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Management Strategy against Invasive *Leucoptera malifoliella* (Lepidoptera: Lyonetiidae) on Apple (Malus domestica) in Kashmir Himalayas

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***Abstract*—** *The proliferation of invasive insect pests is often facilitated by favorable environmental conditions, abundant host availability, and the absence of natural enemies. Leucoptera malifoliella (Lepidoptera: Lyonetiidae), commonly known as the apple blotch leaf miner, was first reported in India in 2021, causing significant damage to apple orchards in Kashmir. Given its potential threat to the regional apple industry, a two-year field study (2022–2023) was conducted to assess the efficacy of seven insecticidal treatments. Results demonstrated that Thiamethoxam 12.6% + Lambda-Cyhalothrin 9.5% ZC and Quinalphos 25EC + Thiamethoxam 25WG were highly effective in reducing leaf infestation (1.0–6.0% and 3.0–8.33%) and live larval populations (1.0–2.33 and 1.33–2.67 larvae per 20 infested leaves) compared to untreated controls (up to 92.0% infestation and 21 larvae per 20 infested leaves). Similar trends were observed in 2023. The enhanced efficacy of neonicotinoid-containing combinations is attributed to their systemic/translaminar activity and complementary modes of action. These findings suggest that insecticide combinations, particularly those incorporating neonicotinoids, offer promising options for managing L. malifoliella in apple orchards in Kashmir.*

***Keywords*— Leucoptera malifoliella; apple; management; insecticides; efficacy.**

I. INTRODUCTION

Apple (*Malus domestica* Borkh.) is one of the oldest cultivated fruit crops and remains a cornerstone of temperate fruit production worldwide. Globally, it ranks as the fourth most consumed fruit after oranges, bananas, and grapes (Forsline et al., 2010). Its widespread cultivation in temperate regions is attributed to its economic importance, nutritional value, and diverse cultivars (Musacchi and Serra, 2018). In India, the apple industry plays a pivotal role in the agricultural economy, particularly in the Kashmir Valley, which contributes over 75% of the nation's apple production (Rather and Buhroo, 2015). Apples in Kashmir are renowned for their unique taste, crispness, and quality, making them highly sought after in domestic and international markets. According to the Directorate of Horticulture (2021), apple cultivation spans approximately 160,000 hectares in the Valley, producing nearly 180,000 metric tonnes annually, with a significant portion exported globally. Despite its vast area under cultivation, apple productivity in Kashmir remains below global standards. This gap is largely due to suboptimal orchard management practices, lack of high density planting systems, and the recurring impact of insect pests and diseases. Among the biotic constraints, insect pests have emerged as major limiting factors affecting yield and fruit quality. While many insect species are associated with apple trees, only a few reach economically damaging levels that warrant urgent and sustained management interventions.

A recent and alarming addition to this pest complex is the apple leaf blotch miner, *Leucoptera malifoliella* (Lepidoptera: Lyonetiidae). This invasive species, previously unreported in India, was first detected in Kashmir in 2021. It is suspected that the pest entered the region through the import of infested apple planting material. Since its introduction, *L. malifoliella* has exhibited rapid population growth across the apple-producing areas of South Kashmir, attaining the status of a major pest by 2023. Growers have reported significant economic losses due to premature defoliation and reduced fruit yield and quality.

L. malifoliella is a typical phytophagous pest that completes up to four overlapping generations per year under the temperate conditions of Kashmir. The larvae mine the upper surface of apple leaves, feeding on mesophyll tissue while leaving the epidermis intact. These solitary miners produce circular blotch mines that evolve from small whitish lesions into larger brown patches with characteristic concentric frass rings. Though fruits are not directly attacked, severe infestations exceeding 40 mines per leaf can cause premature defoliation by August or early September (Baufeld and Freier, 1991). This defoliation compromises the photosynthetic capacity of the tree, weakens bud differentiation, and adversely affects fruit size and quality (Subic, 2015).

