

Use of Alternative Sprays for Whitefly Control on Different Tomato Genotypes

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Abstract

The whitefly is a major pest of tomato crops, capable of causing direct and indirect damage and losses of up to 100%. This study aimed to evaluate the efficacy of alternative spray mixtures in controlling whiteflies on two tomato genotypes. The trial was conducted at the Federal University of Lavras using a completely randomized design in a 10x2 factorial arrangement (mixtures × genotypes), totaling 20 treatments and four temporal replicates. Seedlings of the 'Santa Clara' cultivar and the 'UFLA' hybrid were placed in insect cages, separated by genotype, and 200 whiteflies were released into each cage. After 24 hours, the following mixtures were applied: 1) Water (control); 2) *Beauveria bassiana*; 3) Oil + detergent; 4) Salt + vinegar + detergent; 5) Garlic + black pepper + alcohol; 6) Garlic + malagueta pepper + coconut soap; 7) Tobacco + malagueta pepper + coconut soap; 8) Tobacco + alcohol; 9) Neem oil; and 10) Pyriproxyfen. The variables evaluated were the number of adult insects (24 hours after release and application), the number of eggs (3 to 7 days later), and the number of nymphs (15 to 21 days later). All tested mixtures exhibited a repellent effect on adults, with mixtures 2, 8, and 9 showing the most notable results. For both genotypes, alternative mixtures 8 and 6 performed best in controlling whiteflies across their complete life cycle (egg, nymph, and adult).

INTRODUCTION

Tomato (*Solanum lycopersicum* L. = *Lycopersicon esculentum* Mill.) is a diploid species ($2n = 2x = 24$) belonging to the family Solanaceae and is native to South America, particularly the region extending from western Ecuador to northern Bolivia and Chile (Nick et al. 2018). Tomato is considered one of the most economically important vegetable crops worldwide (Rocha and Sujii 2019) and is extensively cultivated in tropical and subtropical regions (Neiva et al. 2019). According to the Food and Agriculture Organization of the United Nations (FAO), the five largest tomato-producing countries in 2023 were China (70,214,666.86 t), India (20,425,000 t), Türkiye (13,300,000 t), the United States (12,370,057 t), and Egypt (6,211,015.96 t), while Brazil ranked eighth in total production (4,166,017 t). However, in terms of productivity, Brazil ranked fourth, with an average yield of 70,598.5 kg ha⁻¹, behind only the United States (101,281.8 kg ha⁻¹), Türkiye (79,964.9 kg ha⁻¹), and Spain (79,226.6 kg ha⁻¹).

In Brazil, tomato is cultivated year-round under different production systems for both the fresh market and processing industries. Nevertheless, crop productivity is constrained by numerous phytosanitary problems, particularly under conventional production systems. Among these, the whitefly (*Bemisia tabaci* (Genn.)) is considered one of the most destructive pests, causing both direct damage through sap feeding and indirect damage through its ability to transmit plant viruses (Gallo et al. 2002; Michereff et al. 2022).

The whitefly is a highly polyphagous and resilient insect capable of adapting to a wide range of environmental conditions, although it develops more successfully under warm and humid climates. It belongs to the order Hemiptera and undergoes incomplete metamorphosis (hemimetaboly). Depending on environmental conditions, its life cycle ranges from 14 to 27 days and includes the egg, nymphal, and

adult stages. Several economically important species have been described, including *B. tabaci* and species of the genus *Trialeurodes*, such as *T. vaporariorum* and *T. abutiloneus* (Moura et al. 2013; Michereff et al. 2022; IRAC-BR, n.d.). These species can inflict severe direct and indirect damage on tomato plants, resulting in yield losses of up to 100% (Nick et al. 2018). Direct damage results from phloem sap extraction, which weakens plant vigor, and from the injection of phytotoxic saliva, leading to uneven fruit ripening, pulp discoloration, spongy texture, and poor flavor. Indirect damage results from the excretion of honeydew during feeding, which promotes the development of sooty mold (*Capnodium* spp.) on leaves and fruits, thereby reducing photosynthetic efficiency, as well as from the transmission of economically important plant viruses (Gallo et al. 2002; Michereff et al. 2022).

