

ENTOMOLOGY

Enhanced nymphal mortality of the invasive rugose spiraling whitefly, *Aleurodicus rugioperculatus* Martin (Hemiptera: Aleyrodidae) through separate and tank-mix applications of insecticides with additivesMd. Shariful Islam,¹ Gopal Das,² Mohammad Mahir Uddin,¹ Mst. Rokeya Khatun,¹ Md. Shohel Rana,¹ Akibul Islam Tusar,¹ Md. Sajibul Islam¹¹Department of Entomology, Bangladesh Agricultural University, Mymensingh; ²Insect Pest Control Laboratory, Department of Entomology, Bangladesh Agricultural University, Mymensingh, Bangladesh**Abstract**

The rugose spiraling whitefly, *Aleurodicus rugioperculatus* Martin, has recently emerged as a major invasive pest in Bangladesh, causing severe damage to coconut and a variety of fruit, vegetable, and ornamental crops. The nymphs, particularly the second to fourth instars, are covered with thick waxy secretions and cottony filaments, which reduce insecticide penetration and efficacy. This study evaluated five insecticides applied alone or in combination with two additives, Surf Excel Matic Liquid (SEML) and potassium salts of fatty acids (PSFA), using both direct tank-mix and post-application approaches. Factorial analysis revealed that the main effects of insecticide, additive, and application method were significant, whereas their interactions were not, indicating that each factor independently influenced nymphal mortality. Insecticides applied alone provided limited control, whereas inclusion of additives significantly enhanced mortality, with PSFA consistently outperforming SEML. Post-application resulted in slightly higher nymphal suppression, but direct tank mixing of PSFA with insecticides offers a more practical and efficient field strategy. These findings suggest that additives can substantially improve insecticide efficacy, potentially by altering cuticular properties or increasing uptake. While results were obtained under controlled laboratory conditions, environmental factors such as rainfall, UV degradation, and spray coverage may influence performance in the field, and further studies under diverse agroecological conditions are warranted to validate the practical efficiency of additive-insecticide combinations in integrated pest management programs.

Key words: rugose spiraling whitefly, nymph, wax, barrier, insecticides, additives, mortality.

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Introduction

The rugose spiraling whitefly (RSW), *Aleurodicus rugioperculatus* Martin (Hemiptera: Aleyrodidae), is an invasive pest that has recently emerged as a serious threat to agricultural production in Bangladesh and other regions worldwide (Martin, 2004; Shanas *et al.*, 2016; Das *et al.*, 2023). First reported in Belize in 2004, the species rapidly expanded its range, reaching Florida by 2009 (Gonzalez *et al.*, 2013). Its broad host range, high ecological adaptability, and characteristic spiral egg-laying pattern have facilitated successful establishment across diverse agroecosystems. In South Asia, RSW was first recorded in India in 2016, where severe infestations in coconut and oil palm plantations caused substantial economic losses (Shanas *et al.*, 2016; Selvaraj *et al.*, 2017; Sundararaj & Selvaraj, 2017). The pest was subsequently detected in Bangladesh in 2019, raising concerns

for crop productivity, food security, and farmer livelihoods (Dutta *et al.*, 2019). By feeding on phloem sap, RSW weakens host plants and produces honeydew, which promotes sooty mold growth and reduces photosynthetic activity, ultimately decreasing crop yield.

Since its introduction, RSW infestations in Bangladesh have expanded rapidly, affecting a wide range of host crops (Das *et al.*, 2023; Khan, 2023; Swarnaa *et al.*, 2023). Despite its economic significance, no insecticide has been officially recommended for RSW management, prompting farmers to rely on repeated applications of broad-spectrum pesticides. Such practices increase production costs, threaten environmental safety, and disrupt beneficial arthropod populations, often leading to secondary pest outbreaks (Elango *et al.*, 2019; Pradhan *et al.*, 2020; Saranya *et al.*, 2021). Control of immature stages, particularly the second to fourth nymphal instars, remains challenging because they are covered by dense waxy secretions and cottony

filaments, which hinder insecticide penetration (Taravati *et al.*, 2016; Elango *et al.*, 2019; Ullah *et al.*, 2021). Only the first instar (crawler stage) lacks this wax layer, and from the second instar onward, progressive deposition of wax forms a protective barrier that reduces contact toxicity, limiting nymphal mortality (Kovářiková *et al.*, 2017; Fernández-Grandon *et al.*, 2020; Pradhan *et al.*, 2020; Paz *et al.*, 2021). Consequently, repeated insecticide applications often fail to achieve consistent suppression of RSW nymphs in coconut and other crops (Jethva *et al.*, 2020; Pradhan *et al.*, 2020; Khan, 2023).