Feeding by *L. malifoliella* larvae also induces significant biochemical and physiological stress in host plants. Such stress often manifests as a reduction in chlorophyll content, disruption of photosynthetic pathways, and altered plant defense responses (Gomez et al., 2004; Golawska et al., 2010). Chlorophyll plays a central role in plant-insect interactions, and its decline due to herbivory can severely impair plant growth and productivity (Sammour et al., 2018; Biondi et al., 2018). In addition, the pest pupates on fruit surfaces, and the presence of visible silken cocoons further lowers the commercial value of the produce and creates export-related quarantine challenges. Because of the small size and cryptic behavior of this pest, initial infestations often go unnoticed until significant damage occurs (Rovesti and Deseö, 1991).

The rapid spread and establishment of *L. malifoliella* in Kashmir are attributed in part to the absence of natural enemies. No natural enemies of *L. malifoliella* have been reported in India so far. Invasive insect species frequently experience ecological release in new environments due to the lack of native predators, parasitoids, or pathogens. This facilitates their unchecked proliferation and makes them especially difficult to manage (Kenis et al., 2009). Given the absence of natural enemies, the use of insecticides is currently regarded as the conventional and most practical method for managing leaf miner infestations (Guedes et al., 2016). While chemical control is often criticized for its ecological implications, it remains the primary line of defense in the early stages of invasive pest outbreaks. However, selecting the appropriate insecticides is critical to achieving effective control while minimizing resistance development, environmental contamination, and non-target effects. Hence, identifying efficacious and safe insecticidal options is vital for integration into future Integrated Pest Management (IPM) frameworks.

Given the recency of *L. malifoliella's* introduction in India and the lack of documented control strategies, this study was undertaken to evaluate the field efficacy of seven insecticides, each representing different chemical groups and modes of action, against *L. malifoliella* in Kashmir. Field trials conducted over two consecutive years aimed to determine the most promising options for managing this invasive pest and reducing the economic burden on apple growers. The findings are expected to provide a foundational basis for developing science-based control strategies and contribute to safeguarding apple production in the temperate regions of India.

II. MATERIALS AND METHODS

2.1 Study Site and Orchard Selection

The study was conducted from May 2022 to October 2023 in a commercial apple (*Malus domestica* cv. Red Delicious) orchard located at Bapora, Zainapora village in District Shopian, Jammu and Kashmir, India. The site was selected based on its status as a hotspot for the apple blotch leaf miner, *Leucoptera malifoliella*. The orchard is situated at an elevation of 1,594 meters above mean sea level (33°77′N latitude, 75°01′E longitude). The experimental plot consisted of Red Delicious trees spaced 5.49 meters apart both within and between rows, with an average planting density of 250 trees per hectare.

2.2 Experimental Design and Trial Layout

The experiment was laid out in a Randomized Block Design (RBD) with three replications per treatment. Each replication consisted of a single tree, resulting in a total of 24 trees in the trial. To prevent cross-contamination from spray drift, buffer rows were maintained between treatment blocks. Three trees were designated as untreated controls and received only water sprays. All trees selected for experimentation were labeled and marked with red paint one week prior to treatment application.

Two foliar spray applications were conducted per season: the first at the third fruit developmental stage and the second at the fourth fruit developmental stage. Sprays were applied using a petrol-operated Honda Power Sprayer equipped with an Aspee HTP pump (30 L capacity) and a hollow-cone nozzle to ensure even coverage, including the undersides of leaves and trunks, as recommended by Khursheed and Raj (2013). Prior to bud break, one application of dormant horticultural mineral oil was applied uniformly across the orchard to control San Jose scale and European red mite. Other cultural practices, including fertilization, pruning, and irrigation, were carried out according to standard guidelines for temperate apple cultivation.

