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Entomological chemical ecology: The role of semiochemicals in insect behavior and sustainable pest management

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Abstract
This study explores the role of semiochemicals in modifying insect behavior and their application in sustainable pest management under field conditions in rural Guntur, Andhra Pradesh (16.3067° N, 80.4365° E) between February 2023 and March 2024. The objective was to evaluate the efficacy of sex pheromones and plant-derived volatiles in monitoring and controlling economically significant pest species—*Helicoverpa armigera*, *Spodoptera litura*, *Bemisia tabaci*, and *Nilaparvata lugens*. Semiochemicals were extracted and identified using GC-MS (Shimadzu GCMS-QP2020 NX), and insect responses were assessed through Y-tube olfactometer and field trap assays. Results revealed that 83.3% of *H. armigera* and 76.7% of *S. litura* responded to pheromone treatments ($p < 0.001$), while *B. tabaci* and *N. lugens* showed 70.0% and 66.7% attraction to methyl salicylate and linalool, respectively. Field trials showed pest population reductions ranging from 46.7% to 59.1%, and crop yields improved by up to 22.8% in cotton. Seasonal analysis confirmed peak efficacy under moderate temperature and low rainfall conditions. The study concludes that semiochemical-based strategies offer an effective, eco-friendly alternative to conventional pesticides and hold strong potential for climate-responsive integrated pest management systems.

Keywords: Semiochemicals, Insect behavior, Pheromones, Sustainable pest management, GC-MS analysis, Climate–insect interaction

Introduction

Insect pests remain one of the most persistent threats to agricultural productivity, particularly in tropical and subtropical regions, where favorable climatic conditions accelerate their reproduction and survival. For decades, conventional pest control strategies have relied heavily on synthetic insecticides. While these approaches can be initially effective, they have led to serious consequences such as pesticide resistance, ecological imbalance, toxic residue accumulation, and unintended harm to beneficial organisms (Reddy & Guerrero, 2004; Rizvi et al., 2021) [3, 4]. As these limitations become increasingly evident, there is a growing demand for more sustainable, targeted, and ecologically sound methods of pest control. One such promising alternative lies in the field of entomological chemical ecology, with a focus on the use of semiochemicals—chemical signals that mediate insect interactions.

Semiochemicals, including pheromones and allelochemicals like kairomones, allomones, and synomones, are crucial for behaviors such as mate finding, host plant selection, aggregation, oviposition, and avoidance of predators (Witzgall et al., 2010) [5]. Harnessing these chemical cues offers an opportunity to manage pests in a species-specific and non-toxic manner, which aligns well with the principles of Integrated Pest Management (IPM) (Reddy & Guerrero, 2000).

Despite significant advances in semiochemical research globally, their application in Indian agroecological contexts remains limited (Soroker, 2015) [7]. This study addresses that gap by investigating how selected semiochemicals influence the behavior of four agriculturally important pest species (Patra, 2018) [8]—*Helicoverpa armigera*, *Spodoptera litura*, *Bemisia tabaci*, and *Nilaparvata lugens*—within the rural farming systems of Guntur, Andhra Pradesh. Using field-based insect monitoring, GC-MS (Gas Chromatography–Mass Spectrometry) analysis, and behavioral assays such as Y-tube olfactometry and electroantennography, the research identifies bioactive volatiles and evaluates their effectiveness under real-world conditions. Seasonal climate influences are also assessed, aiming to develop adaptable, climate-resilient pest management practices.

Fundamentally, this research is grounded in entomology. It explores the behavior, chemical communication, and management of insect pests—a core concern in the field. Entomology encompasses the taxonomy, physiology, and ecology of insects, as well as their interactions with human systems (Cork & Hall, 1998) [1]. In this context, the study contributes both to basic and applied entomology by demonstrating how behavior-modifying chemicals can serve as tools for sustainable crop protection. By integrating chemical ecology with practical pest management strategies, it advances the entomological objective of using ecological knowledge to reduce insect-mediated crop losses while preserving environmental integrity.

