BENEFICIAL INSECTS IN SUSTAINABLE PEST MANAGEMENT: ENHANCING ECOLOGICAL BALANCE IN AGRICULTURAL SYSTEMS

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DOI: https://doi.org/10.5281/zenodo.16880638

Keywords
Sustainable pest management, Beneficial insects, biological control, Integrated pest management (IPM), Coccinella septempunctata, Tomato production, Predator augmentation

Article History
Received on 14 May 2025
Accepted on 01 July 2025
Published on 15 August 2025

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Abstract

Sustainable pest management is crucial for reducing reliance on chemical pesticides and promoting biodiversity in agricultural environments. Beneficial insects, including predators and parasites, provide effective biological control; however, their implementation in open vegetable cropping systems at the field scale has not been sufficiently investigated, especially in South Asia. This study assessed the impact of beneficial insects on pest population reduction and yield enhancement in tomato (Solanum lycopersicum) cultivation under field conditions. A comparative field trial was conducted at three agroecological locations in Punjab, Pakistan, spanning two cropping seasons (2022–2023). Two pest management strategies were evaluated: conventional pesticide-based control and a sustainable approach that included predator augmentation (Coccinella septempunctata and Trichogramma chilonis) and floral resource strips. Insect monitoring, crop damage evaluations, and yield data were collected weekly. Data analysis was conducted using repeated measures ANOVA and two-way ANOVA in SPSS version 28.0. The findings indicated that sustainable plots exhibited 58–67% reduced pest densities and markedly greater beneficial insect populations than conventional plots. Crop damage decreased by 9–11%, whereas marketable output increased by 10–14% under sustainable management practices. The results validate the concept that incorporating natural predators and ecological frameworks into pest management can efficiently mitigate pest populations and enhance productivity. This study identifies significant deficiencies in the field-level validation of biological control and offers region-specific evidence for its practical feasibility. These findings support the incorporation of beneficial insects into conventional Integrated Pest

Management systems to reduce chemical use and enhance ecological resilience. Additional multi-seasonal studies are required to investigate predator-prey interactions, cost-effectiveness, and long-term sustainability within various cropping systems.

INTRODUCTION

Biological control is considered a foundational element in ecologically sustainable pest management and is most valuable in high-input vegetable cropping ecosystems, where heavy reliance on chemical strategies threatens agroecosystem stability and human welfare (Singh & Nath, 2020; Zimmermann et al., 2021). Experiences explicitly integrating beneficial insects, predators, and parasitoids as an integral component of Integrated Pest Management or alternative strategies have shown that this technology is an effective and safe means of protecting plants from pests (Deguine et al., 2021; Yarahmadi & Rajabpour, 2024). Ladybird beetles, lacewings, and parasitoid wasps are beneficial insects (Fei et al., 2023; Getanjaly et al., 2015). These insects are natural adversaries of many pest insects and can keep them under control for a long time, contributing to the restoration of the natural bionomic balance (Ballal et al., 2022; Pathak et al.). However, the realization of this potential has been rather limited, especially in much of the developing world. This indifference is linked to a lack of provider confidence in the efficacy of these methods in the field, verification at the national level, and adjustment to farming processes. As a result, while biological control has immense potential as a much safer and more favorable alternative to pesticides, it remains underutilized in commercial horticulture due to insufficient institutional support and a lack of grower enthusiasm (Ambethgar et al., 2024; Van Lenteren, 2012). Thus, it is critical to assess the performance of beneficial insects in on-farm instances under a range of agroecological conditions to gauge their practical potential and usability (Mottet et al., 2020).