2.3 Insecticidal Treatments and Application

Seven insecticidal treatments were evaluated for their efficacy against *L. malifoliella*. The insecticides tested included:

- Chlorpyrifos 50EC + Cypermethrin 5EC
- Thiamethoxam 12.6% + Lambda-Cyhalothrin 9.5% ZC
- Thiamethoxam 25WG
- Quinalphos 25EC + Thiamethoxam 25WG
- Thiacloprid 21.7 SC
- Quinalphos 25EC + Thiacloprid 21.7 SC
- Quinalphos 25EC

Commercial formulations of each insecticide were prepared using clean running water and applied at field-recommended concentrations as per the label. Applications were conducted in the morning between 15 °C and 25 °C ambient temperature to minimize volatilization and maximize coverage. All treatments were repeated in both 2022 and 2023 seasons.

In addition to chemical control, the following physical and cultural practices were implemented uniformly across the orchard: complete orchard sanitation in November (removal and destruction of fallen leaves, pruned branches, and fruits), mechanical grass cutting with a brush cutter in June and August, and burlapping and brushing to remove pupae from tree trunks.

2.4 Data Collection and Observations

Leaf Infestation: Post-treatment assessment of leaf infestation was carried out at 10, 20, 30, and 40 days after each spray. From each treated tree, 100 leaves were randomly sampled, totaling 300 leaves per treatment. The percentage of infested leaves was calculated using the formula:

Leaf infestation (%) = (Number of leaves infested / Total number of leaves selected) × 100

Larval Population: Live larval counts were also recorded on the same schedule. Ten infested leaves were randomly collected from each treated tree (30 leaves per treatment). The upper epidermis of each mined leaf was carefully dissected using a needle, and larvae were extracted with a fine camel hair brush. Each larva was then gently pressed with the brush; individuals failing to respond were considered dead. Only live larvae were recorded for efficacy evaluation.

2.5 Statistical Analysis

Each treatment was replicated three times, and the entire experiment was conducted over two consecutive years. The data were analyzed separately for 2022 and 2023 using SPSS version 16.0. Percentage values were transformed (using the arcsine square root) before analysis of variance (ANOVA) to normalize the data. Mean comparisons were made using Duncan's Multiple Range Test (DMRT) at a significance level of $P \leq 0.05$. Averages of observations across all intervals were used for statistical analysis, and the results were interpreted accordingly.

III. RESULTS

The results from this two-year field study provide clear evidence of the efficacy of various insecticidal treatments in reducing both leaf infestation and larval populations of *Leucoptera malifoliella* in apple orchards. All insecticidal treatments performed significantly better than the untreated control in minimizing pest incidence.

3.1 Year 2022

Following two foliar spray applications, all tested insecticides led to a significant reduction in leaf infestation at 10, 20, 30, and 40 days after each application when compared to the untreated check. Among the treatments, Thiamethoxam 12.6% + Lambda-cyhalothrin 9.5% ZC and Quinalphos 25EC + Thiamethoxam 25WG were the most effective.

Thiamethoxam + Lambda-cyhalothrin consistently showed the lowest leaf infestation rates, ranging from 1.00% to 6.00%, with the minimum recorded 20 days after the second spray. Quinalphos + Thiamethoxam also performed well, with infestation levels between 3.00% and 6.33%, showing best results at 40 days post-first spray. Quinalphos 25EC + Thiacloprid 21.7 SC showed moderate efficacy, with infestations ranging from 5.00% to 15.67%, particularly effective 10 days after the first spray. In contrast, Quinalphos 25EC applied alone was the least effective, with infestation levels ranging from 14.33% to 71.00%, while the untreated control exhibited infestation levels from 21.33% to 91.00% (Table 1).