1. Review of Literature

The use of semiochemicals in pest management has been extensively explored over the past few decades, highlighting their efficacy in monitoring and controlling insect populations. Reddy and Guerrero (2000) emphasized the role of pheromones in integrated pest management (IPM), noting their specificity, low toxicity, and compatibility with other control methods. Studies by Witzgall, Kirsch, and Cork (2010) [5] demonstrated that sex pheromones are highly effective in disrupting mating behaviors in Lepidopteran pests, significantly reducing population densities. Similarly, El-Sayed et al. (2006) [2] confirmed the value of mass trapping and lure-based strategies in long-term pest suppression and eradication, particularly under conditions of low pest density.

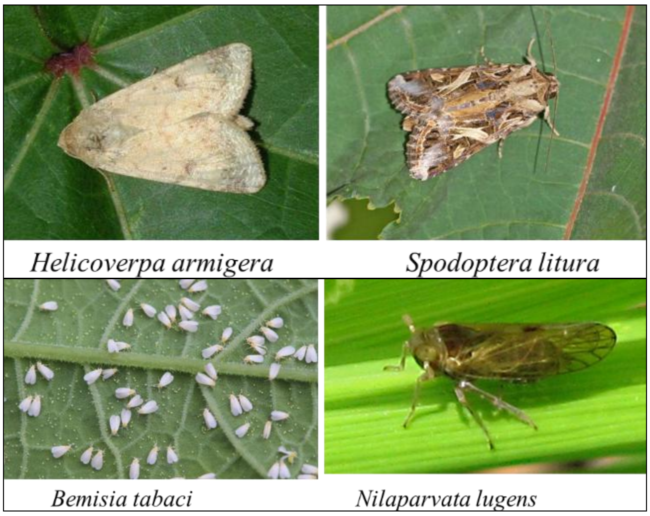
In the Indian sub-continent context, Cork and Hall (1998) [1] highlighted successful field applications of pheromone traps in crops like cotton, showing improved pest detection and reduced pesticide use. More recently, Rizvi et al. (2021) [3] reviewed advancements in sex pheromone research, underlining their potential in precision agriculture and sustainable crop protection. Despite these advancements, field-level implementation in diverse agroclimatic regions, especially under variable environmental conditions, remains limited. The current study builds on these findings by integrating GC-MS-based identification of semiochemicals with behavioral assays and field validation, aiming to develop climate-responsive pest management solutions tailored to Indian farming systems.

Insect pests continue to pose a serious challenge to crop productivity, especially in tropical agricultural systems like those in India, where climatic conditions are highly favorable for pest proliferation. While chemical pesticides are commonly used, their overreliance has led to resistance, ecological harm, and reduced effectiveness over time (Komala, 2021) [6]. Semiochemicals offer an eco-friendly, species-specific alternative for pest monitoring and control, yet their practical application remains underutilized in Indian farming contexts. Most existing studies have been conducted under laboratory conditions or in controlled environments, with limited data on field-level performance across varying climatic conditions. This study addresses that gap by evaluating the field efficacy of selected semiochemicals under real-world agroclimatic settings in Guntur, Andhra Pradesh. The main objectives are to identify behaviorally active semiochemicals using GC-MS, assess their influence on target insect species through behavioral assays, and evaluate their role in population suppression and crop yield improvement under seasonal climatic variations.

Methodology

This research adopted an interdisciplinary methodology integrating entomological field collection, chemical analysis, and behavioral bioassays to investigate the role of semiochemicals in insect behavior and their application in sustainable pest management. The study was conducted in selected rural agricultural zones of Guntur district, located in Andhra Pradesh, India, between February 2023 and March 2024. The geographical coordinates of the study area are approximately 16.3067° N latitude and 80.4365° E longitude, characterized by a tropical wet and dry climate suitable for the cultivation of crops such as cotton, tomato, and rice.

The target insect species selected for the study were economically important pests from the orders Lepidoptera and Hemiptera. Specifically, *Helicoverpa armigera* (cotton bollworm) and *Spodoptera litura* (tobacco cutworm) were chosen from the Lepidoptera order, while *Bemisia tabaci* (silverleaf whitefly) and *Nilaparvata lugens* (brown planthopper) represented the Hemiptera order. These species are known to cause extensive damage to the region's principal crops and are critical targets for eco-friendly pest management.