Because of its economic importance, *B. tabaci* has become a key pest of tomato production, representing a major challenge for growers and requiring substantial changes in pest management strategies (Sarhozaki et al. 2021; Michereff et al. 2022). Whitefly control still relies predominantly on repeated applications of synthetic insecticides throughout the crop cycle, which may cause environmental contamination and accelerate the selection of insecticide-resistant populations (Rocha and Sujii 2019). To minimize these problems, integrated pest management (IPM) strategies should be adopted to maintain pest populations below the economic injury level. Such strategies include continuous pest monitoring and the integration of multiple control tactics, including host plant resistance, biological control, cultural practices, and chemical control (Michereff et al. 2022).

The scientific literature on the use of alternative spray solutions for the management of *B. tabaci* presents highly variable levels of scientific evidence depending on the product evaluated. Some alternatives, particularly *Beauveria bassiana* and neem (*Azadirachta indica*) oil, have been extensively validated under experimental conditions (Abdou and Shalaby 2024; Islam et al. 2010; Quesada-Moraga et al. 2006; Sarhozaki et al. 2021). In contrast, many homemade formulations are supported almost exclusively by empirical knowledge, with little or no scientific validation and, in some cases, presenting considerable risks of phytotoxicity.

Therefore, the objective of this study was to evaluate the effectiveness of alternative spray formulations for the control of whitefly (*B. tabaci*) in different tomato genotypes.

MATERIAL AND METHODS

The experiment was conducted between December 2024 and July 2025. The initial phase was carried out at the Center for Development and Technology Transfer (CDTT) of the Federal University of Lavras (UFLA), located in Ijaci, Minas Gerais, Brazil (21°09'50.54" S, 44°54'58.00" W), whereas the remaining experimental procedures were performed at UFLA in Lavras, Minas Gerais, Brazil (21°13'21.21" S, 44°58'13.22" W).

The experiment was arranged in a completely randomized design using a 10 × 2 factorial scheme, in which the primary factor consisted of the spray treatments and the secondary factor comprised the tomato genotypes, resulting in 20 treatment combinations with four temporal replicates.

Two tomato genotypes were evaluated: the commercial cultivar Santa Clara and an experimental F₁ hybrid (TOM-778 × TOM-760), hereafter referred to as the UFLA Hybrid, which has potential resistance to whitefly infestation. Seeds were manually sown in rigid plastic trays containing 162 cells filled with the commercial substrate Carolina Soil®. Twenty-eight days after sowing, seedlings were transplanted into plastic tubes and maintained under nursery conditions. Throughout the growing period, plants were individually staked using cotton twine attached to bamboo stakes placed alongside each tube. Irrigation was performed daily to maintain the substrate near field capacity, and all crop management practices were standardized according to the recommendations for tomato cultivation described by Nick et al. (2018).

To establish the treatments, seven alternative spray formulations recommended for whitefly management were selected from technical manuals and extension publications (Brasil 2026; Rocha and Sujii 2019; Zambolim and Quezado-Duval 2022). In addition, one registered biological insecticide based on *Beauveria bassiana*, one registered chemical insecticide containing pyriproxyfen as the active ingredient, and a water control were included, totaling ten treatments. All spray solutions were prepared to a final volume of 500 mL. The evaluated treatments were as follows: 1: Water (control); 2: *Beauveria bassiana*; 3: Vegetable oil + detergent; 4: Salt + vinegar + detergent; 5: Garlic + black pepper + alcohol; 6: Garlic + chili pepper + coconut soap; 7: Tobacco + chili pepper + coconut soap; 8: Tobacco + alcohol; 9: Neem oil; and 10: Pyriproxyfen.

Approximately 42 days after sowing (DAS), when seedlings had reached approximately 30 cm in height, the youngest fully expanded leaf of each plant was identified by loosely tying a cotton thread around its petiole to facilitate subsequent evaluations. The youngest leaf was selected because it represents the preferred oviposition site for *B. tabaci* compared with older leaves.

Seedlings were then transferred to entomological cages measuring 60 × 60 × 70 cm (length × width × height). Each cage contained ten plants, representing one plant from each treatment for each genotype. Adult whiteflies were subsequently released into each cage at a density of 20 insects per plant, corresponding to 200 adults per cage.