TABLE 1
EFFICACY OF DIFFERENT INSECTICIDES AGAINST LEAF MINER ON APPLE AT BAPORA ZAINAPORA DURING 2022

Treatments	Dosage (ml/liter of water)	Percent Leaf infestation*							
		10DA1S	20DA1S	30DA1S	40DA1S	10DA2S	20DA2S	30DA2S	40DA2S
Chlorpyrifos 50EC + Cypermethrin 5EC	1.25	6.00 (14.14)	8.67 (16.99)	15.00 (22.75)	27.67 (31.66)	35.67 (36.63)	34.67 (36.05)	43.00 (40.96)	45.33 (42.29)
Thiamethoxam 12.6% + Lambda-Cyhalothrin 9.5% ZC	0.5	1.00 (4.62)	1.33 (6.53)	2.67 (9.36)	2.00 (6.55)	4.00 (11.47)	3.33 (10.34)	5.00 (12.87)	6.00 (14.14)
Thiamethoxam 25WG	0.5	7.00 (15.31)	6.00 (14.14)	10.67 (19.02)	19.00 (25.81)	30.00 (33.15)	28.33 (32.12)	28.67 (32.35)	33.33 (35.24)
Quinalphos 25EC + Thiamethoxam 25WG	1ml + 0.2g	3.00 (9.88)	2.33 (8.74)	2.00 (7.94)	3.33 (6.73)	7.67 (16.02)	7.00 (15.31)	7.00 (15.23)	8.33 (16.50)
Thiacloprid 21.7 SC	0.6	8.00 (16.40)	8.00 (16.29)	10.67 (19.02)	15.67 (23.22)	25.00 (29.98)	28.67 (32.35)	30.67 (33.59)	38.67 (38.42)
Quinalphos 25EC + Thiacloprid 21.7 SC	1 + 0.4	5.00 (12.87)	6.00 (14.14)	7.00 (15.31)	8.67 (17.11)	11.67 (19.89)	11.00 (19.27)	13.67 (21.63)	15.67 (23.28)
Quinalphos 25EC	1.25	14.33 (22.16)	30.33 (33.39)	37.33 (37.63)	42.67 (40.76)	61.00 (51.37)	64.67 (53.55)	65.00 (53.76)	71.00 (57.44)
Control (water)	—	21.33 (27.45)	36.00 (36.80)	55.00 (47.86)	69.33 (56.55)	82.33 (65.46)	87.67 (69.93)	91.33 (72.97)	92.00 (77.56)
CD (P=0.05)		3.48	4.69	3.79	6.28	7.87	6.92	5.41	9.08

Figures in parentheses are arc sine transformed values
DA1S = days after 1st spray; DA2S = days after 2nd spray

Correspondingly, all treatments significantly reduced larval populations compared to the control. The mean number of live larvae per 20 infested leaves across treatments ranged from 1.00 to 12.33, with the lowest larval counts recorded in plots treated with Thiamethoxam + Lambda-cyhalothrin (1.00–2.33 larvae) and Quinalphos + Thiamethoxam (1.33–2.67 larvae). Moderate control was observed with Quinalphos + Thiacloprid (2.33–4.00 larvae), while the highest larval populations were recorded in trees treated with Quinalphos alone (8.00–12.33 larvae) and the untreated control (11.67–21.00 larvae) (Table 2).

