and led to relatively less enhancement at lower concentrations in *P. guildinii* (Figure 2B; Table 4). Overall, the addition of SA or PAM also did not consistently enhance the efficacy of formulated bifenthrin or imidacloprid in *P. guildinii*. However, PAM significantly increased the efficacy of both technical-grade bifenthrin and imidacloprid, while SA only enhanced imidacloprid at high concentrations in *P. guildinii*.

Table 1. Toxicity of formulated insecticides with the adjuvants sodium alginate (SA) and polyacrylamide (PAM) against *Lygus lineolaris* adults 48 h after application.

Compounds	Population	Slope	LC_{50} (µg/mL)	95% Confidence Limits (µg/mL)	χ^2	*p*	ER
Bifenthrin (F)	alone	4.298 ± 0.538	21.78	19.28–24.78	0.58	0.45	--
	+SA 1.25	2.714 ± 0.341	22.75	19.33–27.94	1.93	0.38	0.96
	+SA 2.5	2.384 ± 0.254	30.16	25.71–35.92	0.99	0.80	0.72
	+PAM 0.08	2.108 ± 0.254	20.59	16.70–25.47	0.07	0.80	1.06
	+PAM 0.31	2.573 ± 0.299	17.48	14.88–21.12	1.29	0.27	1.25
Imidacloprid (F)	alone	1.806 ± 0.202	21.72	17.74–27.03	0.33	0.85	--
	+SA 1.25	1.596 ± 0.188	21.26	16.90–27.25	2.93	0.23	0.85
	+SA 2.5	2.597 ± 0.306	29.81	25.11–35.10	1.04	0.60	0.73
	+PAM 0.08	3.712 ± 0.467	31.09	27.46–35.26	1.38	0.24	0.70
	+PAM 0.31	3.721 ± 0.405	27.54	24.16–31.31	1.62	0.45	0.79

Table 2. Toxicity of technical-grade insecticides with the adjuvants sodium alginate (SA) and polyacrylamide (PAM) against *Lygus lineolaris* adults 48 h after application.

Compounds	Population	Slope	LC_{50} (µg/mL)	95% Confidence Limits (µg/mL)	χ^2	*p*	ER
Bifenthrin (T)	alone	2.740 ± 0.256	39.81	37.47–46.35	1.56	0.46	--
	+SA 1.25	4.494 ± 0.498	46.94	42.31–52.18	0.48	0.49	0.85
	+SA 2.5	4.897 ± 0.511	46.75	42.40–51.42	0.07	0.80	0.85
	+PAM 0.08	3.041 ± 0.254	32.30	26.70–35.47	0.07	0.80	1.23
	+PAM 0.31	2.879 ± 0.290	26.47	24.33–29.13	1.64	0.44	1.50
Imidacloprid (T)	alone	1.474 ± 0.212	39.70	31.24–51.28	0.53	0.77	--
	+SA 1.25	2.127 ± 0.218	35.56	30.30–41.83	1.48	0.48	1.12
	+SA 2.5	2.205 ± 0.412	31.75	26.86–37.53	0.35	0.84	1.25
	+PAM 0.08	3.681 ± 0.462	32.79	29.19–37.19	0.10	0.80	1.21
	+PAM 0.31	3.801 ± 0.472	27.40	24.06–31.32	1.53	0.22	1.45

Table 3. Toxicity of formulated insecticides with the adjuvants sodium alginate (SA) and polyacrylamide (PAM) against *P. guildinii* adults 48 h after application.

Compounds	Population	Slope	LC_{50} (µg/mL)	95% Confidence Limits (µg/mL)	χ^2	*p*	ER
Bifenthrin (F)	alone	2.321 ± 0.413	26.36	21.28–33.71	0.07	0.79	--
	+SA 1.25	2.560 ± 0.392	32.15	26.84–40.66	0.86	0.35	0.82
	+SA 2.5	2.369 ± 0.401	40.53	32.64–56.87	1.43	0.23	0.65
	+PAM 0.08	2.361 ± 0.369	22.54	18.79–27.56	0.10	0.75	1.17
	+PAM 0.31	1.552 ± 0.355	19.65	15.73–35.65	1.39	0.24	1.34
Imidacloprid (F)	alone	1.871 ± 0.356	25.54	18.76–38.70	0.38	0.84	--
	+SA1.25	2.450 ± 0.452	20.63	15.81–25.88	0.38	0.54	1.24
	+SA 2.5	2.481 ± 0.441	30.59	24.60–39.70	0.90	0.34	0.80
	+PAM 0.08	1.996 ± 0.411	20.61	15.19–26.95	0.04	0.85	1.23
	+PAM 0.31	2.463 ± 0.434	22.31	17.63–28.09	1.04	0.31	1.14

