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Integrated Pest Management of Brinjal Fruit and Shoot Borer, *Leucinodes orbonalis* (Guenee.): Strategies, Emerging Technologies and Meteorological Drivers

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ABSTRACT

This review comprehensively evaluated the integrated pest management (IPM) strategies for sustainable control of the brinjal fruit and shoot borer, *Leucinodes orbonalis* (Guenee), a major constraint to eggplant production across South and Southeast Asia. The study emphasized a multi-tactical framework that integrated biological, cultural, mechanical, chemical, and emerging biotechnological interventions to minimize pest incidence and crop loss. Biological control constituted a cornerstone of IPM, utilizing key parasitoids such as *Trathala flavoorbitalis* and *Trichogramma chilonis*, as well as microbial agents including *Trichoderma longibrachiatum* and entomopathogenic nematodes (*Heterorhabditis* spp.), which enhanced natural suppression of larval populations. Cultural and mechanical practices-particularly weekly pruning and destruction of infested shoots and fruits, coupled with field sanitation-were essential for disrupting the pest life cycle. Pheromone-based monitoring and mass trapping served as precise tools for surveillance and population reduction, enabling timely and need-based interventions. Chemical control remained an integral component under threshold-based conditions; however, the use of selective insecticides such as Spinosad and Chlorantraniliprole in rotation with biopesticides was recommended to delay resistance and conserve beneficial arthropods. Additionally, transgenic *Bt* brinjal expressing the Cry1Ac protein provided a highly effective and environmentally compatible option, substantially reducing insecticide dependence. Collectively, the integration of these complementary tactics within an ecologically balanced IPM framework offered a sustainable, cost-effective, and scientifically robust approach for managing *L. orbonalis*, improving yield stability, and enhancing profitability in eggplant cultivation systems.

KEYWORDS: IPM, *Bt* brinjal, resistance, biopesticides, *Cry1Ac*

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1. INTRODUCTION

Eggplant (*Solanum melongena* L.) is a major solanaceous vegetable cultivated across tropical and subtropical regions, particularly in South and Southeast Asia (Gautam et al., 2019). It is an important source of nutrition and income for millions of smallholder farmers owing to its high productivity, market demand, and adaptability to varied agro-climatic conditions. However, production is severely constrained by several insect pests, the most destructive being the brinjal fruit and shoot borer *Leucinodes orbonalis* (Guenee.), which remains a persistent problem across Asia (Srinivasam, 2008). The pest attacks the crop from the vegetative to fruiting stages, causing continuous damage and substantial yield losses. Larvae bore into tender shoots and developing fruits, disrupting physiological functions, reducing plant vigour, and impairing fruit quality (Amin et al., 2019). Infested shoots exhibit drooping or withering, while bored fruits become unmarketable due to internal tunnelling and frass contamination (Choudhury et al., 2023). Consequently, yield and market value decline drastically. Reported yield losses range between 30 and 70%, depending on crop stage, varietal susceptibility, and environmental factors (Islam et al., 1999; Dhandapani et al., 2003; Singh et al., 2024). Under severe infestations, marketable yields can fall below economic viability, confirming *L. orbonalis* as the most significant biotic constraint to sustainable brinjal production. Traditionally, farmers have relied heavily on repeated applications of broad-spectrum insecticides, often exceeding 80–100 sprays season^{-1} in some production regions (Dhandapani et al., 2003). Such indiscriminate use has led to multiple challenges, including rapid insecticide resistance, resurgence of secondary pests, depletion of natural enemies, and accumulation of harmful residues on harvested fruits. These practices pose serious environmental and health risks, highlighting the urgent need for sustainable, eco-friendly, and economically viable pest management alternatives. Integrated Pest Management (IPM) offers a comprehensive, ecologically sound framework for managing *Leucinodes orbonalis* while ensuring environmental and economic sustainability (Sharma et al., 2024). IPM integrates compatible tactics-cultural, mechanical, biological, chemical, and biotechnological-based on pest ecology and population dynamics (Thomas et al, 2025). It promotes need-based interventions guided by economic thresholds, conserving beneficial organisms, minimizing residues, and improving profitability. This multi-tactical approach is widely regarded as superior to conventional control methods, as it delays resistance development, enhances ecosystem stability, and sustains long-term productivity (Thomas et al., 2025). Field-based studies across Asia have shown that IPM modules combining pheromone-based monitoring, regular pruning of infested shoots, augmentative releases of egg parasitoids (*Trichogramma chilonis*), and selective application of biorational insecticides can substantially reduce fruit infestation and increase marketable yield (Dhandapani et al., 2003). Integrated strategies that harmonize cultural sanitation, biological control, and judicious chemical use-rotated according to mode of action-consistently outperform conventional insecticide programs (Khater, 2012). Recent demonstrations further support this approach: Kumar et al. (2022) reported that a biorational-based IPM module improved yields and cost-benefit ratios under brinjal cultivation in Tamil Nadu. Similarly, Kumawat et al. (2024) observed that bio-pesticide-led management in the Bundelkhand region significantly increased net incomes compared with conventional sprays. On-farm IPM trials across Telangana confirmed that integrated modules reduced pest incidence and enhanced economic returns relative to standard farmer practices (Rajashekar et al., 2025). Collectively, these studies underscore the effectiveness and economic viability of multi-component IPM strategies for sustainable brinjal production. Recent technological advances have strengthened IPM frameworks for brinjal. Transgenic *Bt* brinjal expressing the *Cry1Ac* protein provides durable resistance against *L. orbonalis*, reducing insecticide dependence and enhancing environmental safety. Additionally, microbial biopesticides and RNA interference (RNAi)-based approaches offer promising eco-friendly alternatives for pest suppression. This review synthesized information on integrated management strategies, emphasizing the synergistic roles of cultural, mechanical, biological, chemical, and emerging biotechnological tools, while addressing field implementation, economic aspects, and ecological implications for sustainable control of the brinjal fruit and shoot borer.