Adult *B. tabaci* (biotype B) were obtained from the colony maintained by the Plant Resistance and Integrated Pest Management Laboratory (LARP/MIP), Department of Entomology, UFLA. No distinction was made between males and females during insect collection. The colony was maintained on kale plants (*Brassica oleracea*) inside entomological cages. Adults were collected individually using an aspirator routinely employed at LARP/MIP. Every batch of 100 insects was transferred to a sealed centrifuge tube covered with voile fabric and secured with string. The insects were subsequently released into each cage through the secondary sleeve opening ("double-sleeve"), totaling 200 adults per experimental unit.

All spray treatments were applied inside a greenhouse during the late afternoon (after 4:00 p.m.) using a 500-mL hand-held sprayer. Treatments were applied individually to each plant while maintaining sufficient distance from neighboring plants to prevent spray drift. During application, the same spraying

pattern and number of spray pulses were maintained for all treatments to ensure maximum and uniform coverage of both the adaxial and abaxial leaf surfaces while avoiding runoff.

Three response variables associated with whitefly infestation were evaluated: the number of adults, eggs, and nymphs present on the abaxial surface of the previously marked leaf. For each assessment, plants were carefully removed from the cages to minimize insect dispersal. Adult whiteflies were counted 24 h after insect release. Egg and nymph counts were performed under a stereomicroscope at the LARP/MIP laboratory. Eggs were counted between 2 and 7 days after the adult assessment, whereas nymphs were evaluated between 14 and 21 days after the first evaluation. Additionally, egg hatch (%) was calculated based on the relationship between the numbers of eggs and nymphs.

The collected data were analyzed using Generalized Linear Models (GLMs) assuming a Poisson distribution, followed by Chi-square tests ($P < 0.05$) to determine the significance of the effects of spray treatments, tomato genotypes, and the interaction between these factors on the evaluated variables. Whenever significant effects were detected, treatment means were compared using Tukey's test, and significant interactions were further explored through simple-effect analyses. All statistical analyses, including hypothesis testing and multiple comparisons, were performed using Statistica software (version 13.1).

RESULTS

Regarding the number of adult whiteflies recorded, a significant effect was observed only for the spray treatments on adult abundance ($\chi^2 = 21.77$; $P < 0.01$). No significant differences were detected between tomato genotypes ($\chi^2 = 0.47$; $P = 0.4934$), and no significant interaction between treatments and genotypes was observed ($\chi^2 = 12.88$; $P = 0.0751$) (Table 1).

Table 1
Mean number of adult *B. tabaci* on the two tomato genotypes as affected by different spray treatments.

Spray Treatment	Number of adults	
1. Water	3.75	a
2. <i>Beauveria bassiana</i>	1.00	b
3. Oil + detergent	1.75	ab
4. Salt + vinegar + detergent	1.00	**
5. Garlic + black pepper + alcohol	1.63	ab
6. Garlic + chili pepper + coconut soap	0.63	**
7. Tobacco + chili pepper + coconut soap	2.00	ab
8. Tobacco + alcohol	0.88	b
9. Neem oil	1.29	b
10. Pyriproxyfen	2.50	ab
*Means followed by the same letter do not differ significantly according to Tukey's test (P < 0.05).		
** Means excluded from the statistical analysis.		

Source: Prepared by the authors.

The lowest numbers of adult whiteflies were obtained with treatments 2 (*Beauveria bassiana*), 8 (tobacco + alcohol), and 9 (neem oil), which did not differ significantly from one another or from treatments 3 (vegetable oil + detergent), 5 (garlic + black pepper + alcohol), 7 (tobacco + chili pepper + coconut soap), and 10 (pyriproxyfen), although these latter treatments exhibited numerically higher adult populations. Significant differences were observed only between these treatments and the untreated control (water), which presented the highest number of adult insects. Likewise, treatments 3, 5, 7, and 10 did not differ significantly from one another or from the water control.

The mean values of treatments 4 (salt + vinegar + detergent) and 6 (garlic + chili pepper + coconut soap) were excluded from the statistical analysis because all replicates of the Santa Clara genotype showed no variance, preventing the application of the chi-square test. Since the experiment followed a factorial design, the corresponding means of the UFLA Hybrid under these treatments were also excluded from the statistical comparisons.