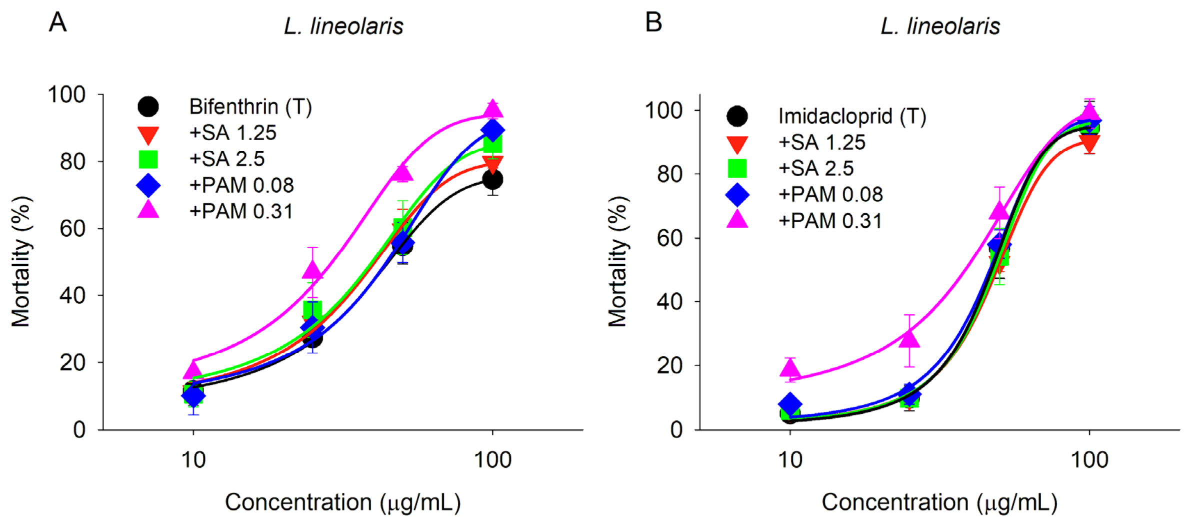

Figure 1. Mortality (%) of the population of adult *Lygus lineolaris* following treatment with technical-grade bifenthrin (**A**) or imidacloprid (**B**) alone or combined with 1.25 and 2.5 g/L sodium alginate (SA) and/or 0.08 and 0.31 mg/L polyacrylamide (PAM) adjuvant solutions 48 h after application. The data were fitted using a sigmoidal curve with SigmaPlot 15.0 software.

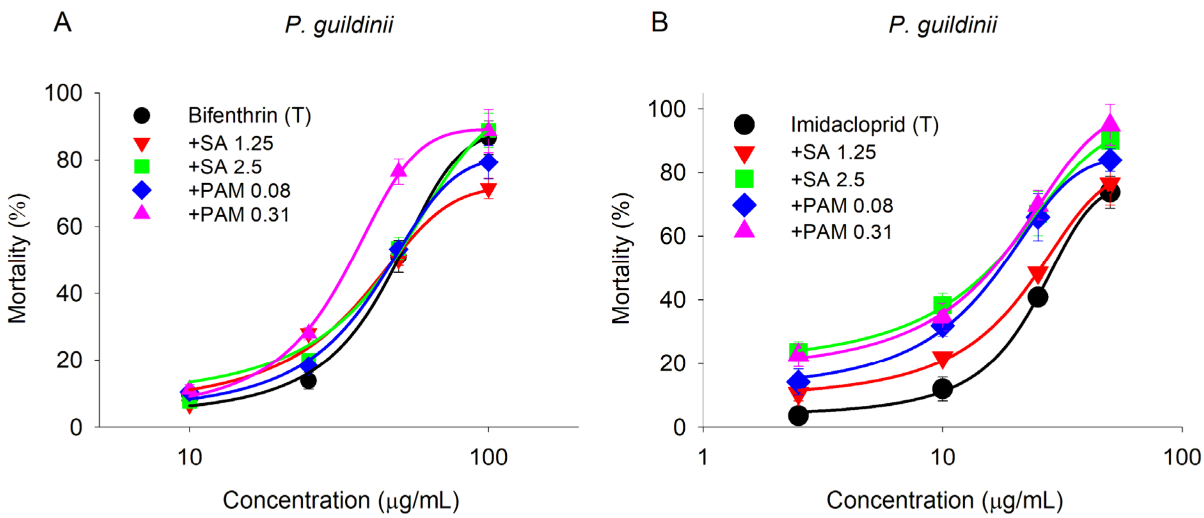

Figure 2. Mortality (%) of the population of adult *Piezodorus guildinii* following treatment with technical-grade bifenthrin (**A**) or imidacloprid (**B**) alone or combined with 1.25 and 2.5 g/L sodium alginate (SA) and/or 0.08 and 0.31 mg/L polyacrylamide (PAM) adjuvant solutions 48 h after application. The data were fitted using a sigmoidal curve with SigmaPlot 15.0 software.

