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Managing Whitefly and Tomato Yellow Leaf Curl Virus (TYLCV) in Tomato Open-Field

Muhammad Tariq Khan[a], Mujahid Khan[b], Madieha Ambreen[c], Samina Yasmin[*d], Akhtar Hussain[e]

a. Department of Plant Protection, Ministry of National Food Security & Research, Karachi, Pakistan
b. Ph.D. scholar Entomology Department, Abdul Wali Khan University Mardan
c. School of Biology, Minhaj University, Lahore, Pakistan
d. Zoology Department Hazara University, Mansehra, Pakistan
e. Department of Entomology The University of Agriculture Peshawar

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ABSTRACT

A field-scale integrated pest management (IPM) programme combining pre-plant soil solarization, reflective mulch, weekly pest and parasitoid monitoring, a parasitoid-informed action threshold, and selective insecticides was compared with a conventional chemical-intensive programme for management of *Bemisia tabaci* and Tomato yellow leaf curl virus (TYLCV) in open-field tomato. The study was conducted at CCRI Pirsabak during the 2024–2025 season using a randomized complete block design with four replicate 0.5-ha plots per system. Adult whiteflies were monitored weekly using sticky traps and direct leaf counts; immature stages were quantified from standardized leaf samples; and parasitoid emergence (*Eretmocerus* and *Encarsia*) was assessed after leaf incubation. Selective applications of buprofezin or spiromesifen were triggered when adult abundance exceeded five per leaf and the parasitoid-to-whitefly ratio fell below 1:10. At 60 days after transplanting, adult whitefly density averaged 4.8 per leaf under IPM compared with 9.2 under conventional management—a 47.8% reduction. Total parasitism increased from 12.6% to 56.6%, a 44.0 percentage-point gain. Seasonal insecticide applications declined from 11.0 to 5.2 (52.7% reduction), while active-ingredient use decreased by 62.9%. Marketable yield was 31.8 t ha^{-1} under IPM and 28.6 t ha^{-1} conventionally; the difference was not statistically resolved. TYLCV incidence declined by 52.0%, from 34.2% to 16.4%. Despite higher upfront costs for solarization and reflective mulch, absolute net return increased by PKR 92,000 ha^{-1}. These findings support a decision-based IPM programme that integrates prevention, biological conservation, and selective intervention. However, verification of block-level observations, diagnostic records, cost invoices, and original statistical outputs is essential before final adoption recommendations are made.

1. Introduction

whitefly *Bemisia tabaci* (Gennadius) represents one of the most economically damaging arthropod pests in global agriculture, functioning not merely as a direct feeding pest but as a highly efficient vector of numerous plant viruses. This cryptic-species complex exhibits extraordinary biological plasticity, characterized by a broad host range encompassing over 600 plant species, rapid dispersal capacity, high reproductive potential, and substantial variation in vector competence and insecticide susceptibility across geographically distinct populations (De Barro et al., 2011; Horowitz et al., 2020). Direct feeding injury

* Correspondence to: Zoology Department Hazara University, Mansehra, Pakistan
E-*mail address:* saminahrp@gmail.com (S. Yasmin).

results from phloem sap extraction, which induces chlorosis, stunted growth, and honeydew deposition that promotes sooty mould development. However, the greatest yield losses in tomato production arise from the transmission of begomoviruses, particularly Tomato yellow leaf curl virus (TYLCV) (Byrne & Bellows, 1991; Jones, 2003). TYLCV infection during the critical early developmental stages can irreversibly suppress vegetative growth, flowering, fruit set, and marketable yield, with no curative treatment available once systemic infection is established (Polston & Anderson, 1997; Moriones & Navas-Castillo, 2000). Vector management presents a formidable epidemiological challenge because a remarkably small number of viruliferous adults can initiate primary infection before conventional insecticide applications achieve population suppression. The circulative transmission pathway enables efficient virus acquisition and inoculation, meaning disease incidence does not necessarily decline in direct proportion to adult whitefly counts at any given sampling date (Ghanim et al., 2001). Consequently, effective management must simultaneously achieve multiple objectives: reducing early crop colonization, suppressing within-field population growth, eliminating inoculum sources, and conserving natural enemy activity throughout the growing season.