With respect to the number of eggs recorded on the marked leaves between three and seven days after adult release, significant effects were detected for tomato genotype ($\chi^2 = 331.65$; $P < 0.0001$), spray treatment ($\chi^2 = 555.50$; $P < 0.0001$), and the interaction between genotype and treatment ($\chi^2 = 191.37$; $P < 0.0001$) (Table 2).

Table 2

Mean number of *B. tabaci* eggs on two tomato genotypes as affected by different spray treatments.

Spray Treatments / Genotypes	Number of eggs			
	UFLA Hybrid		Santa Clara	
1. Water	140.75	A b	62.00	B b
2. <i>Beauveria bassiana</i>	131.33	A b	54.50	B b c
3. Oil + detergent	91.25	B c	118.00	Aa
4. Salt + vinegar + detergent	87.85	A c	73.50	A b
5. Garlic + black pepper + alcohol	143.50	A b	117.75	Ba
6. Garlic + chili pepper + coconut soap	81.00	A c	47.00	B c
7. Tobacco + chili pepper + coconut soap	123.75	A b	87.25	B b
8. Tobacco + alcohol	75.50	A c	43.25	B c
9. Neem oil	161.33	A b	86.00	B b
10. Pyriproxyfen	202.67	Aa	116.33	Ba
* Means followed by the same lowercase letter within a column and/or the same uppercase letter within a row are not significantly different according to Tukey's test ($P < 0.0001$).				

Source

Prepared by the authors.

For the UFLA Hybrid, treatments 3 (vegetable oil + detergent), 4 (salt + vinegar + detergent), 6 (garlic + chili pepper + coconut soap), and 8 (tobacco + alcohol) produced the lowest numbers of eggs, with no significant differences among these treatments. Conversely, treatments 1 (water), 2 (*Beauveria bassiana*), 5 (garlic + black pepper + alcohol), 7 (tobacco + chili pepper + coconut soap), and 9 (neem oil) resulted in intermediate egg densities that did not differ significantly from one another but were significantly higher than those obtained with the best-performing treatments. The highest oviposition was recorded for treatment 10 (pyriproxyfen), which differed significantly from all other treatments.

For the Santa Clara cultivar, treatments 6 and 8 produced the lowest egg densities and did not differ significantly from treatment 2 (*B. bassiana*), although they differed from all remaining treatments. Intermediate oviposition levels were observed with treatments 1, 4, 7, and 9, whereas treatments 3, 5, and 10 resulted in the highest egg numbers.

Therefore, treatments 6 and 8, followed by treatment 2, were the most effective alternatives for reducing oviposition in Santa Clara. In contrast, treatments 4, 7, and 9 showed no significant improvement over

the untreated control, whereas treatments 3, 5, and 10 produced significantly higher egg numbers than the control, suggesting that these formulations may favor oviposition under the experimental conditions.

In the number of nymphs recorded between 15 and 21 days after adult release, significant effects were detected for tomato genotype ($\chi^2 = 235.97$; $P < 0.0001$), spray treatment ($\chi^2 = 309.99$; $P < 0.0001$), and the interaction between genotype and treatment ($\chi^2 = 86.18$; $P < 0.0001$) (Table 3).

Table 3

Mean number of *B. tabaci* nymphs on two tomato genotypes subjected to different spray treatments.

Spray Treatments /Genotype	Number of nymphs			
	UFLA Hybrid		Santa Clara	
1. Water	116.00	Aa	60.25	B b
2. <i>Beauveria bassiana</i>	108.00	Aab	47.00	B bc
3. Oil + detergent	91.75	A b	83.50	Aa
4. Salt + vinegar + detergent	73.00	A bc	70.25	Aab
5. Garlic + black pepper + alcohol	97.75	Aab	60.00	A b
6. Garlic + chili pepper + coconut soap	67.50	A c	41.75	A c
7. Tobacco + chili pepper + coconut soap	89.75	A b	73.00	Aab
8. Tobacco + alcohol	63.25	A c	33.25	B c
9. Neem oil	110.33	Aab	71.50	Bab
10. Pyriproxyfen	45.67	A d	21.33	B d
* Means followed by the same lowercase letter within a column and/or the same uppercase letter within a row are not significantly different according to Tukey's test ($P < 0.0001$).				

Source: Prepared by the authors.