Additives such as surfactants and horticultural soaps have the potential to enhance insecticide efficacy by disrupting wax layers and improving cuticular penetration. Potassium salt of fatty acids (PSFA) and commercial laundry detergents [*e.g.*, Surf Excel Matic Liquid (SEML)] are widely available in Bangladesh and may offer practical solutions for smallholder farmers. While these strategies have been explored in other systems, the combined application of insecticides with PSFA or SEML against wax-coated nymphs of RSW has not yet been investigated in Bangladesh.

The present study, therefore, aimed to evaluate the efficacy of five insecticides applied alone or in combination with two additives (PSFA and SEML) against nymphal stages of *A. rugiperculatus* under controlled laboratory conditions. Two application approaches, direct tank mixing and post-application treatment, were compared to assess their relative effectiveness. We hypothesized that (i) the inclusion of PSFA or SEML would significantly enhance insecticide-induced nymphal mortality, and (ii) the method of application would influence control efficacy. While the study was conducted under laboratory conditions, field factors such as environmental variability, UV degradation, rainfall, and spray coverage may influence additive-insecticide performance. Findings from this study are intended to provide practical insights for developing cost-effective and environmentally sustainable strategies for managing RSW infestations in Bangladesh, thereby supporting crop productivity, farmer livelihoods, and the adoption of integrated pest management practices under real-field conditions.

Materials and Methods

Study period

The present study was conducted under laboratory conditions in the Department of Entomology, Bangladesh Agricultural University, Mymensingh, from January 2024 to March 2025, to evaluate potential management strategies against the nymphal stages of the RSW (*Aleurodicus rugiperculatus* Martin).

Collection and preparation of host plants

The experiment was conducted on 1-year-old native coconut saplings (*Cocos nucifera* L.). Healthy, insect-free saplings were collected from the Government Horticulture Center and kept outside the experimental room for 1 month to recover from transport-related stress (Figure 1A). The saplings were then transplanted into plastic pots containing a mixture of soil, cow dung, and appropriate amounts of triple super phosphate, muriate of potash, and oil cake. After transplantation, the saplings were maintained inside the experimental room for an additional 2 weeks to acclimate to laboratory conditions before the start of the experiment.

Mass rearing of rugose spiraling whitefly

Adult RSWs were initially collected along with infested leaflets from coconut plants at Bangladesh Agricultural University (24.7196°N, 90.4267°E), Mymensingh, Bangladesh. Approximately 200 adults, confirming both males and females, were carefully transferred onto previously prepared coconut saplings using a soft camel hairbrush and enclosed in a mosquito-net cage (4×4×4 ft) (Figure 1B). After mating, females began oviposition (Figure 1C and D) and a full generation was completed in 35-37 days under room conditions (temperature: 28.5±0.21°C; relative humidity: 78.3±1.4%; photoperiod: 16:8 h, D:L). The RSW population was maintained for several generations, and the resulting nymphs were subsequently used in the experiments.

Tested additives and insecticides

The following additives and pesticides were evaluated against the nymphs of RSW. Treatments 1 and 2 are additives, while treatments 3 to 7 are insecticides (Table 1). Insecticide doses were applied according to the manufacturer's label recommendations. For additives, a preliminary pilot experiment was conducted using three concentrations, and the most effective concentration was selected for use in the main experiments.

Additives used in this experiment

SEML: the detergent used was SEML (Unilever Company Ltd., Bangladesh), a household laundry detergent. Its main active ingredient is sodium dodecyl benzene sulphonate. The liquid detergent was applied at a concentration of 2.0 mL/L. This detergent was selected because it is widely available to farmers in Bangladesh, inexpensive, and can be easily adopted in practical pest management, unlike laboratory-grade detergents such as sodium dodecyl sulfate or Tween, which are less accessible.

Potassium salts of fatty acids (Fytoclean)

PSFA, commonly known as horticultural soaps, act as biodegradable insecticidal surfactants. They disrupt the protective waxy cuticle of soft-bodied insects, including the nymphs of whiteflies, causing desiccation and cellular dehydration. By softening the epicuticular wax and reducing the insect's ability to retain water, these compounds enhance the penetration and efficacy of applied insecticides (Russell IPM Ltd., Deeside, United Kingdom).