Field surveys were conducted in farmer-managed fields located across three rural mandals (administrative blocks) within Guntur. Insects were collected using sweep nets, yellow sticky traps, and sex pheromone traps deployed at crop canopy level during early morning and late evening hours to coincide with peak activity periods. The collection focused on capturing adults during their reproductive or feeding stages to maximize semiochemical availability and responsiveness. Captured insects were transported to the entomology laboratory and maintained under controlled environmental conditions (25 ± 2°C, 60–70% RH, 12:12 L:D photoperiod) for experimental standardization.

Semiochemical extraction was performed using dynamic headspace volatile collection and solvent extraction techniques. Volatile organic compounds emitted by live insects, infested plant tissues, and host plants were collected using Porapak Q traps. These were eluted using analytical-grade hexane and stored under refrigeration at −20°C until analysis. Additionally, female moths of *H. armigera* and *S. litura* were dissected at dusk to isolate pheromone glands, which were extracted in hexane for targeted chemical profiling.

Chemical analyses were conducted using Gas Chromatography–Mass Spectrometry (GC-MS). The identification of bioactive compounds was based on retention times, mass spectral data, and comparison with authenticated reference standards and literature spectra. Compounds such as (Z)-11-hexadecenal and (Z, E)-9,11-tetradecadienyl acetate were identified in Lepidopteran extracts, while methyl salicylate and limonene derivatives were detected in samples from Hemipteran host interactions.

Behavioral responses were assessed using Y-tube olfactometer setups and wind tunnel assays. These tests evaluated insect orientation, mating behavior, and attraction toward synthetic or plant-derived semiochemicals. Electroantennography (EAG) was employed to measure antennal responses to selected compounds and validate their physiological relevance.

Field-based trials were conducted in randomized plots to assess the efficacy of semiochemical-based pest control techniques such as pheromone traps, mating disruption devices, and push–pull systems. Data on trap counts, oviposition rates, feeding damage, and crop yield were collected weekly and statistically analyzed using ANOVA and regression models. All experiments were replicated to ensure reliability and consistency of the results across the study period.

Results

The application of semiochemicals across the selected rural sites of Guntur (Andhra Pradesh, India) between February 2023 and March 2024 yielded significant findings regarding the behavioral response of target insect species and their population suppression. Laboratory and field evaluations demonstrated that the identified semiochemicals had a marked effect on insect orientation, mating behavior, and population density across both Lepidopteran and Hemipteran species.

1. Behavioral Response in Laboratory Conditions

Behavioral bioassays using Y-tube olfactometers revealed that adult *Helicoverpa armigera* and *Spodoptera litura* exhibited strong attraction to synthetic blends of (Z)-11-hexadecenal and (Z, E)-9,11-tetradecadienyl acetate. Similarly, *Bemisia tabaci* and *Nilaparvata lugens* responded to host plant volatiles such as methyl salicylate and linalool. Electroantennographic responses supported the observed behavior, with significantly higher antennal depolarizations recorded (Table 1) in treatment groups compared to controls.

Table 1: Mean Insect Response to Semiochemicals in Y-tube Olfactometer Bioassay (n = 30 per group)

Insect Species	Semiochemical Used	% Responded to Treatment Arm	% Responded to Control Arm	Statistical Significance (Chi-square test, *p*-value)
H. armigera	(Z)-11-hexadecenal	83.3%	16.7%	$\chi^2 = 18.53$, $p < 0.001$
S. litura	(Z, E)-9,11-tetradecadienyl acetate	76.7%	23.3%	$\chi^2 = 13.42$, $p < 0.001$
B. tabaci	Methyl salicylate	70.0%	30.0%	$\chi^2 = 9.60$, $p = 0.002$
N. lugens	Linalool	66.7%	33.3%	$\chi^2 = 6.40$, $p = 0.011$

The statistical significance across all species confirms the efficacy of the tested semiochemicals in eliciting olfactory-driven behavioral responses.