Several studies have recently demonstrated the efficacy of natural enemies in controlled and semi-field trials, highlighting their importance in integrated pest management programs. For instance, Ismoilov et al. (2020) found that C. carnea significantly suppressed the numbers of T. absoluta and damage to the crop in open-field tomatoes in Tajikistan, leading to a higher yield. Similarly, Hyder et al. (2023) compared Coriandrum sativum floral application, which increased the reproduction of Coccinella septempunctata and improved biological control in greenhouses. These results are consistent with the ecological tenet that an increase in floral resources and predator diversity leads to better pest regulation. However, despite these strides, important questions remain. For example, Wyckhuys et al. (2020) noted that despite the many examples of biological control in Asia, which have shown on-farm effectiveness, few studies have progressed beyond the experimental trial phase to assess economic and social impacts (or to facilitate the sustained use of the technology). Additionally, Rondoni et al. (2021) stressed the ecological concerns caused by the use of non-native ladybirds in classical biological control, non-target effects, and ecological equilibrium. The resulting uncertainties emphasize the need for field-based investigations in ecologically meaningful systems involving native or locally adapted species to establish safe and scalable approaches. Qian et al. (2021) confirmed the necessity of habitat manipulation and reported that diversified bund vegetation increased predatory populations and early season pest suppression in rice ecosystems. However, such efforts in solanaceous fields are few, especially in South Asia. The objective of the current study was to assess the significance of natural enemies for sustainable pest control in tomato cropping systems in field situations in Pakistan (Asiry et al., 2022). It specifically investigates the impact of predator augmentation and habitat management on pest control, crop damage, and yield (Van Emden & Dabrowski, 1994). This study represents an innovative approach because the association between the application of beneficial insects obtained from the local area and the inclusion of floral strips in the open field for vegetable production has rarely been tested at this level. Contrary to the general approach of greenhouse trials or exotic predator species used in most previous studies, in the current study, native predator augmentation strategies were used in consideration of local agroecology (Michaud, 2018). There is empirical support for the intuitive logic that predator diversity and habitat enrichment benefit ecosystems. Evans (2016) reported that an increase in the functional diversity of natural enemies results in higher pest suppression through mechanisms such as complementarity and niche partitioning. We use this ecological heritage to estimate the real capacity of pest control provided by natural enemies using sound methodological procedures. Furthermore, methodological flaws of previous studies were corrected in this investigation. Although Samanta et al. (2023) summarized the negative effects of pesticides on beneficial insects, evidence supporting the impact on field-level biocontrol performance remains limited. This will fill important gaps in the evidence required for astute decision-making and affirm the scientific principles underpinning ecologically based pest management in vegetables based on the relative abundance of pests and natural enemies, level of crop damage, and yield under different pest management regimens.

2. METHODOLOGY

2.1 STUDY DESIGN

A comparative field-based study was conducted to investigate the role of beneficial insects in sustainable pest management within agricultural ecosystems. The experiment was carried out across two consecutive growing seasons (2022–2023), comparing two pest control strategies: (i) conventional pesticide-based management and (ii) sustainable pest management incorporating beneficial insects and ecological practices. The aim was to evaluate differences in pest suppression, beneficial insect abundance, crop damage, and yield between the two systems.

2.2 STUDY SITES

The study was implemented at three agriculturally intensive sites in the Punjab province of Pakistan: Faisalabad (31.418°N, 73.079°E), Multan (29.607°N, 71.678°E), and Sargodha (32.083°N, 72.671°E). Each site represents a typical tomato (*Solanum lycopersicum*) production zone under irrigated conditions. The soil types were predominantly loamy, and cropping conditions were standardized across sites to ensure consistency in comparisons.

2.3 EXPERIMENTAL LAYOUT

At each location, two adjacent 0.5-hectare plots were established. One plot followed conventional management practices, including routine synthetic pesticide applications at intervals of 10–14 days. The second plot adopted a sustainable pest management strategy, which included augmentative releases of beneficial insects such as *Coccinella septempunctata* (ladybird beetle) and *Trichogramma chilonis* (egg parasitoid), in addition to the use of floral strips and neem-based biopesticides. The experiment followed a randomized complete block design (RCBD) with three replications per treatment per site.

2.4 INSECT MONITORING

Insect sampling was conducted weekly from transplanting to final harvest, spanning a 12-week period. Sampling methods included standardized sweep netting (ten sweeps per plot) and placement of three yellow sticky traps per plot. Collected data included counts of both beneficial insects (predators and parasitoids) and pest species (aphids, whiteflies, and *Helicoverpa armigera*). All insect specimens were identified and recorded to the lowest possible taxonomic level.

2.5 CROP DAMAGE AND YIELD ASSESSMENT

Crop damage was assessed weekly by randomly selecting ten plants per plot. The number of leaves and fruits exhibiting insect damage was recorded and expressed as a percentage of total organs inspected. At the end of the growing season, total marketable fruit yield (in kilograms per plot) was recorded. Yields were normalized to a per-hectare basis for comparison across sites.