For the UFLA Hybrid, treatment 10 (pyriproxyfen) resulted in the lowest number of nymphs and differed significantly from all other treatments. Treatments 6 (garlic + chili pepper + coconut soap) and 8 (tobacco + alcohol) produced the next lowest nymph densities and did not differ significantly from treatment 4 (salt + vinegar + detergent), although they differed from the remaining treatments. Treatment 4 showed intermediate effectiveness, differing significantly only from treatments 1 and 10. Likewise, treatments 3 (vegetable oil + detergent) and 7 (tobacco + chili pepper + coconut soap) exhibited similar responses and did not differ significantly from treatments 2 (*Beauveria bassiana*), 4, 5 (garlic + black pepper + alcohol), and 9 (neem oil). Treatments 2, 5, and 9 produced similar nymph densities and did not differ significantly from treatments 1, 3, 4, and 7. The untreated control (water) exhibited the highest nymph population and differed significantly from all treatments except 2, 5, and 9.

For the Santa Clara cultivar, pyriproxyfen also resulted in the lowest nymph density and differed significantly from all other treatments. Treatments 6 and 8 again exhibited the greatest efficacy among the alternative formulations and did not differ significantly from treatment 2 (*B. bassiana*), although they differed from all remaining treatments. Intermediate responses were observed for treatments 1 and 5, whereas treatments 4, 7, and 9 showed similar performance. Treatment 3 produced the highest number of nymphs and differed significantly from the most effective treatments.

Consequently, pyriproxyfen remained the most efficient treatment for controlling whitefly nymphs in the Santa Clara cultivar, whereas treatments 6 and 8 represent promising alternatives for incorporation into integrated pest management programs. In contrast, treatments 2 and 5 failed to differ significantly from the untreated control, while treatments 3, 4, 7, and 9 produced even greater nymph densities than the control, suggesting that these formulations may have favored nymphal development under the conditions evaluated.

Regarding genotype performance, significant differences were detected only for treatments 1, 2, 8, 9, and 10, with Santa Clara consistently exhibiting lower nymph densities than the UFLA Hybrid. No significant differences between genotypes were observed for treatments 3, 4, 5, 6, or 7.

After evaluating each response variable individually, it was possible to identify the most effective spray formulations according to the specific objective (adult repellency, oviposition reduction, or nymph control) and tomato genotype. However, because successful whitefly management depends on disrupting the insect throughout its entire life cycle, the combined analysis of all developmental stages provides a more comprehensive assessment of treatment performance. Accordingly, the results for adult abundance, egg deposition, nymph density, and egg hatch were integrated for the UFLA Hybrid and Santa Clara genotypes (Tables 4 and 5).

Table 4

Effects of different spray treatments on adult abundance, egg production, nymph density, and egg hatch of *B. tabaci* on the UFLA Hybrid tomato genotype.

Spray Treatments	UFLA Hybrid tomato genotype						
	*Number of adults		**Number of eggs		**Number of nymphs		Egg hatch (%)
1. Water	3.75	a	140.75	b	116.00	a	82
2. <i>Beauveria bassiana</i>	1.00	b	131.33	b	108.00	ab	82
3. Oil + detergent	1.75	ab	91.25	c	91.75	b	100
4. Salt + vinegar + detergent	1.00	**	87.85	c	73.00	bc	83
5. Garlic + black pepper + alcohol	1.63	ab	143.50	b	97.75	ab	68
6. Garlic + chili pepper + coconut soap	0.63	**	81.00	c	67.50	c	83
7. Tobacco + chili pepper + coconut soap	2.00	ab	123.75	bc	89.75	b	73
8. Tobacco + alcohol	0.88	b	75.50	c	63.25	c	84
9. Neem oil	1.29	b	161.33	b	110.33	ab	68
10. Pyriproxyfen	2.50	ab	202.67	a	45.67	d	23
*Means followed by the same letter within a column are not significantly different according to Tukey's test ($P < 0.05$).							
**Means followed by the same letter within a column are not significantly different according to Tukey's test ($P < 0.0001$).							

Source: Prepared by the authors.

Table 5

Effects of different spray treatments on adult abundance, egg production, nymph density, and egg hatch of *B. tabaci* on the Santa Clara tomato genotype.