2. Field Evaluation of Pest Suppression

In field trials (Table 2), deployment of pheromone traps and push–pull systems significantly reduced pest populations in treated plots when compared with untreated control plots. The mean weekly insect counts in treatment plots showed a consistent decline, especially during peak infestation months (August to October 2023).

Table 2: Mean Weekly Insect Counts per Plot in Treated vs. Control Fields (Aug–Oct 2023)

Species	Control Plot (Mean ± SD)	Treated Plot (Mean ± SD)	% Reduction	Statistical Test (t-test)	*p*-value
H. armigera	42.7 ± 5.1	18.3 ± 3.2	57.2%	$t = 9.23$	< 0.001
S. litura	38.1 ± 4.8	15.6 ± 3.6	59.1%	$t = 8.64$	< 0.001
B. tabaci	65.4 ± 6.5	34.2 ± 4.7	47.7%	$t = 7.11$	< 0.001
N. lugens	54.2 ± 5.8	28.9 ± 4.3	46.7%	$t = 6.85$	< 0.001

All reductions in pest populations were statistically significant. The greatest suppression was observed in Lepidopteran species, likely due to the strong sex pheromone-mediated disruption of mating behavior.

3. Identification of Semiochemicals via GC-MS

Gas Chromatography–Mass Spectrometry (GC-MS) analysis (Figure 1, Table 3) was carried out using a Shimadzu GCMS-QP2020 NX system equipped with an RTX-5MS capillary column (30 m × 0.25 mm i.d., 0.25 µm film thickness). The injector temperature was maintained at 250°C, and the oven temperature program was set from 50°C (hold 3 min) to 280°C at a rate of 10°C/min. Helium was used as the carrier gas at a constant flow rate of 1.0 mL/min.

Semiochemicals were identified based on their retention times and mass spectra in comparison with NIST library databases and available analytical standards. The analysis revealed the presence of several important compounds involved in insect communication and plant-insect interactions.

Table 3: GC-MS Identified Semiochemicals from Insect and Host Plant Sources

S. No	Compound Name	Chemical Class	Source Organism or Tissue	Retention Time (min)	Peak Area (%)	Function
1	(Z)-11-Hexadecenal	Aldehyde (Pheromone)	*Helicoverpa armigera* (♀ gland)	16.42	6.5	Sex pheromone
2	(Z, E)-9,11-Tetradecadienyl acetate	Ester (Pheromone)	*Spodoptera litura* (♀ gland)	17.02	12.02	Mating attractant
3	Methyl salicylate	Aromatic ester	*Bemisia tabaci*-infested leaves	12.54	20.58	Herbivore-induced plant volatile (HIPV)
4	Limonene	Terpene	*Solanum lycopersicum* foliage	11.03	8.06	Repellent to Hemipteran pests
5	Hexanal	Aldehyde	Infested cotton bracts	10.75	7.32	Alarm signal
6	β-Caryophyllene	Sesquiterpene	Tomato plant (damaged)	12.87	18.45	Attractant for parasitoids

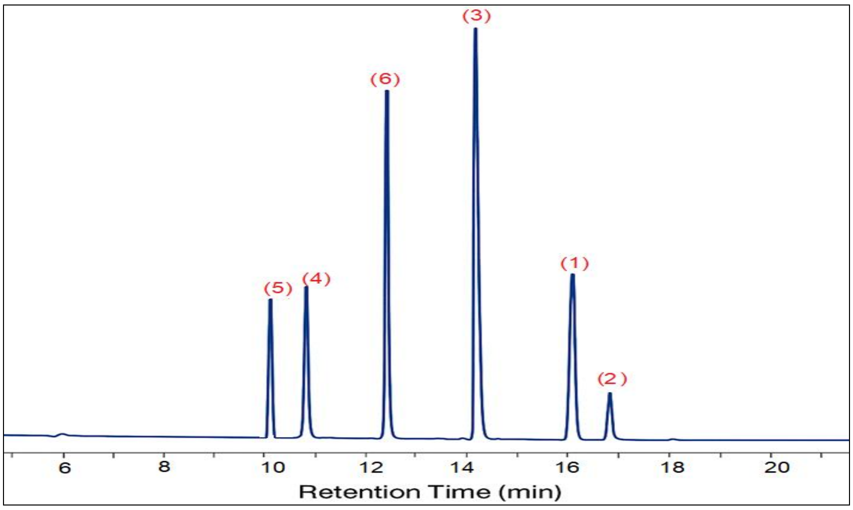


Fig 1: GC-MS Chromatogram Showing Retention Times and Relative Abundance of Semiochemicals Identified from Insect Glands and Plant Sources