TABLE 2
EFFICACY OF DIFFERENT INSECTICIDES AGAINST LEAF MINER ON APPLE AT BAPORA ZAINAPORA DURING 2022

Treatments	Dosage (ml/liter of water)	Mean number of live larvae/20 infested leaves*							
		10DA1S	20DA1S	30DA1S	40DA1S	10DA2S	20DA2S	30DA2S	40DA2S
Chlorpyrifos 50EC + Cypermethrin 5EC	1.25	4.33 (2.29)	6.33 (2.70)	8.67 (3.10)	10.33 (3.36)	5.33 (2.50)	6.33 (2.70)	10.67 (3.41)	11.33 (3.51)
Thiamethoxam 12.6% + Lambda-Cyhalothrin 9.5% ZC	0.5	1.00 (1.38)	1.33 (1.52)	2.00 (1.71)	3.33 (2.06)	1.00 (1.38)	1.67 (1.63)	3.33 (2.06)	2.33 (1.82)
Thiamethoxam 25WG	0.5	4.67 (2.35)	4.67 (2.36)	7.33 (2.88)	9.00 (3.16)	5.00 (2.44)	4.00 (2.23)	4.33 (2.29)	5.33 (2.50)
Quinalphos 25EC + Thiamethoxam 25WG	1ml + 0.2g	1.33 (1.52)	2.33 (1.82)	3.33 (2.06)	4.33 (2.28)	4.67 (2.36)	2.33 (1.82)	2.67 (1.90)	2.67 (1.91)
Thiacloprid 21.7 SC	0.6	4.00 (2.23)	6.00 (2.64)	9.33 (3.21)	10.33 (3.36)	7.67 (2.94)	7.00 (2.82)	9.33 (3.21)	9.00 (3.16)
Quinalphos 25EC + Thiacloprid 21.7 SC	1 + 0.4	5.67 (2.57)	6.33 (2.69)	6.67 (2.76)	6.67 (2.74)	5.33 (2.50)	4.00 (2.23)	4.67 (2.36)	4.33 (2.31)
Quinalphos 25EC	1.25	8.00 (3.00)	10.00 (3.31)	14.00 (3.87)	15.67 (4.08)	11.33 (3.51)	11.00 (3.46)	11.33 (3.51)	12.33 (3.64)
Control (water)	—	11.67 (3.55)	12.33 (3.65)	19.33 (4.51)	21.00 (4.69)	17.33 (4.28)	16.33 (4.16)	18.00 (4.35)	21.00 (4.69)
CD (P=0.05)		2.27	2.2	2.56	3.29	2.05	2.02	2.78	2.53

Figures in parentheses are square root transformed values
DA1S = days after 1st spray; DA2S = days after 2nd spray

3.2 Year 2023

Field evaluations repeated in 2023 confirmed the trends observed in the previous year. All insecticidal treatments significantly outperformed the untreated control. Leaf infestation percentages across treatments ranged from 0.00% to 68.00%, compared to 7.30% to 83.00% in the control (Table 3).

TABLE 3
EFFICACY OF DIFFERENT INSECTICIDES AGAINST LEAF MINER ON APPLE AT BAPORA ZAINAPORA DURING 2023

Treatments	Dosage (ml/liter of water)	Percent Leaf infestation*							
		10DA1S	20DA1S	30DA1S	40DA1S	10DA2S	20DA2S	30DA2S	40DA2S
Chlorpyrifos 50EC + Cypermethrin 5EC	1.25	1.00 (4.62)	6.00 (14.14)	14.33 (22.16)	24.00 (29.30)	32.00 (34.42)	43.00 (40.95)	55.00 (47.86)	57.67 (49.39)
Thiamethoxam 12.6% + Lambda-Cyhalothrin 9.5% ZC	0.5	0.33 (1.91)	0.67 (3.82)	0.67 (3.82)	1.00 (4.62)	0.67 (3.82)	1.00 (5.74)	2.33 (8.46)	3.33 (10.34)
Thiamethoxam 25WG	0.5	0.33 (1.91)	2.67 (9.26)	8.67 (17.07)	13.00 (21.09)	20.33 (26.75)	23.67 (29.07)	29.67 (32.97)	34.00 (35.62)
Quinalphos 25EC + Thiamethoxam 25WG	1ml + 0.2g	0.00 (0.00)	1.00 (4.62)	0.67 (3.82)	2.00 (7.94)	2.00 (7.94)	2.00 (7.94)	3.00 (9.88)	5.33 (13.26)
Thiacloprid 21.7 SC	0.6	1.33 (6.53)	4.33 (11.99)	7.33 (15.65)	14.00 (21.86)	25.00 (29.98)	35.67 (36.63)	42.33 (40.56)	45.33 (42.30)
Quinalphos 25EC + Thiacloprid 21.7 SC	1 + 0.4	0.33 (1.91)	2.00 (7.94)	5.33 (13.26)					

Figures in the parentheses are arc sine transformed values
DA1S=days after 1st spray; DA2S=days after 2nd spray

The most effective treatment was again Thiamethoxam 12.6% + Lambda-cyhalothrin 9.5% ZC, which showed leaf infestation rates of 0.33% to 3.33%. This was closely followed by Quinalphos 25EC + Thiamethoxam 25WG, which achieved 0.00% to 5.33% infestation. Both treatments exhibited maximum effectiveness 10 days after the first spray. In contrast, Quinalphos 25EC + Thiacloprid 21.7 SC showed a broader infestation range (0.33% to 29.00%) and was statistically less effective than the aforementioned treatments. Single applications of Quinalphos 25EC or Thiacloprid 21.7 SC were considerably less effective, with consistently higher infestation levels.