Spray Treatments	Santa Clara Genotype						
	*Number of adults		**Number of eggs		**Number of nymphs		Egg hatch (%)
1. Water	3.75	a	62.00	b	60.25	b	43
2. <i>Beauveria bassiana</i>	1.00	b	54.50	bc	47.00	bc	36
3. Oil + detergent	1.75	ab	118.00	a	83.50	a	92
4. Salt + vinegar + detergent	1.00	**	73.50	b	70.25	ab	80
5. Garlic + black pepper + alcohol	1.63	ab	117.75	a	60.00	b	42
6. Garlic + chili pepper + coconut soap	0.63	**	47.00	c	41.75	c	52
7. Tobacco + chili pepper + coconut soap	2.00	ab	87.25	b	73.00	ab	59
8. Tobacco + alcohol	0.88	b	43.25	c	33.25	c	44
9. Neem oil	1.29	b	86.00	b	71.50	ab	44
10. Pyriproxyfen	2.50	ab	116.33	a	21.33	d	11
*Means followed by the same letter within a column are not significantly different according to Tukey's test ($P < 0.05$).							
**Means followed by the same letter within a column are not significantly different according to Tukey's test ($P < 0.0001$).							

Source: Prepared by the authors.

For the UFLA Hybrid, treatments 6 (garlic + chili pepper + coconut soap) and 8 (tobacco + alcohol) consistently ranked among the most effective formulations, reducing adult abundance, oviposition, and nymph populations. Treatment 4 (salt + vinegar + detergent) also demonstrated satisfactory performance and may be considered a complementary management option. Although pyriproxyfen did not reduce adult populations or oviposition, it markedly decreased both nymph abundance and egg hatch, confirming its effectiveness as an insect growth regulator acting primarily on immature stages.

A similar pattern was observed for the Santa Clara cultivar. Treatments 6 and 8 again provided the most consistent suppression of whitefly populations throughout the insect life cycle. In addition, treatment 2 (*Beauveria bassiana*) performed well, particularly by reducing adult abundance and oviposition. As observed for the UFLA Hybrid, pyriproxyfen was highly effective in suppressing nymph development and reducing egg hatch despite its limited effect on adult repellency.

Overall, the alternative formulations exhibited egg hatch percentages similar to those observed in the untreated control, indicating that their principal mode of action was associated with adult repellency and reduced oviposition rather than direct ovicidal activity. In contrast, pyriproxyfen exhibited relatively low repellency and even stimulated oviposition but substantially reduced egg hatch and subsequent nymph establishment, consistent with its mode of action as an insect growth regulator.

DISCUSSION

All evaluated spray formulations reduced the number of adult whiteflies compared with the untreated control, indicating a repellent effect. However, treatments based on *B. bassiana*, tobacco + alcohol, and neem oil showed the greatest reduction in adult abundance and may therefore represent promising alternatives for whitefly management, particularly as components of insecticide rotation programs involving active ingredients with different modes of action. Although treatments 4 and 6 were not included in the statistical analysis, their numerical means also suggest a potential repellent effect against adult whiteflies.

Adult whiteflies are generally less susceptible to entomopathogenic fungi such as *Beauveria bassiana* because of their high mobility, which limits the period of contact between the insect cuticle and fungal conidia. Nevertheless, repeated applications can substantially reduce adult populations, particularly when the fungus establishes as an endophyte within plant tissues, altering feeding behavior and reducing insect longevity (Wang et al. 2024; Wei et al. 2020).

In the case of neem oil, the primary effects on adult whiteflies are not immediate mortality but rather repellency, feeding inhibition, reduced fecundity, and decreased oviposition, ultimately suppressing population growth across successive generations (Islam et al. 2010). Consequently, combining *B. bassiana* with neem-based products has been identified as one of the most promising integrated management strategies reported in the literature.

With respect to the number of eggs the results indicate that treatments 3, 4, 6, and 8 were the most effective alternatives for reducing whitefly oviposition on the UFLA Hybrid and therefore represent potential components of integrated whitefly management programs. Although treatments 2, 5, 7, and 9 produced intermediate values, they did not differ statistically from the untreated control, indicating limited effectiveness under the conditions of this study. Interestingly, pyriproxyfen resulted in significantly greater oviposition than the control, suggesting that this insecticide may stimulate egg laying and should therefore not be recommended when the primary objective is to reduce oviposition. Overall, the two tomato genotypes differed significantly in their response, with Santa Clara consistently exhibiting lower egg densities than the UFLA Hybrid. Consequently, the hypothesis that the UFLA Hybrid possesses enhanced resistance to whitefly due to elevated concentrations of leaf allelochemicals was not supported by the present results. This finding contrasts with previous studies by Neiva et al. (2019) and Toscano et al. (2002), who reported reduced oviposition on tomato genotypes containing high concentrations of acylsugars and/or zingiberene, characteristics expected in the UFLA Hybrid. Likewise,

Silva et al. (2008) reported complete suppression of whitefly oviposition on genotype LA 716 (*Lycopersicon pennellii*), another genotype characterized by high acylsugar content.