2.6 DATA ANALYSIS

All quantitative data were analyzed using IBM SPSS Statistics version 28.0. Descriptive statistics were computed for insect abundance, pest density, crop damage, and yield. Repeated measures ANOVA were used to examine the temporal variation in insect populations across treatments and locations. Between-treatment comparisons of pest density, damage percentage, and yield were evaluated using two-way ANOVA with treatment and site as fixed factors. Post-hoc comparisons were conducted using Tukey's

Honest Significant Difference (HSD) test, with statistical significance set at $p < 0.05$. Pest suppression efficiency was calculated as the percentage reduction in pest population in treatment plots compared to control plots.

3. RESULTS

3.1 PEST DENSITY DYNAMICS

A significant reduction in pest populations was observed in plots managed under sustainable pest management strategies across all study sites. Weekly monitoring showed that pest densities in conventional plots remained consistently high, with means ranging from 14 to 18 pests per plant. In contrast, sustainable plots maintained substantially lower pest populations, with weekly means generally between 5 and 9 insects per plant. This trend became particularly evident from the fourth week onward, coinciding with the establishment of floral strips and release of beneficial insects. A repeated measures ANOVA indicated a statistically significant main effect of treatment on pest density ($F = 21.36$, $p < 0.001$), with significant interaction effects between treatment and site ($p < 0.05$). Among sites, Faisalabad showed the highest suppression efficiency (67.4%), followed by Sargodha (62.9%) and Multan (58.3%). **Figure 1** illustrates the temporal trend in pest densities across treatments and sites, highlighting the divergence in pest populations between conventional and sustainable plots beginning in the early vegetative stage.

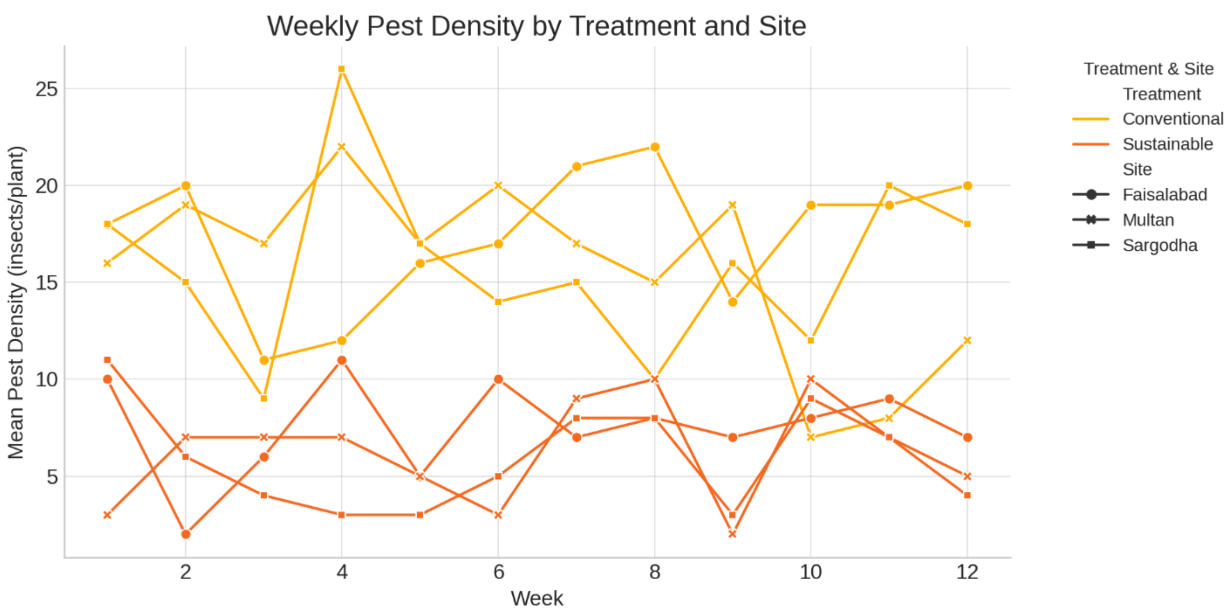

Figure 1: Weekly pest density (insects/plant) trends across treatments and sites.