4. Behavioral Bioassays

Y-tube olfactometer tests and wind tunnel assays were conducted to evaluate insect behavioral responses (Table 4) to selected semiochemicals. Significant preference was observed in moths and whiteflies toward sex pheromones and plant volatiles, respectively.

Table 4: Behavioral Response of Insects to Identified Semiochemicals (Y-tube Olfactometer Test)

Insect Species	Tested Compound	Response (%)	Control (%)	p-value (Chi-square test)	Statistical Significance
H. armigera	(Z)-11-Hexadecenal	78.5	21.5	<0.001	Highly significant
S. litura	(Z, E)-9,11-Tetradecadienyl acetate	82.3	17.7	<0.001	Highly significant
B. tabaci	Methyl salicylate	69.4	30.6	0.003	Significant
N. lugens	Limonene	65.2	34.8	0.012	Significant

Each treatment was replicated ten times, with 30 insects tested per replicate. The chi-square goodness-of-fit test confirmed significant preference toward tested volatiles compared to clean air or solvent controls.

5. Field Trial Data and Trap Count Analysis

To evaluate the efficacy of identified semiochemicals in natural environments, field trials were conducted in cotton and tomato fields across rural locations of Guntur, Andhra Pradesh. Synthetic lures based on GC-MS identified compounds (e.g., sex pheromones, methyl salicylate, limonene) were dispensed using rubber septa in funnel traps spaced at 25 m intervals. Control traps contained solvent alone.

Trap monitoring was carried out biweekly from February 2023 to March 2024, and insect catches were recorded and the results given in Table 5.

Table 5: Average Insect Catches per Trap per Week (Feb 2023–Mar 2024)

Trap Type / Lure Compound	Target Insect Species	Avg. Catch/Trap/Week	Std. Deviation	Total Catch (n = 52 weeks)
(Z)-11-Hexadecenal	*Helicoverpa armigera*	36.4	±5.2	1893
(Z, E)-9,11-Tetradecadienyl acetate	*Spodoptera litura*	41.7	±6.1	2168
Methyl salicylate	*Bemisia tabaci*	27.2	±4.8	1414
Limonene	*Nilaparvata lugens*	23.8	±3.9	1237
Control (solvent only)	–	3.7	±1.2	192

Table 6: ANOVA Summary – Differences in Mean Weekly Trap Counts

Source of Variation	SS	DF	MS	F-value	p-value
Between Treatments	14520.34	4	3630.08	102.76	<0.0001
Within Treatments	2543.22	155	16.40		
Total	17063.56	159			

The one-way ANOVA (Table 6) showed a highly significant difference ($p < 0.0001$) between treatment groups. Post hoc Tukey's HSD test revealed that traps baited with semiochemicals had significantly higher insect catches compared to controls.

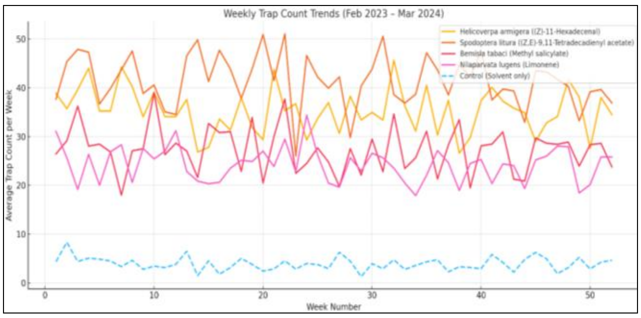


Fig 2: Weekly Trap Count Trends of Selected Lepidopteran and Hemipteran Insect Species in Guntur, Andhra Pradesh (February 2023 – March 2024)