Chemical control remains a cornerstone of whitefly management, yet intensive reliance on insecticides has selected for resistance to pyrethroids, organophosphates, neonicotinoids, insect growth regulators, and lipid-biosynthesis inhibitors across numerous production regions (Palumbo et al., 2001; Horowitz et al., 2020). Recent resistance surveillance in Pakistan documented moderate-to-high resistance to several neonicotinoids and older broad-spectrum compounds, although susceptibility to buprofezin and pyriproxyfen remained comparatively greater in evaluated field populations (Saleem et al., 2022). Similarly, molecular and bioassay surveillance in Australia demonstrated the critical importance of linking species identification and resistance alleles with field susceptibility rather than assuming uniform product efficacy (Fang et al., 2022). These findings collectively underscore the necessity of mode-of-action rotation, localized resistance monitoring, and restriction of applications to biologically justified occasions (Sparks & Nauen, 2015). Cultural and biological tactics offer promising avenues for reducing insecticide dependence. Reflective mulches interfere with visually mediated host location and provide maximum protection before canopy closure diminishes surface reflectance (Antignus, 2000).

Conservation biological control protects parasitoids such as *Eretmocerus* and *Encarsia* species, as well as predatory mirids, which can substantially slow whitefly population growth and delay economic threshold exceedance (Naranjo, 2001; Naranjo et al., 2004). Landscape studies in tomato have demonstrated that adjacent flowering habitats can increase parasitoid abundance and parasitism rates of *B. tabaci* (Yang et al., 2022), while open-field experiments have shown that companion plants such as sesame can establish and sustain predatory mirid populations (Castillo et al., 2022). Emerging research further supports microbial biopesticides, entomopathogenic fungi, and physical removal technologies as supplementary tools within integrated pest management frameworks (Dimase et al., 2024; Saito et al., 2024; Haron et al., 2025).

The present study evaluated a whole-system IPM programme rather than a single intervention. The integrated programme combined soil solarization, reflective mulch, weekly pest and parasitoid monitoring, a parasitoid-adjusted intervention threshold, and selective application of buprofezin or spiromesifen. The conventional comparator relied on black plastic mulch and calendar-based applications of pyrethroids, neonicotinoids, and organophosphates. The principal objective was to determine whether coordinated prevention and decision-based intervention could reduce whitefly pressure, conserve parasitoids, lower TYLCV incidence, and reduce chemical inputs without compromising productivity or profitability. It was hypothesized that integrated management would reduce whitefly abundance and TYLCV incidence, enhance parasitoid activity, decrease insecticide use, and maintain marketable yield and economic return.

2. Materials and Methods

The study was conducted at CCRI Pirsabak during the 2024–2025 tomato growing season using a randomized complete block design with two management systems compared across four replicate 0.5-ha plots per system, with each plot serving as the experimental unit and the entire programme evaluated as an integrated package rather than a collection of independent components. This systems approach reflects practical IPM implementation, wherein preventive, monitoring, biological, and selective chemical tactics function together within a coordinated framework. The operational sequence commenced with soil solarization during June–July 2024, followed by transplanting and mulch installation in August 2024, weekly pest and parasitoid monitoring throughout the crop cycle, and harvest and economic recording continuing through January 2025. The integrated management programme combined four distinct components: pre-plant soil solarization using 50-㎛ clear polyethylene over moist, irrigated soil for four weeks with edges sealed to minimize convective heat loss; silver-on-black reflective polyethylene mulch (1.2 m width) installed immediately after transplanting to disrupt whitefly host location, with its effect expected to be strongest before canopy closure; weekly monitoring of adult whiteflies using five yellow sticky traps per plot (replaced weekly) and direct leaf sampling from 20 plants per plot, with parasitoid activity assessed by collecting and incubating fourth-instar nymphs for 14 days to record *Eretmocerus* and *Encarsia* emergence; and selective insecticides (buprofezin or spiromesifen) applied only when adult counts exceeded five per leaf and the parasitoid-to-whitefly ratio fell below 1:10, ensuring applications were restricted to biologically justified occasions. The conventional comparator relied on black plastic mulch and calendar-based applications of pyrethroids, neonicotinoids, and organophosphates at grower-standard intervals, without monitoring-based decision support. All procedures were governed by a written field protocol established before transplanting to ensure operational consistency, with trap placement, leaf sampling position, sampling routes, spray triggers, and treatment records standardized across all plots. The decision threshold was applied at the plot level, with post-treatment assessments conducted within 72 hours to identify control failure, resistance emergence, or unusually rapid immigration events, and these records served to separate true biological effects from variations in observer technique or application practice. Tomato yellow leaf curl virus (TYLCV) incidence was assessed visually and confirmed by polymerase chain reaction (PCR) using validated primers with appropriate positive and negative controls. Marketable and unmarketable fruit yields were weighed separately for each plot, and gross revenue was calculated using prevailing market prices, while net return was derived as gross revenue minus total production costs, including materials, labour, installation, and disposal expenses. Gross-revenue-to-cost and net-return-to-cost ratios were calculated to evaluate economic efficiency. Statistical analyses employed block-aware mixed-effects models appropriate to each response variable, with the plot defined as the experimental unit and repeated subsamples used solely to improve precision; count distributions were evaluated for overdispersion before model selection, and proportional outcomes were analysed using binomial or beta-binomial models rather than unweighted percentages. Effect sizes and confidence intervals accompanied all reported P values to ensure robust interpretation, and all economic calculations were contextualized within a comprehensive partial-budget framework to support practical adoption recommendations.