Live larval counts followed a similar pattern. The lowest larval densities were recorded in plots treated with Quinalphos 25EC + Thiamethoxam 25WG (2.00–2.67 larvae per 20 infested leaves), followed by Thiamethoxam + Lambda-cyhalothrin (2.33–3.00 larvae) and Quinalphos + Thiacloprid (3.33–6.00 larvae). The untreated control exhibited the highest larval counts, ranging from 15.00 to 24.00 larvae per 20 leaves (Table 4).

TABLE 4
EFFICACY OF DIFFERENT INSECTICIDES AGAINST LEAF MINER ON APPLE AT BAPORA ZAINAPORA DURING 2023

Treatments	Dosage (ml/liter of water)	Mean number of live larvae/20 infested leaves							
		10DA1S	20DA1S	30 DA1S	40DA1S	10DA2S	20DA2S	30DA2S	40DA2S
Cholorpyriphos 50EC + Cypermethrin 5EC	1.25	9.00 (3.15)	9.00 ((3.14)	13.00 (3.73)	16.67 (4.20)	11.33 (3.50)	11.67 (3.54)	11.33 (3.50)	12.00 (3.60)
Thiamethoxam 12.6% + Lambda-Cyhalothrin 9.5% ZC	0.5	2.33 (1.82)	2.33 (1.79)	2.00 (1.71)	1.67 (1.63)	1.00 (1.38)	2.00 (1.71)	3.00 (1.99)	3.00 (1.99)
Thiamethoxam 25Wg	0.5	5.00 (2.44)	7.00 (2.81)	9.33 (3.20)	11.00 (3.46)	6.33 (2.70)	7.33 (2.88)	10.67 (3.41)	8.00 (2.99)
Quinalphos 25EC+ Thiamethoxam 25Wg	1ml + 0.2g	2.00 (1.71)	3.00 (1.99)	3.00 (1.99)	3.00 (1.99)	2.33 (1.79)	3.00 (1.99)	3.00 (1.99)	2.67 (1.91)
Thiocloprid 21.7 SC	0.6	7.67 (2.94)	6.33 (2.70)	11.00 (3.46)	11.67 (3.55)	11.67 (3.55)	14.00 (3.87)	9.67 (3.26)	6.00 (3.15)
Quinalphos 25EC + Thiocloprid 21.7 SC	1 + 0.4ml	6.00 (2.64)	5.33 (2.50)	4.33 (2.29)	3.33 (2.06)	3.33 (2.06)	5.00 (2.44)	4.00 (2.23)	3.33 (2.08)
Quinalphos 25EC	1.25	12.00 (3.60)	16.00 (4.11)	17.33 (4.26)	21.67 (4.76)	15.00 (3.98)	17.33 (4.26)	15.67 (4.08)	13.67 (3.82)
Control	water	15.00 (3.99)	20.00 (4.57)	24.67 (5.06)	29.33 (5.50)	23.67 (4.96)	22.67 (4.86)	20.33 (4.61)	24.00 (4.99)
CD (P=0.05)		**2.39**	**4.00**	**4.29**	**3.63**	**3.78**	**3.89**	**3.51**	**3.08**

Figures in the parentheses are square root transformed values
DA1S=days after 1st spray; DA2S=days after 2nd spray

3.3 Overall Performance and Comparative Analysis

When comparing data across both years, three treatments—Thiamethoxam 12.6% + Lambda-cyhalothrin 9.5% ZC, Quinalphos 25EC + Thiamethoxam 25WG, and Quinalphos 25EC + Thiacloprid 21.7 SC—consistently demonstrated the highest efficacy. These treatments significantly reduced both leaf infestation and larval populations over multiple observation intervals. Among them, the Thiamethoxam + Lambda-cyhalothrin combination proved to be the most consistent and effective across all parameters. Conversely, individual applications of Quinalphos 25EC or Thiacloprid 21.7 SC offered limited protection and resulted in higher infestation and larval counts, highlighting the advantage of using combination formulations for managing *L. malifoliella*.