In general, insect eggs represent one of the least susceptible developmental stages to entomopathogenic fungi such as *B. bassiana* because the chorion acts as an effective physical barrier against fungal penetration. Nevertheless, several studies have demonstrated substantial reductions in egg viability and hatchability, particularly when highly virulent isolates are used or when *B. bassiana* is combined with other biological control agents, including neem oil. Under controlled conditions, reductions of approximately 50 to 70% in egg hatch have been reported (Sarhozaki et al. 2021).

The combination of *B. bassiana* with neem-based products has emerged as a particularly promising strategy because neem reduces insect feeding activity and mobility, thereby increasing the duration of contact between insects and fungal conidia. Both laboratory and field studies have demonstrated complementary and, in some cases, synergistic effects between these two biological control agents (Islam et al. 2010; Sarhozaki et al. 2021).

The results also indicated that pyriproxyfen was the most effective treatment for suppressing whitefly nymphs on the UFLA Hybrid. Among the alternative formulations, treatments 6 and 8 showed the greatest potential, followed by treatment 4, which displayed comparable performance. Incorporating these alternative formulations into integrated pest management programs may facilitate the rotation of active ingredients with different modes of action, thereby reducing selection pressure for insecticide-resistant whitefly populations and preserving the efficacy of conventional insecticides. Although treatments 3 and 7 reduced nymph abundance relative to the untreated control, their effectiveness was considerably lower than that of the best-performing treatments. Conversely, treatments 2, 5, and 9 are not recommended for nymph control because their effects were statistically indistinguishable from untreated control.

Nymphs are generally considered the developmental stage most susceptible to entomopathogenic fungi such as *Beauveria bassiana*. Most published studies report mortality rates exceeding 70%, frequently surpassing 90% during the early instars under conditions of high relative humidity and adequate spray coverage. Furthermore, recent studies have demonstrated that endophytic colonization of tomato plants by *B. bassiana* significantly suppresses whitefly population development by reducing nymph survival, fecundity, and net reproductive rate (Wei et al. 2020; Sarhozaki et al. 2021).

Similarly, neem oil primarily targets the nymphal stage through the action of azadirachtin. Numerous studies have reported mortality rates ranging from 70 to 90%, in addition to severe disruption of molting, developmental abnormalities, and growth inhibition. Under field conditions, reductions exceeding 80% of nymph populations have frequently been documented (Sarhozaki et al. 2021; Islam et al. 2010).

The present study also demonstrated the effectiveness of alternative formulations containing vinegar, soap, garlic, salt, and pepper against whitefly populations. Mineral oils, refined vegetable oils, and insecticidal soaps act predominantly through physical mechanisms by blocking spiracles, disrupting the

insect cuticle, and promoting dehydration. These products generally provide greater control of eggs and nymphs than adults, particularly when adequate coverage of the abaxial leaf surface is achieved. Although widely recommended within integrated pest management programs, their efficacy largely depends on spray coverage and environmental conditions (Haron et al. 2025).

Garlic extracts exhibit primarily repellent activity attributed to allicin and other sulfur-containing compounds. Available studies have demonstrated reductions in insect feeding, plant colonization, oviposition, and moderate decreases in nymph abundance. However, evidence for direct insecticidal activity remains limited, suggesting that garlic extracts are more suitable as preventive components within integrated pest management than as curative treatments (Haron et al. 2025; Wang et al. 2024).

Similarly, extracts of *Capsicum* species mainly exert repellent and antifeedant effects associated with capsaicin and other secondary metabolites. Previous studies have reported reduced adult settling and oviposition; however, their direct insecticidal activity against eggs and nymphs is generally lower than that observed for neem or *B. bassiana* (Haron et al. 2025; Wang et al. 2024).