Laboratory experiment

All experiments were conducted under laboratory conditions. The study followed a completely randomized design, with treatments randomly assigned to experimental units to minimize the influence of uncontrolled variation. Each treatment was replicated five times. To avoid cross-contamination from insecticides, control experiments were carried out with particular care. Tank-mix applications were prepared by combining either normal detergent or Fytoclean with each of the five selected insecticides and applied to the nymphs. Because tank-mix applications can potentially cause insecticide incompatibility or phytotoxicity, an additional set of treatments was included in which the insecticides were applied 6 hours after the application of either detergent or Fytoclean. Preliminary observations indicated that applications made three hours after additive treatment did not yield notable effects, suggesting that a longer interval is necessary for the additives to soften the waxy layer covering the nymphs and thereby enhance insecticide penetration.

Treatment application method

In all laboratory bioassays, each nymph (or egg) was considered an experimental unit, with 10 individuals per replicate. Treatments were applied using a micropipette (Eppendorf, Hamburg, Germany)

at a defined volume of 50 μL per nymph. This volume was selected to ensure accurate and complete coverage of each nymph without runoff while avoiding disturbance to the cottony structures that could displace the organisms. A micropipette was used instead of a

Table 1. List of additives and insecticides with their active ingredients, trade names, and concentrations.

Treatments	Trade name with concentrations	Active ingredient
T1	Surf Excel Matic Liquid @ 2.0 mL/L water	Sodium dodecyl benzene sulphonate
T2	Fytoclean @ 5.0 mL/L water	Potassium salt of fatty acid
T3	Fizimite @ 1.0 mL/L water	Polyoxyethylene 10 lauryl ether
T4	Gladius 10 SC @ 2.0 mL/L water	Flometoquin
T5	Fytomax @ 2.0 mL/L water	Azadirachtin 0.2%
T6	Torit 80WDG @ 0.50 g/L water	Nitenpyrum + pymetrozine
T7	Movento 240 SC@ 1.0 mL/L water	Spirotetramat
T8	Untreated control	Only water

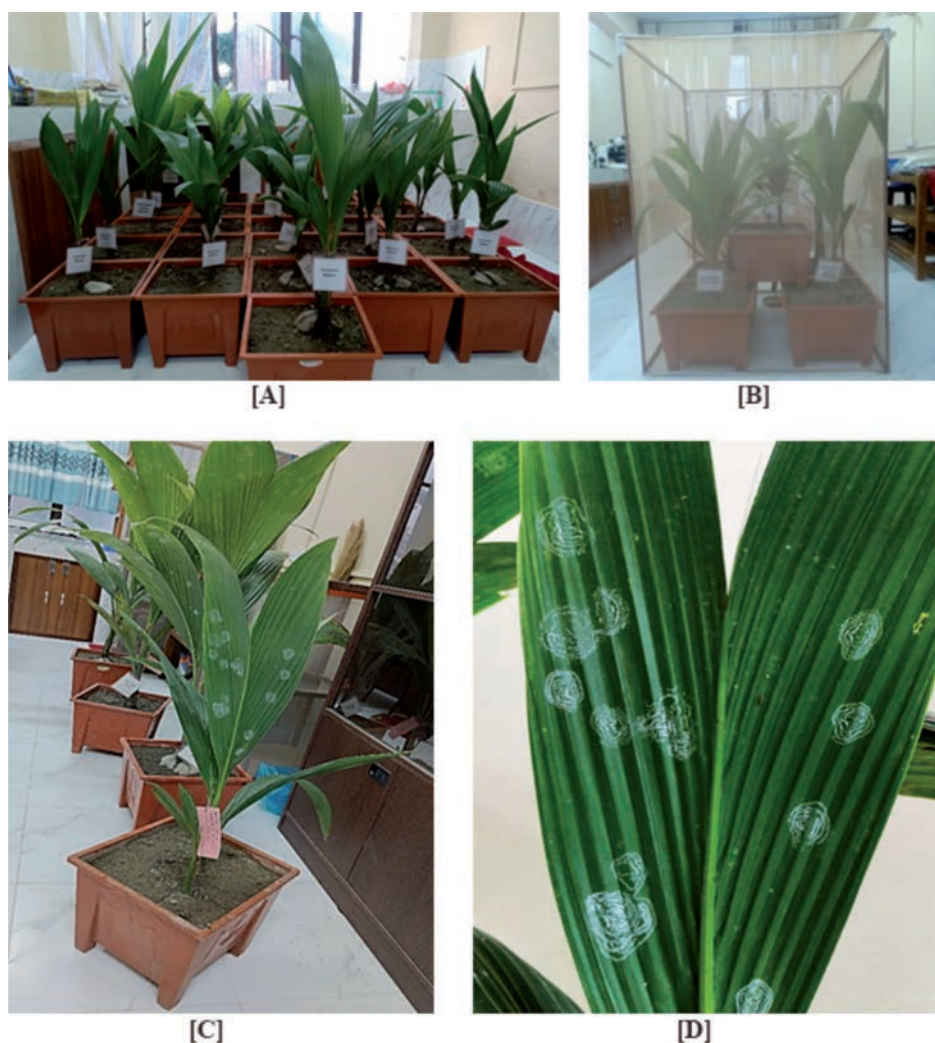


Figure 1. Management of host plants (A), adult release in the net cage (B), egg spirals laid on the ventral surface of the coconut leaf (C), and a large image of egg spirals (D).