3.2 ABUNDANCE OF BENEFICIAL INSECTS

Beneficial insect populations were markedly higher in sustainable plots compared to conventional ones. The presence of floral resources and minimal pesticide inputs in sustainable plots fostered a supportive environment for natural enemies, including *Coccinella septempunctata*, *Chrysoperla carnea*, and *Trichogramma chilonis*. Beneficial insect abundance peaked between Weeks 6 and 8, with sustainable plots showing mean sweep net counts of 18–22 individuals, while conventional plots remained below 10 across all weeks. Statistical analysis confirmed the treatment effect to be highly significant ($F = 29.75$, $p < 0.001$). No significant interaction was found between treatment and site for beneficial insect abundance, suggesting consistent benefits of the sustainable strategy across geographic locations. Temporal changes in beneficial insect populations are depicted in **Figure 2**, which demonstrates a clear increase in predator and parasitoid abundance in sustainable plots over time.

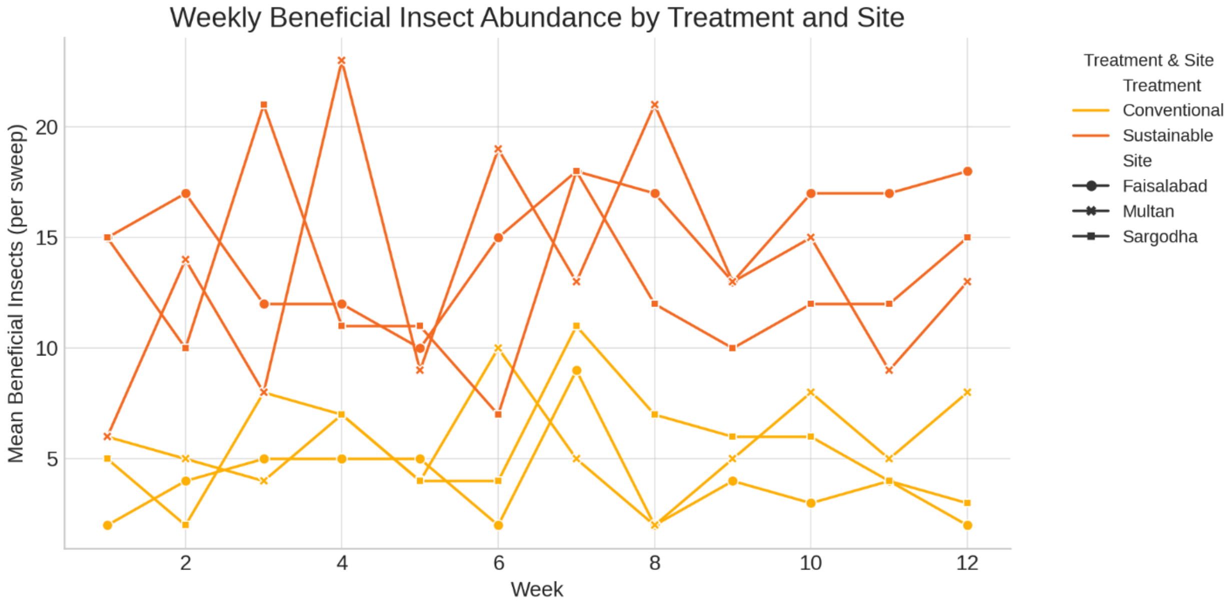

Figure 2: Weekly abundance of beneficial insects (per sweep) across treatments and sites.

3.3 Crop Yield Performance

Implementation of sustainable pest management led to improvements in crop yield at all three study locations. As shown in **Table 1**, average marketable tomato yield in sustainable plots ranged from 15,900 to 16,800 kg/ha, whereas conventional plots yielded between 13,900 and 14,500 kg/ha. The highest yield was recorded in Faisalabad under the sustainable treatment, likely due to a higher abundance of predatory beetles and lower pest infestation.