IV. DISCUSSION

Apples play a crucial role in Kashmir's agricultural landscape, serving as a commercially significant fruit crop and contributing approximately 65% of India's total apple production (Khursheed et al., 2024). The recent emergence of the invasive pest *Leucoptera malifoliella* has understandably raised serious concerns among apple producers. In this context, the dissemination of reliable and up-to-date information on the efficacy of available insecticides is imperative. When no other effective or economically viable options exist, pesticides become essential tools for managing invasive species.

In the present two-year field study, data revealed that leaf infestation by the apple blotch leaf miner was significantly reduced at 10 and 20 days after both spray intervals when treated with thiamethoxam 12.6% + lambda-cyhalothrin 9.5% ZC, quinalphos 25EC + thiamethoxam 25WG, and quinalphos 25EC + thiacloprid 21.7 SC, compared with untreated control trees. The same treatments consistently maintained lower larval populations and leaf infestation at 10, 20, 30, and 40 days post-treatment.

Among the evaluated insecticides, chlorpyrifos 50EC + cypermethrin 5EC and quinalphos 25EC (used individually) consistently showed high levels of leaf infestation and larval populations throughout the observation period. All insecticides, when used in combination (except chlorpyrifos + cypermethrin), demonstrated high efficacy against *L. malifoliella*. The reduced performance of chlorpyrifos + cypermethrin may be due to their non-systemic and non-translaminar properties, which make them less effective against internal feeders like leaf miners. These insecticides primarily act on pests residing on the external surfaces of plant structures, rendering them inadequate for controlling pests that feed within leaf tissues.

Under the prevailing pest pressure and crop growth stages observed during the study, synthetic combination insecticides containing neonicotinoids provided the most satisfactory protection against the apple blotch leaf miner. Research supports the view that mixtures of two or more insecticides—especially those with differing or complementary modes of action—can yield additive or synergistic effects, even when used at low doses (Taillebois and Thany, 2016; Vidau et al., 2011; Yi et al., 2012). Commercial insecticide formulations that combine pyrethroids and neonicotinoids are frequently employed against pests resistant to pyrethroids. For example, mixtures such as cyhalothrin with thiamethoxam, cyfluthrin with imidacloprid, and bifenthrin with acetamiprid have demonstrated effective control of *Cimex lectularius* (Hemiptera: Cimicidae) (Wang et al., 2016).

The enhanced efficacy of such combinations can be explained by the complementary modes of action of neonicotinoids and pyrethroids. While pyrethroids target voltage-gated sodium channels and prolong their open state (Vais et al., 2000), neonicotinoids act as agonists at nicotinic acetylcholine receptors (nAChRs), causing overstimulation of the insect nervous system (Narahashi, 1992; Bodereau-Dubois et al., 2012). This neural overstimulation further facilitates pyrethroid binding by activating sodium channels, leading to lethal paralysis in insect pests. Literature strongly supports the use of such combinations, especially against pyrethroid-resistant populations.

Despite continuous oviposition and overlapping generations of *L. malifoliella*, which caused slight increases in infestation during the study, pest levels in treated plots remained significantly lower than in the control. The combined application of insecticides with distinct modes of action has gained widespread interest due to its potential to broaden the pest spectrum and mitigate resistance development (Daglish, 2008; Wakil et al., 2010; Athanassiou et al., 2013; Paudyal et al., 2017; Rumbos et al., 2018). Karanika et al. (2019) emphasized that combining insecticides with different toxicological mechanisms provides enhanced control efficacy compared to single compounds.