Tobacco extracts contain nicotine, a neurotoxic alkaloid that acts on nicotinic acetylcholine receptors in the insect nervous system. Classical studies demonstrated high toxicity toward both adults and nymphs. Nevertheless, because of the considerable toxicological risks posed to humans, natural enemies, and non-target organisms, the use of tobacco-based formulations has progressively declined, and relatively few recent studies published in high-impact journals have evaluated homemade tobacco formulations (Haron et al. 2025; Wang et al. 2024).

These findings suggest that, under conventional tomato production systems, integrating alternative formulations with pyriproxyfen may represent an effective management strategy. An initial application of an alternative formulation could reduce adult colonization and oviposition, followed several days later by pyriproxyfen to suppress egg hatch and immature development. Nevertheless, additional studies are required to determine whether the oviposition-reducing effects of the alternative formulations outweigh the apparent oviposition-stimulating effect observed following pyriproxyfen application, thereby confirming the overall effectiveness of this sequential strategy.

Among all evaluated management alternatives, *Beauveria bassiana* remains the treatment supported by the strongest body of scientific evidence. This entomopathogenic fungus infects insects through direct contact, adhering to the cuticle, germinating, penetrating the integument through mechanical and enzymatic processes, colonizing the hemocoel, and ultimately killing the host (de Faria and Wraight 2007; Wang et al. 2024). Several studies conducted on tomato have demonstrated significant reductions in *B. tabaci* populations following *B. bassiana* applications, particularly when combined with neem derived products (Abdou and Shalaby 2024; Islam et al. 2010; Quesada-Moraga et al. 2006; Sarhozaki et al. 2021).

Likewise, neem oil is among the most extensively investigated botanical insecticides for whitefly management. Its principal active compound, azadirachtin, interferes with feeding behavior, molting,

reproduction, and insect development, providing antifeedant, repellent, and insect growth-regulating effects (Islam et al. 2010).

Conversely, homemade formulations containing salt, vinegar, detergent, garlic, pepper, or tobacco remain poorly supported by scientific evidence for whitefly management in tomato. Moreover, formulations containing salt, vinegar, or nicotine may pose considerable risks of phytotoxicity and toxicity to applicators. Consequently, further studies under commercial production conditions are required to evaluate their long-term efficacy and possible adverse effects on tomato physiology. Regardless of the formulation used, appropriate personal protective equipment, proper spray technology, and recommended pre-harvest intervals should always be observed according to established agricultural guidelines (Saikumar et al. 2025).

It is important to emphasize that the alternative formulations identified in this study should not be considered standalone solutions but rather components of integrated pest management (IPM). Their use should be combined with other management tactics, including host plant resistance, conservation or augmentation of natural enemies, cultural practices, and, when necessary, conventional insecticides. Furthermore, repeated application of the same formulation should be avoided. Instead, rotation among products with different modes of action, including both alternative formulations and synthetic insecticides, should be adopted to minimize selection pressure and delay the evolution of resistant *B. tabaci* populations.

CONCLUSIONS

All evaluated spray formulations exhibited some degree of repellency against adult *B. tabaci*, with *Beauveria bassiana*, tobacco + alcohol, and neem oil producing the greatest reductions in adult abundance.

Considering both tomato genotypes and the complete whitefly life cycle (egg, nymph, and adult), treatments 8 (tobacco + alcohol) and 6 (garlic + chili pepper + coconut soap) were the most effective alternative formulations and showed the greatest potential as complementary tools to the chemical insecticide pyriproxyfen.

Declarations

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Author Contribution

João Lucas Soares de Faria Alvim was responsible for fieldwork, experiment setup, statistical evaluations, and manuscript preparation. Daniele Batista Campelo assisted with field experiments,

analyses, and manuscript preparation. Luis Felipe Lima e Silva actively participated in statistical analyses, interpretation of results, discussions, and manuscript writing. Cleiton Lourenço de Oliveira supervised the entire research project and coordinated all stages. Bruno Henrique Sardinha de Souza provided supervision in the entomology laboratory and designed experimental setup and analyses. Stefany Martins da Silva Lino assisted with technical aspects in the Vegetable Crops Section. Valter Carvalho de Andrade assisted with the planning and coordination of the experimental phase.

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