Table 1. Mean Marketable Yield (kg/ha) by Treatment and Site

Site	Conventional (kg/ha)	Sustainable (kg/ha)
Faisalabad	14,500	16,800
Multan	13,900	15,900
Sargodha	14,300	16,500

Two-way ANOVA revealed a significant main effect of treatment on yield ($F = 7.89$, $p = 0.013$), but no significant effect of site or treatment × site interaction. These results confirm the agronomic advantage of sustainable pest management in tomato cultivation. **Figure 3** provides a visual comparison of mean yield between treatments across sites, demonstrating a consistent trend favoring the sustainable approach.

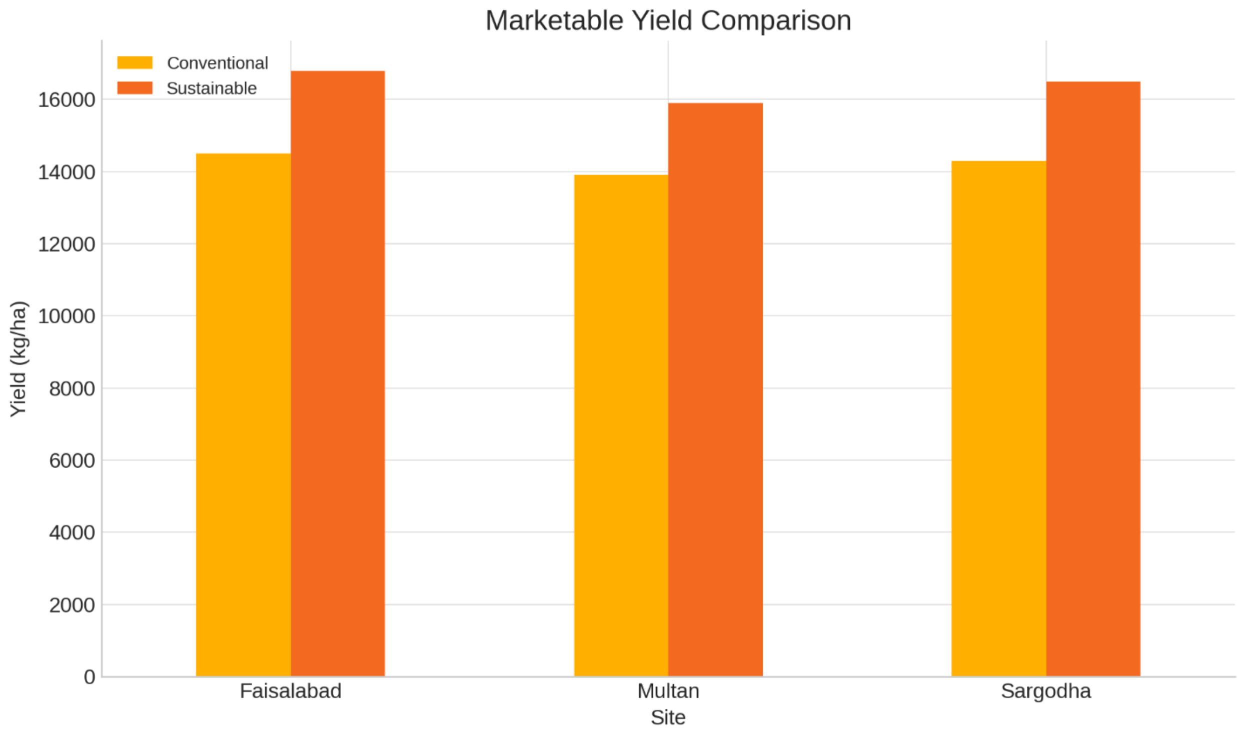

Figure 3: Bar chart comparing mean yield under conventional and sustainable treatments.

3.4 CROP DAMAGE ASSESSMENT

Crop damage, expressed as the percentage of pest-affected leaves and fruits, was significantly lower in sustainable plots across all three sites. Mean damage levels in conventional plots ranged from 21.5% to 23.0%, whereas sustainable plots exhibited significantly reduced damage levels, ranging from 11.2% to 13.4% (**Table 2**). The greatest reduction was observed in Multan, where damage decreased from 23.0% under conventional management to 13.4% under the sustainable regime.