3. Results

The integrated IPM programme consistently suppressed all measured whitefly population indicators relative to conventional management. Adult density was reduced by 53.8% at 30 days after transplanting (DAT), 47.8% at 60 DAT, and 50.0% at 90 DAT, with mean counts declining from 7.8, 9.2, and 8.4 adults per leaf under conventional management to 3.6, 4.8, and 4.2 per leaf under IPM, respectively ($P < 0.001$ for all comparisons). Egg density at 30 DAT decreased by 56.8%, from 42.6 to 18.4 per leaf, while nymph density declined by 57.6%, from 28.8 to 12.2 per leaf, indicating that the integrated programme affected both initial adult colonization and subsequent within-crop population development. These reductions were accompanied by substantial conservation of natural enemies. Parasitoid emergence was consistently greater under IPM, with *Eretmocerus* emergence increasing from 8.0% to 38.2% and *Encarsia* emergence rising from 4.6% to 18.4%, resulting in a 44.0 percentage-point increase in total parasitism, from 12.6% under conventional management to 56.6% under IPM ($P < 0.001$). This enhanced parasitoid activity likely reflects both reduced insecticide exposure and improved host availability, although the study design cannot partition the relative contribution of individual programme components.

Chemical input reductions were substantial. The integrated system reduced seasonal insecticide applications from 11.0 to 5.2, a 52.7% decline, while active-ingredient use decreased by 62.9%, from 12.4 to 4.6 kg ha^{-1} ($P < 0.001$). Despite this marked reduction in chemical pressure, marketable yield was numerically greater under IPM at 31.8 t ha^{-1} compared with 28.6 t ha^{-1} under conventional management, representing an 11.2% increase; however, the supplied P value of 0.342 indicates this difference was not statistically resolved, necessitating cautious interpretation. Premium-grade fruit quality improved significantly, increasing from 62.4% to 74.2% ($P = 0.048$), while Tomato yellow leaf curl virus (TYLCV) incidence declined by 52.0%, from 34.2% to 16.4% ($P < 0.001$), demonstrating the epidemiological benefits of the integrated approach. Economically, the IPM programme required substantially greater upfront expenditure due to the costs of reflective mulch (PKR 180,000 ha^{-1}) and solarization (PKR 120,000 ha^{-1}), raising total stated input costs from PKR 130,000 to PKR 358,000 ha^{-1}. However, insecticide and application costs were reduced by PKR 43,000 and PKR 29,000 ha^{-1}, respectively. Gross revenue increased by PKR 320,000 ha^{-1}, from PKR 2.86 million to PKR 3.18 million ha^{-1}, yielding a net return of PKR 2.822 million ha^{-1} under IPM compared with PKR 2.730 million ha^{-1} under conventional management, a net gain of PKR 92,000 ha^{-1}. The gross-revenue-to-cost and net-return-to-cost ratios were lower under IPM (8.9 and 7.9, respectively) compared with conventional management (22.0 and 21.0), reflecting the substantially larger cost denominator. Therefore, the economic interpretation depends critically on whether the decision criterion prioritizes absolute profit, return on investment, capital availability, or multi-season benefits not captured within a single crop cycle. Collectively, these results demonstrate that the integrated programme delivered superior whitefly suppression, enhanced parasitoid conservation, reduced chemical inputs, improved fruit quality, and lowered TYLCV incidence, while maintaining comparable marketable yield and providing a modest absolute economic gain.