2. CULTURAL AND MECHANICAL PRACTICES

Sanitation, pruning and crop management are lowcost, highimpact practices that reduce available larval habitat and lower population carryover; they are frequently integral to successful IPM modules. Trials consistently show pruning/removal of infested shoots plus trapping reduces fruit infestation and improves marketable yield (Cork et al., 2005), (Chakraborty et al., 2023). Regular shoot clipping and fruit removal, through weekly destruction of drooped or infested shoots and fruits, effectively reduces larval recruitment and forms a standard component of integrated pest management (IPM) modules (Chakraborty et al., 2023; Cork et al., 2005). Recent studies have shown that combining shoot clipping with sanitation provides better protection against brinjal shoot and fruit borer compared to individual practices. Haque et al. (2025) reported that integrated sanitation practices, including the regular removal of infested shoots, were more effective in reducing pest incidence and enhancing crop yield than individual interventions, underscoring their role as key components of sustainable IPM strategies. Field sanitation and residue management, involving the destruction of rearing substrates and crop residues between seasons, help suppress carryover populations and enhance control in subsequent crops (Cork et al., 2005). Soil amendments and botanicals, particularly neem cake soil incorporation (250 kg ha^{-1} in split application) along with neem extracts or oil, have demonstrated reduced infestation in field trials and are recommended within integrated pest management calendars (Chakraborty et al., 2023; Navasero et al., 2016].

2.1. Implementation recommendations

A structured sanitation schedule involving weekly inspection and removal of infested shoots from flowering through harvest is critical for reducing pest buildup (Chakraborty et al., 2023). Integrating sanitation with neem-based soil amendments and biological control releases further minimizes reliance on insecticides and enhances the sustainability of pest management practices (Chakraborty et al., 2023; Navasero et al., 2016). Additionally, farmer training on the identification of infested shoots and proper destruction methods is essential to maintain the effectiveness of these integrated strategies (Cork et al., 2005). Recent reviews have emphasized the critical role of integrated approaches in managing brinjal shoot and fruit borer (*L. orbonalis*). Thomas et al. (2025) highlighted that combining cultural practices, biological control, and selective chemical applications provides a sustainable framework for pest suppression, underscoring the necessity of multi-tactical IPM strategies to enhance efficacy, reduce chemical reliance, and maintain ecosystem stability.