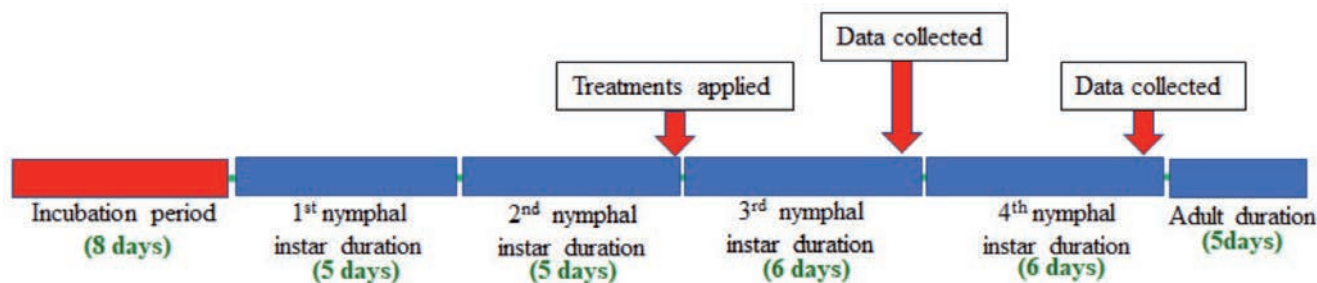


Figure 2. Treatment application protocol.

conventional sprayer to provide precise and controlled application directly onto individual nymphs, ensuring consistent exposure and uniform contact. This approach minimized experimental artifacts and enhanced the reproducibility and reliability of the laboratory bioassay.

Treatment application protocol and data collection schedule

The treatment application protocol and data collection schedule are shown in Figure 2. At 28-30°C, the total life cycle of *A. rugioperculatus* is completed within approximately 35-37 days. The first nymphal instar is wax-free and transparent (Figure 3A), which allows insecticides to penetrate easily through the cuticle; therefore, this stage was excluded from the study. The production of wax and cottony filaments begins at the second instar and becomes progressively denser from the third instar onward (Figure 3B). Consequently, the timing of insecticide application was considered critical, and the total life cycle duration was carefully evaluated. Since a dense wax layer develops by the end of the second instar, all treatments were applied at this stage. The end of the second instar was confirmed by nymphal size, the presence of cottony filaments, and increased wax thickness, as observed under a zoom stereomicroscope (AmScope, Model: SM-1TSZZ-144S-10M, United Scope LLC, Irvine, CA, USA). After treatment application, nymphs were examined under the microscope at regular intervals, and mortality data were recorded on the 5th and 10th day post-treatment. Control treatments followed the same protocol.

Assessment of eggs and nymphal mortality

Five coconut saplings were selected for each experiment. From each sapling, one spiral containing clearly visible nymphs was chosen, and 10 nymphs (or eggs) were randomly selected per spiral ($n=10$). Treatments were applied as described previously using a micropipette (Eppendorf, Hamburg, Germany) at a volume of 50 μ L per individual. Mortality was recorded at 5 or 10 days after treatment (DAT) application under a zoom stereomicroscope. Percent mortality for each replicate was calculated as the number of dead individuals divided by the total number treated, multiplied by 100. The same procedure was repeated for all saplings, and mean values were obtained for each treatment. This protocol was consistently applied across all experiments.

Microscopic observation

Nymphal mortality was determined by the complete absence of movement following gentle probing and a lack of response to tactile or visual stimuli, ensuring reliable discrimination between live and

dead individuals. Microscopic observations further confirmed mortality through distinct morphological changes, including body darkening and disruption of waxy secretions or cottony filaments (Figure 4B, red circled). In contrast, healthy or untreated nymphs maintained their natural coloration with intact wax layers and filamentous coverings (Figure 4A).