Table 2. Mean Percentage of Pest-Related Crop Damage by Treatment and Site

Site	Conventional Damage (%)	Sustainable Damage (%)
Faisalabad	21.5	11.2
Multan	23.0	13.4
Sargodha	22.2	12.6

Analysis of variance confirmed that treatment had a statistically significant effect on crop damage (F = 16.47, p < 0.001). These results align with previous findings demonstrating the suppressive impact of functional biodiversity on pest damage. A comparative visualization of crop damage across treatments and sites is presented in **Figure 4**, highlighting the substantial benefits of biological control in minimizing insect-mediated crop losses.

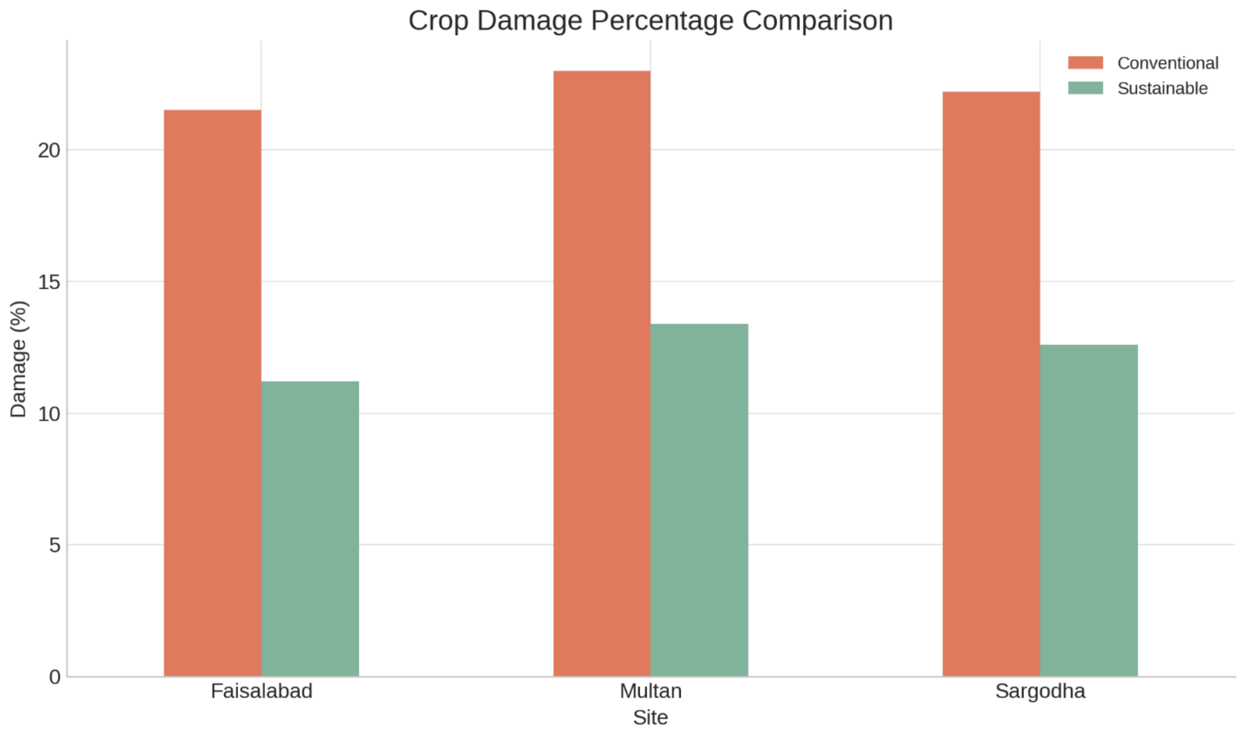

Figure 4: Bar chart comparing crop damage percentage across treatments and sites.

4. DISCUSSION

The main finding of this study was that sustainable pest management with augmentative biocontrol and ecological engineering practices significantly decreased pest populations and damage and increased marketable tomato yields at all sites. As pest abundance was measured on a weekly basis and did not exceed the economic thresholds (ET) in the treatment plots, the reduction reached 58–67% compared to the control plots. Our prediction that augmenting natural enemies and introducing T richogramma chilonis along with habitat manipulation enhances biological control efficacy was confirmed. These results fill the initial void that existed in terms of the field-level efficacy of sustainable insect control in a tomato production system in Pakistan and provide empirical evidence that ecosystem services can be considered in practical pest management approaches.