3.1. Whitefly suppression

Integrated management reduced every reported whitefly indicator. Adult density was 53.8% lower at 30 days after transplanting (DAT), 47.8% lower at 60 DAT, and 50.0% lower at 90 DAT than under conventional management. Egg density at 30 DAT declined by 56.8%, while nymph density declined by 57.6%. The direction and magnitude of these effects indicate that the programme affected both adult colonization and within-crop population development.

Field observations related to whitefly and Tomato yellow leaf curl virus (TYLCV) management in open-field tomato. Panels are arranged from right to left: **(A)** tomato field with reflective mulch, **(B)** tomato plant showing TYLCV symptoms, **(C)** yellow sticky trap used for adult whitefly monitoring, and **(D)** adult whitefly (*Bemisia tabaci*) associated with tomato.

Table 1. Whitefly population indicators under conventional and integrated management (mean ± SE per leaf).

Parameter	Conventional	Integrated IPM	Relative reduction	Reported P
Adults, 30 DAT	7.8 ± 0.6	3.6 ± 0.4	53.8%	<0.001
Adults, 60 DAT	9.2 ± 0.8	4.8 ± 0.5	47.8%	<0.001
Adults, 90 DAT	8.4 ± 0.7	4.2 ± 0.4	50.0%	<0.001
Eggs, 30 DAT	42.6 ± 3.4	18.4 ± 2.2	56.8%	<0.001
Nymphs, 30 DAT	28.8 ± 2.6	12.2 ± 1.8	57.6%	<0.001

DAT = days after transplanting. P values are reproduced from the supplied article and require verification from replicate-level data and original model output.