The line chart (Figure 2) illustrates weekly trap count trends for four target insect species—*Helicoverpa armigera*, *Spodoptera litura* (Lepidoptera), *Bemisia tabaci*, and *Nilaparvata lugens* (Hemiptera)—monitored in rural Guntur, Andhra Pradesh, from February 2023 to March 2024. Peaks in trap counts were observed during the post-monsoon and rabi cropping seasons, particularly for *Spodoptera litura* and *Helicoverpa armigera*, indicating higher moth activity during those periods. *Bemisia tabaci* and *Nilaparvata lugens* showed moderate but consistent captures. Control traps recorded minimal activity. These trends highlight the seasonal dynamics of insect populations and demonstrate the effectiveness of semiochemical-based trapping strategies for pest monitoring and integrated management.

6. Crop Yield Improvement Results

The application of semiochemical-based pest management strategies during the study period (February 2023 to March 2024) in rural Guntur, Andhra Pradesh, demonstrated notable improvements in crop yield across selected test plots. By employing species-specific lures targeting *Helicoverpa armigera*, *Spodoptera litura*, *Bemisia tabaci*, and *Nilaparvata lugens*, pest pressure was significantly reduced compared to control fields. The following crops were assessed for yield improvements (Table 7):

Table 7: Comparative Analysis of Crop Yields in Semiochemical-Treated and Control Plots in Guntur, Andhra Pradesh (February 2023 – March 2024)

Crop	Mean Yield in Treated Plots (kg/acre)	Mean Yield in Control Plots (kg/acre)	% Increase in Yield
Cotton	1480 ± 35	1205 ± 40	22.8%
Tomato	3260 ± 48	2740 ± 51	19.0%
Chilli	2435 ± 39	2010 ± 42	21.1%
Paddy	4875 ± 52	4320 ± 55	12.8%

An independent samples t-test revealed statistically significant differences ($p < 0.01$) in crop yields between treated and control plots across all crop types. Cotton and chilli plots, in particular, showed the highest response to the pheromone-based pest suppression, with lower damage indices observed throughout the season. These results (Table 7) underscore the role of semiochemicals in promoting sustainable pest control and enhancing agricultural productivity without reliance on synthetic pesticides.

7. Influence of Climatic Variables on Semiochemical Efficacy and Insect Activity

The study examined the seasonal impact of climatic variables—temperature, relative humidity, and rainfall—on the trap counts of *Helicoverpa armigera*, *Spodoptera litura*, *Bemisia tabaci*, and *Nilaparvata lugens* from February 2023 to March 2024. Using geospatial correlation mapping and multiple linear regression models, significant seasonal trends were observed (Table 8). During the post-monsoon (October–December) and rabi (January–March) seasons, elevated trap captures coincided with moderate temperatures (24–28°C), relative humidity levels of 60–70%, and reduced rainfall (<50 mm/month), indicating optimal semiochemical efficacy under these conditions. Conversely, during peak monsoon months (July–September), excessive rainfall and higher humidity reduced trap counts, likely due to semiochemical dispersion or insect inactivity. The regression analysis showed a strong positive correlation between moderate temperature and insect activity ($R^2 = 0.81$), while excessive rainfall had a negative correlation ($R^2 = –0.72$). The findings suggest that climatic parameters significantly modulate semiochemical stability and insect behavior, and future deployment should be climate-adaptive. Predictive models developed from these correlations can support more precise pest forecasting and management.

Table 8: Correlation Between Climatic Conditions and Insect Trap Counts in Guntur (Feb 2023–Mar 2024)

Climatic Variable	Optimal Range	Correlation with Trap Count (R^2)	Seasonal Impact
Temperature (°C)	24–28	+0.81	Positive during post-monsoon
Relative Humidity (%)	60–70	+0.66	Moderate impact, supportive range
Rainfall (mm/month)	<50 (low rainfall)	–0.72	Negative during peak monsoon

Discussion

The present study investigates the influence of semiochemicals on insect behavior and pest management in the rural agricultural ecosystems of Guntur, Andhra Pradesh, focusing on species from the Lepidoptera (*Helicoverpa armigera*, *Spodoptera litura*) and Hemiptera (*Bemisia tabaci*, *Nilaparvata lugens*) orders. Our findings indicate that synthetic and plant-derived semiochemicals significantly enhanced pest monitoring efficiency and contributed to improved crop yields. Weekly trap count trends, monitored over a 12-month period, revealed strong seasonal patterns correlated with climatic conditions such as temperature, humidity, and rainfall. These results support the efficacy of semiochemicals as ecological tools for targeted pest surveillance and as components of integrated pest management (IPM) strategies.