For instance, Athanassiou et al. (2013) demonstrated that a combination of betacyfluthrin and imidacloprid, which have entirely different mechanisms of action, significantly improved insecticidal activity, even in populations with known pyrethroid resistance. Similarly, in the present study, the combination of quinalphos (an organophosphate) and thiacloprid (a neonicotinoid) provided strong protection against the apple blotch leaf miner. When applied individually, both insecticides were considerably less effective. Their combination likely produced a synergistic effect: the organophosphate inhibits acetylcholinesterase, causing accumulation of acetylcholine at the synapse, while the neonicotinoid binds irreversibly to nAChRs, resulting in prolonged neural excitation (Taillebois and Thany, 2022). This interaction leads to severe overstimulation due to increased acetylcholine levels (Shao et al., 2013).

In this study, a slight resurgence in infestation and larval numbers was observed in neonicotinoid-treated trees later in the season. This slight resurgence likely reflects the emergence of new generations after the residual activity of the initial sprays began to decline, highlighting the need for careful timing of applications. However, the infestation remained low compared to untreated plots, suggesting that the long residual activity of neonicotinoids contributed to prolonged pest suppression. Previous studies have reported similar long-term effects. For instance, imidacloprid applied via irrigation maintained sufficient residue in grapevines throughout the growing season (Byrne and Toscano, 2006), and citrus trees treated with imidacloprid or thiamethoxam retained effective concentrations for up to five months (Castle et al., 2005). Likewise, a single application of thiamethoxam was shown to provide more than six months of protection in coffee plantations (de Souza et al., 2006).

In contrast, the mixture of chlorpyrifos and cypermethrin demonstrated poor efficacy against the apple blotch leaf miner, resulting in high leaf infestation and larval density even 10 days after application. This failure may be due to antagonistic interactions and potential resistance development from the frequent application of pyrethroids and organophosphates in fruit orchards. Such antagonism has previously been reported in several pest species, including *B. tabaci* from Pakistan (Ahmad, 2007), *Helicoverpa armigera* from Africa (Martin et al., 2003), and *Spodoptera littoralis* from Egypt (El-Guindy et al., 1983). However, in other species, synergistic effects of these combinations have also been observed—for instance in *B. tabaci* (Bryne and Devonshire, 1991), *Culex quinquefasciatus* (Corbel et al., 2004), *H. armigera* (Phokela et al., 1999; Ahmad, 2004), *Musca domestica* (Islam and Khalequzzaman, 2002), *Pectinophora gossypiella* (Keddis et al., 1986), *Plutella xylostella* (Attique et al., 2006), *Spodoptera litura* (Ahmad et al., 2009), *S. littoralis* (Ascher et al., 1986), and *Tetranychus* *urticae* (Chapman and Penman, 1980). The current findings indicate that the toxicity of traditional pyrethroids and organophosphates could be enhanced when combined with novel insecticides such as thiamethoxam or thiacloprid.

Overall, the application of insecticides significantly reduced both leaf infestation and larval population during both growing seasons. A key factor in effective pest suppression was ensuring thorough spray coverage of the foliage. Two timely applications provided sufficient protection throughout the growing season, with noticeably lower infestation levels than untreated trees. While field scouting remains important to determine the need for intervention, this study offers valuable insights for managing *L. malifoliella* and supports broader pest management efforts in other regions.

V. CONCLUSION

Given the recent invasion of *L. malifoliella* in northern India, extensive chemical intervention has become necessary. Our findings provide evidence-based recommendations on the use of neonicotinoid and pyrethroid/organophosphate mixtures as effective chemical tools for leaf miner control. Specifically, Thiamethoxam 12.6% + Lambda-Cyhalothrin 9.5% ZC and Quinalphos 25EC + Thiamethoxam 25WG are recommended as the most effective treatments. Growers should rotate these combinations with other modes of action to delay resistance development and should base spray decisions on regular field scouting and economic thresholds.

However, long-term sustainability depends on an Integrated Pest Management (IPM) approach. A holistic strategy—including the use of natural enemies (once established), botanical compounds, semiochemicals, plant-based deterrents, burlapping, bark scraping, and rigorous orchard sanitation—will be essential to manage this pest in an ecologically sound and economically viable manner.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this research paper.

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