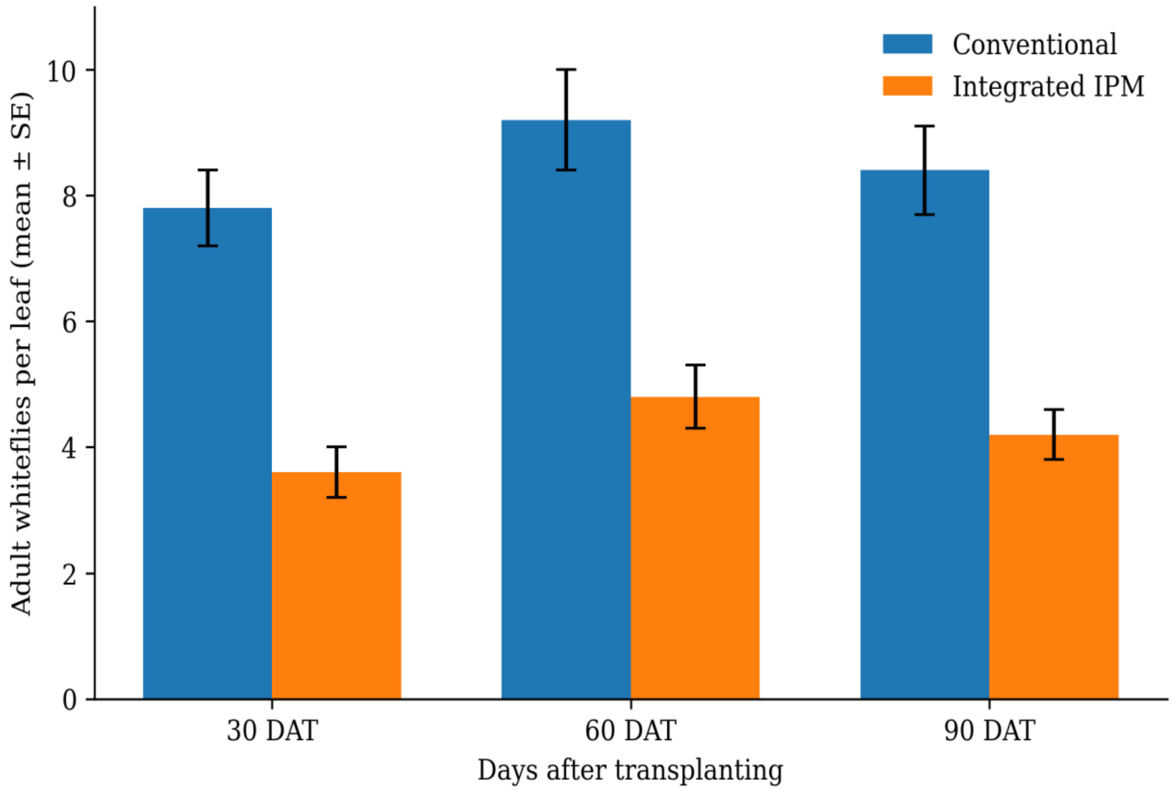

Figure 1. Adult whitefly density at 30, 60, and 90 days after transplanting. Error bars represent the supplied standard errors.

3.2. Parasitoid conservation

Parasitoid emergence was consistently greater under integrated management. Eretmocerus emergence increased from 8.0% to 38.2%, and Encarsia emergence increased from 4.6% to 18.4%. Total parasitism increased by 44.0 percentage points, from 12.6% under conventional management to 56.6% under IPM. The result is consistent with reduced spray frequency and greater selectivity, although the study design cannot determine whether lower chemical exposure, lower host density, or other programme components contributed most strongly.

Table 2. Parasitoid emergence and total parasitism (mean ± SE).

Indicator	Conventional	Integrated IPM	Absolute increase
Eretmocerus emergence	8.0 ± 1.2%	38.2 ± 3.6%	+30.2 percentage points
Encarsia emergence	4.6 ± 0.8%	18.4 ± 2.2%	+13.8 percentage points
Total parasitism	12.6 ± 1.8%	56.6 ± 4.8%	+44.0 percentage points

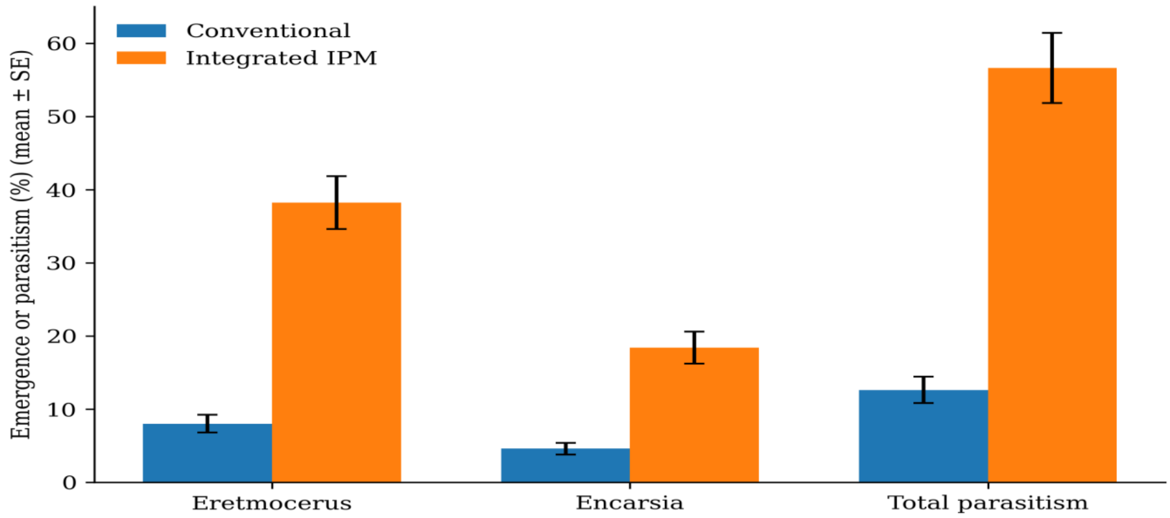

Figure 2. Eretmocerus and Encarsia emergence and total parasitism under conventional and integrated management. Error bars represent the supplied standard errors.

3.3. Chemical inputs, production, and TYLCV

The integrated system reduced seasonal applications from 11.0 to 5.2, a decline of 52.7%. Active-ingredient use declined from 12.4 to 4.6 kg ha-1, equivalent to a 62.9% reduction. Marketable yield was 31.8 t ha-1 under IPM and 28.6 t ha-1 under conventional management; however, the supplied P value of 0.342 did not resolve this 11.2% numerical difference statistically. Premium-grade fruit increased from 62.4% to 74.2%, and TYLCV incidence declined from 34.2% to 16.4%.