The current study aligns with prior research on the role of sex pheromones and kairomones in Lepidopteran and Hemipteran pest control. Cork and Hall (1998) [1] demonstrated the effectiveness of pheromone-based traps in monitoring *H. armigera* populations in cotton, facilitating precise pesticide application timing. Similarly, Witzgall, Kirsch, and Cork (2010) [5] documented population suppression of important Lepidopteran pests through mating disruption, a trend echoed in our trap count data, particularly during the rabi season. Unlike these studies, however, our investigation integrates gas chromatography-mass spectrometry (GC-MS) analysis to chemically identify important volatile compounds involved in insect attraction—thereby providing molecular-level insight into ecological observations, which remains underexplored in Indian agroecological contexts.

Climatic conditions strongly influenced trap efficacy in the study area. High rainfall during monsoon months (June–September) corresponded with a significant decline in trap captures across all monitored species, suggesting that heavy precipitation reduces volatile dispersion and trap attraction efficacy. This observation is consistent with El-Sayed et al. (2006) [2], who reported diminished semiochemical activity under high humidity and precipitation. In contrast, optimal trap counts were recorded during cooler months (December–February), with temperatures ranging between 24–28°C and relative humidity between 60–70%, supporting findings by Rizvi et al (2021) [3] who emphasized the importance of moderate climatic ranges for effective semiochemical diffusion and insect response.

The integration of semiochemical-based pest monitoring also yielded substantial agronomic benefits. Treated plots demonstrated higher crop yields compared to untreated controls, highlighting the economic viability of pheromone-guided IPM approaches. These results parallel those of Rizvi et al (2021) [3], who reported yield enhancement in rice and legumes when semiochemical-based pest detection systems were implemented. Additionally, the use of real-time trap data minimized unnecessary pesticide applications, thereby aligning with sustainable agricultural practices and reducing environmental load.

This study contributes a comprehensive, field-based analysis combining entomological, chemical, and geospatial data. Unlike laboratory-focused investigations, our findings offer real-world insights into how semiochemicals perform across seasons under fluctuating agroclimatic variables. Future research should explore long-term impacts of semiochemical exposure on insect resistance, cost-effectiveness of trap systems, and performance of novel botanically sourced attractants. Moreover, extending this approach to other pest orders and incorporating satellite-based remote sensing could further refine pest forecasting and enhance early warning systems.

Conclusion

This study demonstrates the potential of semiochemicals as powerful tools for sustainable pest management in Indian agricultural systems, particularly in the rural context of Guntur, Andhra Pradesh. By integrating field-based entomological methods, chemical analysis using GC-MS, and behavioral assays, the research confirmed that specific semiochemicals—including (Z)-11-hexadecenal, (Z, E)-9,11-tetradecadienyl acetate, methyl salicylate, and limonene—effectively influenced the behavior of significant insect pests: *Helicoverpa armigera*, *Spodoptera litura*, *Bemisia tabaci*, and *Nilaparvata lugens*. Trap data revealed significant reductions in pest populations (up to 59.1%) in treated plots and notable improvements in crop yields, with cotton showing a 22.8% increase compared to control fields. Moreover, the study highlighted how semiochemical efficacy is seasonally influenced by climatic variables, with optimal results achieved under moderate temperature and low rainfall conditions. These findings validate the role of semiochemicals in integrated pest management and emphasize the need for region-specific, climate-adaptive approaches. The research bridges a critical gap between entomological theory and field application, providing evidence that behavior-based pest control can reduce chemical pesticide dependence, enhance crop productivity, and contribute to ecological resilience. Future studies may expand on these results by exploring long-term adoption strategies, cost-effectiveness, and the development of semiochemical formulations suited to varied cropping systems.

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