Table 4. Toxicity of technical-grade insecticides with the adjuvants sodium alginate (SA) and polyacrylamide (PAM) against *P. guildinii* adults 48 h after application.

Compounds	Population	Slope	LC_{50} (μg/mL)	95% Confidence Limits (μg/mL)	χ^2	*p*	ER
Bifenthrin (T)	alone	3.488 ± 0.442	48.55	42.53–56.72	0.02	0.89	--
	+SA1.25	3.164 ± 0.470	43.63	37.12–51.63	0.43	0.51	1.11
	+SA 2.5	3.206 ± 0.441	43.93	38.07–51.68	0.36	0.55	1.10
	+PAM 0.08	2.642 ± 0.412	47.45	39.54–57.08	0.24	0.63	1.03
	+PAM 0.31	2.278 ± 0.341	28.60	22.35–35.29	2.91	0.23	1.70
Imidacloprid (T)	alone	1.474 ± 0.212	39.70	31.24–51.28	0.53	0.77	--
	+SA 1.25	1.274 ± 0.388	26.86	17.45–44.66	1.00	0.32	1.48
	+SA 2.5	1.670 ± 0.396	14.78	8.63–20.16	0.19	0.66	2.68
	+PAM 0.08	3.092 ± 0.449	22.04	18.19–26.35	0.95	0.33	1.80
	+PAM 0.31	2.032 ± 0.421	14.51	9.57–19.00	0.48	0.49	2.73

4. Discussion

In this study, we investigated the impact of two hydrocolloid polymer adjuvants, SA and PAM, in combination with technical-grade or formulated bifenthrin and imidacloprid on *P. guildinii* and *L. lineolaris*. PAM significantly improved the efficiency of technical-grade bifenthrin and imidacloprid, while SA specifically enhanced the efficiency of imidacloprid at high concentrations against *P. guildinii*. Furthermore, both SA and PAM at high concentrations effectively enhanced the effectiveness of technical-grade bifenthrin and imidacloprid for *L. lineolaris*. However, no significant enhancement was observed with any formulated insecticide for SA or PAM in either *L. lineolaris* or *P. guildinii*. This disparity in formulation may explain the results. Compared with formulated insecticides, which are mixtures containing additional components such as solvents or stabilizers for application readiness, technical-grade insecticides are characterized by their purity and high concentration of active ingredients (imidacloprid (purity 98.3%) and bifenthrin (purity 98.0%)). In this study, the percentage of active ingredients in formulated bifenthrin and imidacloprid were only 25.1% (Tundra ®EC) and 40.7% (Advise Four), respectively. Previous studies have utilized hydrocolloid polymer adjuvants for various purposes in pest management. SA has been employed as a hydrophilic pesticide carrier to enhance the insecticidal efficacy of phloxine B [46]. Additionally, a combination of SA, PAM, and montmorillonite (MMT) has been used to create a stretchable double-network nanocomposite hydrogel for the sustained release of acetamiprid for pest control [47]. Moreover, a PAM hydrogel matrix has been explored for developing a novel liquid delivery system targeting pest ant species attracted to sugary liquids. Thiamethoxam was successfully absorbed into the interior of the PAM matrix, suggesting that the PAM hydrogel has potential as a cost-effective alternative for controlling Argentine ants [48]. Several studies have highlighted the synergistic application of hydrocolloid polymer adjuvants and pesticides in pest management across various insect pests, including mosquito larvae [49], Argentine ants [50], and Ambrosia beetles [51].

A comparison between SA and PAM revealed similar improvements in the efficacy of imidacloprid against *P. guildinii*. However, the high concentration of PAM significantly augmented the efficacy of bifenthrin by 1.70-fold, whereas no enhancement effect was observed for the SA–bifenthrin combination in *P. guildinii*. In *L. lineolaris*, only the combinations of high concentrations of PAM with bifenthrin or imidacloprid exhibited synergistic interactions, with no effect observed for SA. The quantification of drift reduction due to formulation and adjuvant type, as emphasized by Oliveira et al. [13], suggested that the formulation type influences the efficacy of adjuvant–pesticide combinations. While the SA/PAM–imidacloprid combination displayed high synergy, high-concentration PAM showed less synergistic effects on bifenthrin in *P. guildinii*. Furthermore, SA and PAM exhibited different enhancement efficiencies in *P. guildinii* compared to *L. lineolaris*. The varying effects of bifenthrin and imidacloprid on *L. lineolaris* and *P. guildinii* indicated species-specific responses.