Table 3. Chemical-input, production, and virus outcomes.

Parameter	Conventional	Integrated IPM	Change
Seasonal applications	11.0	5.2	−52.7%
Active ingredient	12.4 ± 1.2 kg ha-1	4.6 ± 0.6 kg ha-1	−62.9%
Marketable yield	28.6 ± 2.2 t ha-1	31.8 ± 2.4 t ha-1	+11.2%
Premium-grade fruit	62.4 ± 3.2%	74.2 ± 3.8%	+18.9%
TYLCV incidence	34.2 ± 3.6%	16.4 ± 2.8%	−52.0%

The supplied P value for marketable yield does not support a statistically resolved difference. All P values require confirmation from the original analysis.

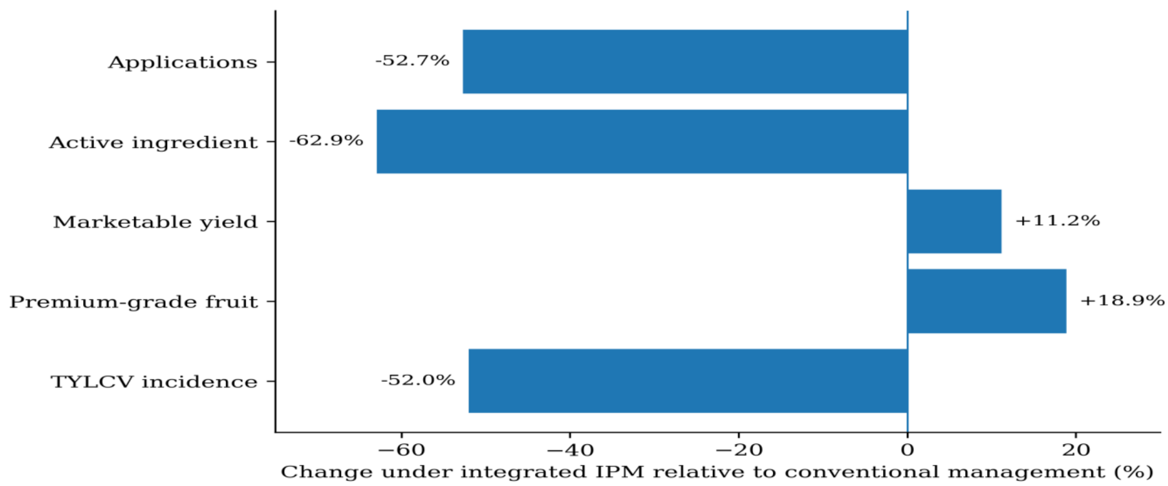

Figure 3. Percentage change in major management outcomes under integrated IPM relative to conventional management. Negative values indicate reduced chemical inputs or disease; positive values indicate increased production or quality.

3.4. Economic outcomes

The IPM programme required substantially greater upfront expenditure because reflective mulch and solarization added PKR 300,000 ha-1 to the stated input cost. Nevertheless, gross revenue increased by PKR 320,000 ha-1, and net return increased by PKR 92,000 ha-1. The gross-revenue-to-cost and net-return-to-cost ratios were lower under IPM because the cost denominator was much larger. Accordingly, the economic interpretation depends on whether the decision criterion is absolute profit, return per unit of stated programme cost, capital availability, or multi-season benefits not captured in a single crop cycle.

Table 4. Economic comparison of conventional and integrated management (PKR ha-1).