Statistical analysis

Mortality data were first corrected using Abbott's formula (Abbott, 1925). The corrected data were examined for normality of

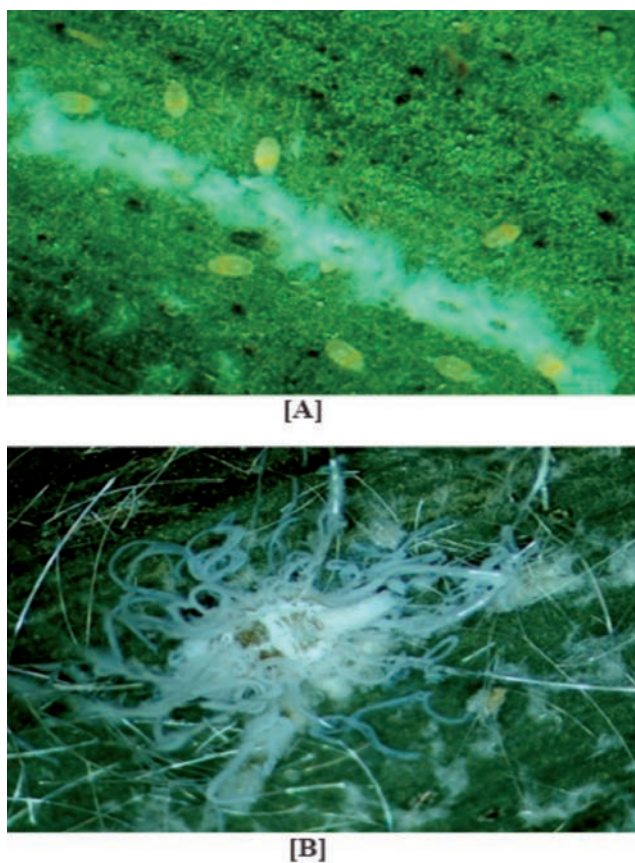


Figure 3. First (A) and 4th instar nymph (B). First instar nymph is known as a crawler and waxless or transparent, while the 4th instar nymph is densely waxed along with cottony filaments.

residuals using the Shapiro-Wilk test and for homogeneity of variances using Levene's test. Data meeting these assumptions were analyzed using a three-way factorial analysis of variance (ANOVA) to evaluate the effects of insecticide, additive, and application method, as well as their interactions, on nymphal mortality. When significant effects were detected, treatment means were compared using Tukey's honestly significant difference test) at $p \leq 0.05$. All analyses were conducted using R software (version 4.3.1).

Results

Efficacy of Surf Excel Matic Liquid and potassium salt of fatty acids on the mortality of nymphs of rugose spiraling whitefly

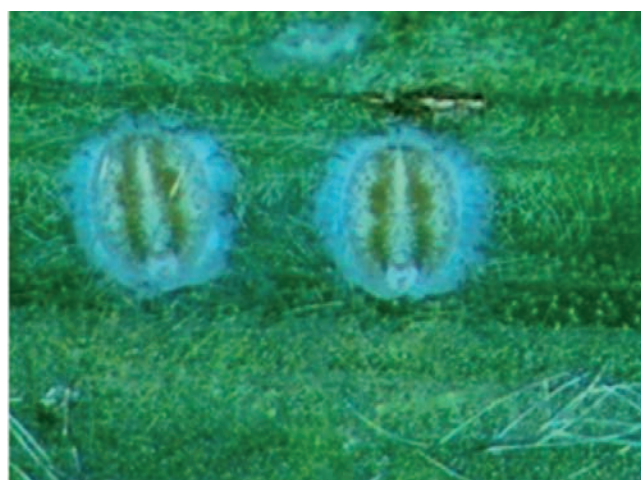
SEML and PSFA significantly increased nymphal mortality of RSW compared to the untreated control ($F_{2,12}=188.2$, $p < 0.01$; Figure 5). A significant difference was also observed between the two treatments (SEML vs. PSFA; post-hoc test $p < 0.05$). Mortality in the

water-treated control ranged from 1.56% to 2.2%. SEML resulted in 8.77% mortality at 5 DAT with no significant change observed up to 10 DAT (10.71%). PSFA caused 17.05% mortality at 5 DAT, and this level similarly remained statistically unchanged at 10 DAT (18.36%).

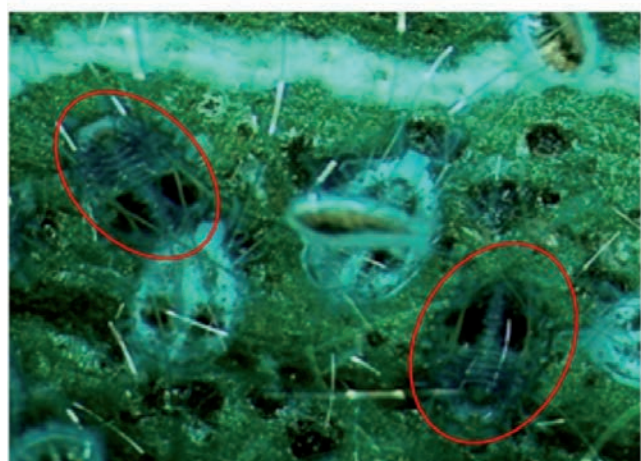
Efficacy of selected insecticides on the mortality of rugose spiraling whitefly nymphs