Adjuvant products generally do not exhibit any pesticidal activity, and neither of the hydrocolloid polymer adjuvants (SA or PAM) at the two concentrations induced any mortality on their own in either *P. guildinii* or *L. lineolaris*. However, their interaction with technical-grade bifenthrin or imidacloprid demonstrated enhanced efficacy. The mechanisms underlying this synergy are not fully understood. The conventional expectation is that pesticide and adjuvant combinations in a tank mix would show additive toxicity without chemical interaction. However, the adjuvant–pesticide combinations exhibited synergistic interactions, surpassing what was predicted by concentration addition [52]. SA or PAM hydrogels act as hydrophilic polymeric media with polymeric chains, allowing for the absorption of a large amount of liquid [53]. Some adjuvants improve pesticide performance through better absorption, while others enhance spray qualities by modifying the physical properties of the spray solution [13]. SA composites have been reported to have promising adsorption potential, suggesting their use in wastewater containing imidacloprid [54]. Additionally, drug carriers based on SA have been reported to improve the solubility of hydrophobic drugs [55,56] and inhibit the photodegradation of active compounds such as imidacloprid [57]. Adjuvants may also enhance permeability through insect cuticular waxes, similar to mechanisms allowing for increased ion permeability through the leaf cuticle [58]. The cuticular waxes between *P. guildinii* and *L. lineolaris* may differ. On the other hand, considering spray application, using a spray tower with SA/PAM–insecticide composition may impact droplet size. The size of droplets influences their behavior during application; larger droplets may fail to penetrate obstacles, while very small droplets may not deposit effectively on the target insect [59]. While antagonistic effects are possible with adjuvant–pesticide combinations [52], no significant antagonistic effects of SA or PAM were observed in *P. guildinii* and *L. lineolaris*.

Adjuvants can be incorporated into pesticide formulations or added separately to pesticide tank mixes, each serving specific enhancement purposes [13]. Different techniques, such as encapsulation, coacervation, electrostatic gelation, matrix embedding, and hydrogel formulation, can be employed. The bioencapsulation of pesticides, through methods such as using a cholesteryl-grafted SA derivative in the presence of Ca^{2+}, has proven effective in creating self-assembled nanoparticles encapsulating acetamiprid [10]. Alginate–gelatin hydrogel beads offer an effective alternative for extended mosquito attraction and control [52]. The incorporation of liquid bait with hydrogel PAM matrices can significantly reduce pesticide use while ensuring effective control [48]. Nanocomposite hydrogels containing SA, PAM, and 5.0% MMT exhibited a maximum acetamiprid loading rate of 13.32% and a minimum pesticide release rate of 76.11% [47]. In recent years, the application of nanotechnology in agriculture has shown significant potential for developing innovative insecticide formulations. Nanoencapsulation provides advantages such as safer handling, more efficient pesticide use, and reduced environmental exposure. In insect control, nanotechnology addresses specific agricultural challenges in plant–pest interactions, providing novel approaches for crop protection. For example, the delivery of the pesticide imidacloprid (Admire), an SA nanoparticle nanoformulation, to plants represents a novel technology for improving crop yield and safety [60].

This study demonstrated that SA and PAM serve as sustainable and effective carriers of technical-grade pyrethroid and neonicotinoid insecticides used for the economically significant insect pests *P. guildinii* and *L. lineolaris*. This approach offers a promising alternative to conventional formulations, presenting an innovative solution to improve pest management practices. However, the observed increase in insecticide efficiency is specific to the evaluated combinations, and additional factors influencing spray efficacy need to be considered in field applications. The comprehensive testing of various spray mixtures is necessary before defining reference sprays for comparing and rating drift reduction treatments. Similar to the adoption of adjuvants, the adoption of improved and safer application technologies can reduce pesticide waste, protect farmers, enhance the economics of pest control, and promote environmental and ethical practices.

5. Conclusions

Two hydrocolloid polymer adjuvants, sodium alginate (SA) and polyacrylamide (PAM), enhanced the efficacy of two technical-grade insecticides against *L. lineolaris* or *P. guildinii*. However, no significant effects were observed with any SA or PAM in combination with formulated insecticide. High concentrations of PAM exhibited significant synergistic effects with technical-grade bifenthrin or imidacloprid on either *P. guildinii* or *L. lineolaris*. In particular, PAM improved the efficiency of technical-grade imidacloprid by up to 2.72-fold in *P. guildinii*. In contrast, a high concentration of SA also had a 2.68-fold synergistic effect on technical-grade imidacloprid in *P. guildinii*, while no enhancement effect was observed for the SA–technical-grade bifenthrin or imidacloprid combination in *L. lineolaris*.

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