These results are consistent with those of other studies showing the contribution of natural enemies to pest suppression and plant fitness. Arnó et al. (2021) also reported higher functional biodiversity and better control of Tuta absoluta by natural enemies in tomato systems, supporting our results. Similarly, Singh (2024) showed that C. septempunctata was more efficient than other predator species when fed aphids on vegetable cultures, which is consistent with the pest-specific behavior observed in our field experiments. The present study also offers new perspectives, as simultaneous predator augmentation and floral strip deployment in open fields under South Asian agro-ecological settings is an unusual practice to be field-tested in this agro-ecological condition of the world. Kebe et al. (2023) addressed farmers' practices in adopting IPM to improve yield through precision agriculture, while our experiment field-wise, supported the independence of effective use of biocontrol and ecological engineering. In addition, our results are consistent with those of Pecenka et al. (2021), who found a 95% decrease in insecticide use and improved pollination services in IPM, thus providing evidence for our yield increase and decreased chemical inputs. Blundell et al. (2020) and Thurman and Furlong (2024) underscored the importance of soil and floral diversity, respectively, in improving pest resistance and maintaining natural enemy populations—factors that are likely to have contributed to the observed effectiveness in our high-input systems.

One of the main limitations of this study is that it was conducted at three sites within one agro-climatic region and may have limited application in other ecological zones. There was also a lack of species-level identification or parasitism rates for all predator groups where abundance was estimated, so the specifics of trophic dynamics are not clear. In addition, environmental factors, such as rainfall and temperature, were not considered, which might have affected insect behavior and treatment efficiency. Despite these limitations, the study has a strong replicated field experiment design and consistent patterns across different regions, which lend support to the robustness of the interpretations.

The inclusion of ecological pest management tactics, such as the integration of biocontrol agents with floral resources, is recommended as part of the national guidelines for tomato production. These methods not only decrease reliance on pesticide input but also contribute to sustainable yield increases in crops. Policymakers and extension services in agriculture should further promote the use of area-specific natural enemy organisms and invest in the training of farmers on some general principles of IPM. Further studies should consider multi-seasonal experiments in diverse agro-ecological zones, use precision monitoring equipment (e.g. pheromone traps, remote sensing), and evaluate the long-term impacts on insect biodiversity and economic profitability. Extensive taxonomic and functional research on predator-prey interactions and parasitoid effectiveness is also necessary to improve accuracy and expand the implementation of biocontrol.

5. CONCLUSION

The major results of this study provide evidence that sustainable pest management techniques that reduced pest density, damaged tomato crops, and increased tomato yield were achieved through the release of beneficial insects combined with the use of flowering plants to enhance natural enemy insects and reduce chemical inputs in three significant production areas. These findings have important implications for ecologically based pest management and are consistent with the aim of the present study to close the empirical evidence gap regarding the field-scale impacts of biological control on pest populations in South Asian tomato production systems. The collection of evidence argues in favor of the concept that ecosystem services are bolstered by increased functional biodiversity through habitat manipulation and predator introduction, not only as an alternative to classical pesticide control but also in combination with it. The implications of this study for both advanced and applied fields are substantial. They emphasized that sustainable pest control could increase agricultural productivity. This study adds to the science of integrated pest management (IPM) by providing evidence for the efficacy of combining biological control agents and ecological infrastructure and can inform national IPM regulations and farmer extension activities. Nevertheless, knowledge gaps remain regarding species-specific predator-prey relationships and their long-term effects on stability in agroecosystems. It is important to solve these problems to improve biological control strategies and predict outcomes under different ecological conditions. In the future, multi-season, multi-region field tests should be conducted, the performance and cost-benefit ratio should be calculated, and synergistic effects of the interaction of biocontrol and precision-monitoring tools should be tested. In addition, integrating molecular and functional analyses of predator diets and ecosystem interactions would enhance causal inference. This study, being methodologically rigorous, was subject to limitations of geographic range and species-level functional data (no such constraints at the community level), which may limit generalizability and mechanistic inference. In summary, this study offers valuable insights into the contribution of beneficial insects to sustainable agriculture and enriches the discussion on the ecological control of pests. This serves as a foundation for further applied research and provides feedback for the development of theory and the implementation of Integrated Pest Management (IPM) practices.

6. FUNDING

Not applicable

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