All insecticidal treatments induced significantly higher mortality of RSW nymphs compared to the control ($F_{5,24}=473.84$, $p < 0.001$; Table 2), with distinct variation in their efficacy. At 5 DAT, corrected mortality ranged from 20.22% with Movento 240 SC to 37.79% with Torit 80 WDG, whereas the control caused only 2.90%. By 10 DAT, Torit 80 WDG consistently exhibited the highest mortality (49.55%), followed by Gladius 10 SC (44.50%) and Fizimite (39.80%), while Movento 240 SC remained the least effective (24.77%) compared to 3.60% in the control.

Table 3 shows that the efficacy of insecticides against RSW



[A]



[B]

Figure 4. A) Untreated or fresh nymph; B) dead nymphs with red encircled.

Table 2. Efficacy of five insecticides on the mortality of rugose spiraling whitefly nymphs.

Treatments	Corrected mortality (% \pm standard error)	
	5 DAT	10 DAT
Fizimite @ 1.0 mL/L	28.41 \pm 2.31 ^b	39.80 \pm 4.02 ^c
Gladius 10 SC @ 2.0 mL/L	31.52 \pm 2.24 ^b	44.50 \pm 3.41 ^b
Fytomax @ 2.0 mL/L	29.32 \pm 3.30 ^c	36.56 \pm 2.31 ^c
Torit 80WDG @ 0.50 g/L	37.79 \pm 3.51 ^a	49.55 \pm 3.30 ^a
Movento 240 SC@ 1.0 mL/L	20.22 \pm 2.11 ^d	24.77 \pm 2.61 ^d
Level of significance	$p < 0.01$	$p < 0.01$
CV%	13.60	16.18

Values represent means \pm standard error (n=10). Within each column, means followed by different letters are significantly different (Tukey's honestly significant difference test, $p < 0.05$). DAT, days after treatment; CV, coefficient of variation.

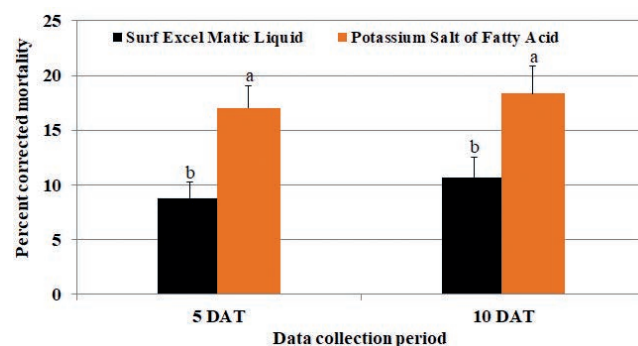


Figure 5. Percent corrected mortality (means \pm standard error) of nymphs following treatment with Surf Excel Matic Liquid and potassium salt of fatty acid (n=10 nymphs/replicate). At each day after treatment (DAT), means followed by different letters are significantly different (Tukey's honestly significant difference test, $p < 0.05$).

nymphs varied considerably depending on the additive and application method. Overall, both factors influenced insecticidal performance, with PSFA consistently enhancing mortality compared with the SEML or treatments without additives. Among the tested insecticides, Torit 70 WDG showed the highest efficacy across treatments. The highest mortality (77.7±1.46%) was recorded when Torit 70 WDG was combined with PSFA using the post-application method, which was statistically similar to PSFA applied through direct mixing (75.0±2.89%). Mortality decreased when SEML was used as an additive (61.5-65.0%) and was lowest without additives (52.5-55.0%). A similar pattern was also observed for Gladius 10 SC, where PSFA treatments resulted in the highest mortality (63.5-

67.3%), followed by SEML (56.3-58.5%), while treatments without additives produced the lowest mortality (46.2-47.4%).

Moderate mortality levels were recorded for Fizimite and Fytomax. For both insecticides, PSFA treatments produced the highest mortality (52.5-57.9%), whereas SEML and no-additive treatments resulted in comparatively lower mortality (40.0-45.5%). In contrast, Movento 240 SC exhibited the lowest efficacy, with mortality ranging from 22.2±1.85% to 30.0±2.31% across all treatments (Table 3). Most combinations involving PSFA or SEML were statistically similar, while the lowest mortality occurred when Movento 240 SC was applied without additives through direct mixing.