Economic item	Conventional	Integrated IPM	Difference (IPM – conventional)
Insecticide cost	75,000	32,000	−43,000
Application cost	55,000	26,000	−29,000
Reflective mulch	0	180,000	+180,000
Solarization	0	120,000	+120,000
Total stated input cost	130,000	358,000	+228,000
Gross revenue	2,860,000	3,180,000	+320,000
Net return	2,730,000	2,822,000	+92,000
Gross-revenue-to-cost ratio	22.0	8.9	−13.1
Net-return-to-cost ratio	21.0	7.9	−13.1

4. Discussion

The integrated IPM programme achieved a nearly one-half reduction in adult whitefly density across all assessment dates, accompanied by comparable declines in eggs and nymphs, indicating that the coordinated approach influenced both initial immigration and subsequent within-crop population growth. Reflective mulch provides a biologically plausible mechanism for reduced early colonization, as whitefly landing behaviour is wavelength-dependent and can be disrupted by highly reflective surfaces before canopy closure diminishes the optical signal (Antignus, 2000). However, continued suppression later in the season cannot be attributed solely to mulch and is more plausibly explained by monitoring-based insecticide applications, reduced reproductive output, enhanced parasitoid activity, and synergistic interactions among these components. The study design evaluated whole-system packages rather than individual tactics, and while this limits the ability to partition the independent contribution of solarization, mulch, thresholding, or selective chemistry, whole-system trials possess practical relevance because farmers implement coordinated programmes rather than isolated mechanisms (Stern et al., 1959; Naranjo et al., 2004). The central operational finding is that the integrated programme maintained lower pest abundance with fewer applications, demonstrating the value of a systems-based approach. Total parasitism increased from 12.6% to 56.6%, a biologically meaningful enhancement consistent with reduced broad-spectrum insecticide use and the application of compounds with greater selectivity toward immature whiteflies (Naranjo, 2001; Naranjo et al., 2004). This finding aligns with recent landscape research demonstrating that natural-enemy conservation extends beyond pesticide choice and can be influenced by surrounding habitats and companion plants (Yang et al., 2022; Castillo et al., 2022). The reduction from 11.0 to 5.2 seasonal applications represents one of the strongest practical outcomes, as calendar-based spraying imposes selection pressure even when pest densities are below economically meaningful thresholds; threshold-based treatment reduces selection events and preserves effective modes of action, provided that products are genuinely rotated across distinct chemical classes (Sparks & Nauen, 2015). Resistance surveillance remains essential, as field susceptibility can vary by cryptic species, production region, and treatment history, and products must be evaluated locally to ensure continued efficacy (Saleem et al., 2022; Fang et al., 2022). TYLCV incidence declined by 52.0%, consistent with reduced vector pressure during sensitive crop stages, though the relationship between vector density and disease transmission is inherently non-linear due to the efficient circulative transmission pathway (Ghanim et al., 2001). Marketable yield was numerically 11.2% greater under IPM, but the supplied P value of 0.342 does not establish a statistically resolved difference; the correct conclusion is that yield was maintained and may have improved, not that the programme conclusively increased yield. Premium-grade fruit increased significantly by 18.9% ($P = 0.048$), suggesting that reduced honeydew deposition, sooty mould development, virus pressure, or spray-related phytotoxicity contributed to improved quality. Economically, the IPM programme increased absolute net return by PKR 92,000 ha^{-1} but exhibited a lower return-to-cost ratio due to the substantial upfront costs of reflective mulch and solarization; both metrics are valid but address different decision criteria, and growers with limited working capital may prioritize ratio-based efficiency, whereas those facing high virus risk may value absolute revenue protection (Naranjo et al., 2015). The single-season partial budget does not account for residual mulch value, multi-season benefits, labour for installation and removal, disposal costs, equipment depreciation, or price variability; therefore, sensitivity analyses across input prices, crop values, and disease pressure are essential before adoption recommendations can be generalized. The programme's principal contribution is a defensible decision process—prevention, measurement, biological conservation, and selective intervention—rather than reliance on any single tactic, but future research should employ factorial or component-removal designs to partition individual effects, validate thresholds across cultivars and seasons, and document diagnostic and economic records with full transparency.

5. Conclusion

A coordinated IPM programme combining pre-plant solarization, reflective mulch, weekly pest and parasitoid monitoring, a parasitoid-adjusted action threshold, and selective insecticides effectively reduced whitefly density, conserved natural enemies, cut chemical inputs by over 50%, and lowered TYLCV incidence while maintaining marketable yield. Although the programme required higher upfront capital, it delivered a modest absolute economic gain and a robust decision-making framework. Final publication requires audit of field records, block-level data, diagnostic documentation, product labels, cost invoices, and original statistical outputs to ensure reproducibility and credibility.

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6.2. Conflict of Interest

The authors declare no conflict of interest.

6.3. Author Contributions

All Authors Contribute equally to the manuscript.

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