Table 4 presents the results of the three-way factorial ANOVA

Table 3. Main and interaction effects of insecticides, additives, and application methods on the mortality (%) of nymphs of rugose spiraling whitefly.

Insecticide	Additive	Method	% mortality (mean ± standard error)	Tukey's HSD
Torit 70 WDG	PSFA	Post application	77.7±1.46	a
	PSFA	Direct mixing	75.0±2.89	ab
	SEML	Post application	65.0±1.73	cd
	SEML	Direct mixing	61.5±0.87	de
	None	Post application	55.0±1.53	fg
	None	Direct mixing	52.5±1.04	g
Gladius 10 SC	PSFA	Post application	67.3±4.33	bc
	PSFA	Direct mixing	63.5±1.25	cd
	SEML	Post application	58.5±2.02	ef
	SEML	Direct mixing	56.3±1.20	ef
	None	Post application	47.4±2.65	hi
	None	Direct mixing	46.2±0.61	hi
Fizimite	PSFA	Post application	57.9±2.25	ef
	PSFA	Direct mixing	56.5±2.11	fg
	SEML	Post application	45.5±2.60	ij
	SEML	Direct mixing	41.37±0.32	j
	None	Post application	42.2±1.85	jk
	None	Direct mixing	41.4±1.39	jk
Fytomax	PSFA	Post application	57.2±3.57	ef
	PSFA	Direct mixing	52.5±1.44	gh
	SEML	Post application	45.0±2.31	ij
	SEML	Direct mixing	41.0±1.73	j
	None	Post application	41.2±1.85	jk
	None	Direct mixing	40.0±1.15	jk
Movento 240 SC	PSFA	Post application	30.0±2.31	kl
	PSFA	Direct mixing	29.0±2.00	kl
	SEML	Post application	29.0±3.27	kl
	SEML	Direct mixing	28.4±3.10	kl
	None	Post application	29.0±1.15	kl
	None	Direct mixing	22.2±1.85	l

Values represent means ± standard error (n=10). Means followed by different letters are significantly different (Tukey's honestly significant difference test, p<0.05). Data were collected at 10-day intervals. PSFA, potassium salt of fatty acid; SEML, Surf Excel Matic Liquid; HSD, honestly significant difference.

Table 4. Three-way analysis of variance for the effects of insecticide, additive, and application method on nymphal mortality (%).

Source of variation	df	Sum of squares	Mean square	F	p
Insecticide (I)	4	13471.25	3367.81	316.76	<0.001
Additive (A)	2	3433.19	1716.6	161.45	<0.001
Method (M)	1	164.57	164.57	15.48	<0.001
I×A	8	763.03	95.38	8.97	<0.001
I×M	4	3.78	0.95	0.09	0.986
A×M	2	0.57	0.28	0.03	0.974
I×A×M	8	61.46	7.68	0.72	0.671

df, degrees of freedom.

examining the effects of insecticide, additive, and application method on the mortality of RSW nymphs. The analysis revealed that insecticide, additive, and application method all had significant effects on mortality. Among the main factors, insecticide showed the strongest effect ($F=316.76$, $p<0.001$), followed by additive ($F=161.45$, $p<0.001$), while application method also had a significant but comparatively smaller effect ($F=15.48$, $p<0.001$). A significant interaction between insecticide and additive ($I\times A$) was found ($F=8.97$, $p<0.001$), indicating that the effectiveness of additives varied depending on the insecticide used. However, the insecticide \times method ($I\times M$) interaction was not significant ($F=0.09$, $p=0.986$), suggesting that the relative efficacy of insecticides was consistent across application methods. Likewise, the additive \times method ($A\times M$) interaction was not significant ($F=0.03$, $p=0.974$). The three-way interaction among insecticide, additive, and application method ($I\times A\times M$) was also non-significant ($F=0.72$, $p=0.671$).

Discussion

As the RSW is an invasive pest in Bangladesh, effective management strategies are still not well established. In particular, control measures based on chemical insecticides remain poorly studied under local conditions. Thus, coconut farmers in Bangladesh often apply different broad-spectrum insecticides indiscriminately to manage RSW infestations; however, the results are often unsatisfactory. So far, only a few scattered studies have investigated insecticide-based control strategies against this pest in the country (Khan, 2023; Dutta *et al.*, 2025; Rahman *et al.*, 2025).

The RSW is a hemipteran insect pest that undergoes three developmental stages: egg, nymph, and adult (Elango *et al.*, 2019; Das *et al.*, 2023). Adult whiteflies are relatively weak fliers and typically remain on the abaxial (underside) surface of leaves (Pradhan *et al.*, 2020). Insecticides are generally more effective against the adult stage, and both contact and systemic insecticides can provide satisfactory suppression of adult populations (Kumara *et al.*, 2015; Khan, 2023; Naik *et al.*, 2024). However, effective management of the nymphal stages remains a major challenge. The nymphs are protected by dense cottony secretions and a thick waxy layer that can limit the penetration of insecticides to the target sites within the insect body. Consequently, despite repeated insecticide applications, a substantial proportion of nymphs often survive due to their protective waxy covering and cottony secretions, later emerging as adults and sustaining high population levels in the treated fields.

To address this challenge, the efficacy of five insecticides with different modes of action was evaluated against the nymphs of the RSW in combination with two additives and two application methods. A three-way factorial analysis revealed that insecticide type, additive, and application method significantly influenced nymphal mortality. Both the main effects and their interactions contributed to variations in mortality, indicating that the performance of insecticides can be enhanced depending on the additive used and the method of application. These findings demonstrate that integrating suitable additives with insecticides can improve the overall effectiveness of chemical control strategies against this invasive pest.

In the present study, the combined formulation of pymetrozine and nitenpyram (Torit 70 WDG) produced approximately 50% nymphal mortality. This mortality increased significantly to nearly 75% with the addition of PSFA under direct mixing and to about 78% under the post-application approach. In contrast, the addition of SEML resulted in comparatively lower mortality, reaching approxi-

mately 62% and 65% under direct mixing and post-application, respectively. Pymetrozine primarily acts through ingestion with limited cuticular penetration, so additives have minimal effect on its efficacy (He *et al.*, 2011; Liu *et al.*, 2025). In contrast, nitenpyram, a neonicotinoid acetylcholine receptor agonist, exhibits both contact and systemic activity (Amirzade *et al.*, 2014; Ma *et al.*, 2017). The addition of PSFA improved cuticular penetration by disrupting the epicuticular wax layer, which allowed nitenpyram to act more effectively as a contact insecticide. Its local systemic activity, through translaminar movement, further increased nymphal mortality by delivering the compound to target tissues *via* ingestion of toxic sap (Palumbo *et al.* 2001; Singh & Kumar, 2006; Casida, 2018; Thany, 2025). Similarly, Flometoquin (Gladius 10 SC) is a fast-acting insecticide with both contact and systemic activity, and its nymphal toxicity largely mirrored that of nitenpyram (Takeuchi *et al.*, 2024). On the other hand, Movento 240 SC (Spirotetramat) is primarily systemic, causing only 29% mortality, and the addition of PSFA did not improve its effect, likely due to the limited influence of contact-enhancing additives (Amirzade *et al.*, 2014; Ma *et al.*, 2017). Collectively, these results highlight that the efficacy of sap-sucking insecticides depends on their mode of action and that additives can synergistically enhance contact-active compounds but have a limited effect on systemic insecticides.

Two application strategies were evaluated: direct mixing and post-application. Across all insecticides, post-application slightly increased nymphal mortality; however, it required two separate spray operations, making it more labor-intensive and less practical for large-scale use. In contrast, direct mixing achieved substantial mortality with a single application, offering a more feasible and cost-effective approach for farmers. These results suggest that combining insecticides with PSFA or SEML may provide a practical strategy to overcome the resilience of wax-covered nymphs.

While laboratory experiments clearly demonstrate the efficacy of PSFA and SEML, environmental and agronomic factors-including temperature, rainfall, crop type, and the presence of natural enemies may influence field performance (Wafula *et al.*, 2017; Mustafa *et al.*, 2020; Choyon *et al.*, 2022; Narayanamma *et al.*, 2024). Although PSFA and SEML generally exhibit low toxicity to humans and beneficial arthropods, potential phytotoxicity or unintended effects on non-target organisms should be carefully monitored during field application. Therefore, although laboratory results provide proof-of-concept, further field trials are essential to validate efficacy, optimize application timing and methods, and ensure sustainable and environmentally safe management of RSW across diverse cropping systems.

Conclusions

Our laboratory study demonstrates that additives, including SEML and PSFA, can enhance insecticide efficacy against RSW nymphs by improving penetration through the protective waxy layer; however, this effect was not observed for all insecticides, reflecting differences in their modes of action. While the post-application method provided slightly higher control than that of direct mixing, its labor-intensive nature limits large-scale adoption. Direct mixing of PSFA/SEML with insecticides, therefore, offers a more practical and effective strategy for field application. These findings highlight the potential of optimizing additive-insecticide combinations; however, environmental factors such as rainfall, UV degradation, and spray coverage may influence their effectiveness under

field conditions. Further studies under diverse agroecological settings are warranted to validate these strategies and identify sustainable, environmentally friendly alternatives for integrated pest management.

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