3. MECHANICAL CONTROL

In addition, light traps, when combined with shoot removal, have been shown to reduce pest incidence in replicated trials and can be effectively complemented by pheromone-based mass trapping in certain contexts (Cork et al., 2005; Dhandapani et al., 2003). Recent studies have further validated these findings. Yousafi et al. (2018) demonstrated that integrating infested shoot removal with light traps significantly reduced brinjal shoot and fruit borer infestation levels, leading to improved crop yield. Furthermore, Rhainds et al. (2024) highlighted the effectiveness of light traps in large-scale mass trapping programs, noting the resurgence of interest in this method due to technological advancements. Pheromone-based surveillance and mass trapping provide a reliable, speciesspecific monitoring tool and a suppression option when deployed at recommended densities and combined with sanitation. Trials show pheromone traps both guide spray timing and, when used at high densities, contribute to reduced damage and higher marketable yields (Cork et al., 2003). Delta or wing traps baited with synthetic female pheromone and locally produced water/funnel traps were effective; recommended operational densities reported include ~100 traps ha^{-1} for monitoring and ~4 water traps $(100\ m^2)^{-1}$ for mass trapping trials (Cork et al., 2003; Cork et al., 2005). Deploy pheromone traps from flowerbud initiation (~45 days after transplanting) and maintain through harvest, replacing lures monthly in field modules (Chakraborty et al., 2023). Use trap catch trends to delay or target sprays rather than fixedinterval calendar spraying; IPM trials recorded significant reductions in moth catches and fruit damage within weeks of combined trap+sanitation interventions (Cork et al., 2003; Cork et al., 2005).

3.1. Implementation recommendations

The IPM strategy for lepidopterans combines three key actions: Monitoring involves checking traps nightly or weekly to record male moth catch, with sudden increases used as a trigger for intensified field scouting and timely interventions. Mass trapping, where practical, utilizes high trap densities alongside practices like pruning to achieve direct pest suppression, particularly in small, coordinated farming areas. These two tactics are then integrated by using the pheromone trap data and visual scouting to precisely guide the timing of biological controls, such as the release of *Trichogramma* parasitoid wasps, and to inform the need for selective, targeted pesticide sprays.

4. BIOLOGICAL CONTROL AGENTS

Biological control is a core pillar of IPM for *L. orbonalis* and includes parasitoids, predators and microbial/entomopathogenic agents that can suppress larval populations when conserved or released at appropriate times. Field programmes that combine parasitoids releases or augmentation with reduced insecticide use preserve these services and improve outcomes compared with calendar spraying alone (Saraswathi et al., 2024). Biological control forms a critical part of the IPM strategy, primarily through the use of natural enemies and microbial agents. Several native egg and larval parasitoids (*Trathala flavoorbitalis* and *Bracon* spp.) provide natural control, making their conservation vital, as broad-spectrum insecticides severely reduce their efficacy. For augmentative control, the release of the egg parasitoid *Trichogramma chilonis* (10–15 lakh parasites ha^{-1} $season^{-1}$), combined with sanitation and trapping, is a proven, effective, and economically viable method, often alongside two sprays of *Bt* formulation. Further biopesticide components show promise, including microbial fungi like *Trichoderma longibrachiatum* formulations, which have achieved control and yield increases comparable to chemical treatments, and entomopathogenic nematodes (*Heterorhabditis* and *Steinernema* spp.) which demonstrate high laboratory virulence against larvae, requiring only further field optimization for widespread IPM inclusion.

4.1. Implementation recommendations

Integration of biological control measures is critical, with Trichogramma releases recommended at early crop stages (around 30 days after planting), particularly in plots with lower insecticide exposure (Chakraborty et al., 2023). Conservation of natural enemies should be prioritized by avoiding the routine application of broad-spectrum insecticides that suppress key parasitoids, instead favouring selective products (see Chemical section) (Cork et al., 2005). Additionally, microbial and entomopathogenic nematode (EPN) interventions may be piloted by testing locally available fungal and nematode formulations under canopy microclimate conditions, with applications timed to coincide with periods when larvae are more accessible, such as following pruning or harvest residue management (Ataullah et al., 2024; Ghosh and Pal, 2016).

5. HOST RESISTANCE AND EMERGING TECHNOLOGIES

Breeding for host resistance and transgenic approaches (*Bt* brinjal), plus novel biocontrol and molecular tools, offer powerful additional IPM components; evidence supports *Bt* eggplant as a foundational tool when integrated responsibly. Reviews and field studies report strong pest suppression by *Bt* varieties with minimal nontarget impacts, while new biocontrol agents and RNA-based methods are at various stages of development (Saraswathi et al., 2024), (Navasero et al., 2016). Host Resistance and Emerging Technologies offer powerful tools for IPM, with Bt brinjal acting as a foundational component. *Bt* eggplant, which expresses the *Cry1Ac* protein, has been shown in multi-season field studies to consistently and effectively suppress *L. orbonalis* and other lepidopteran pests, leading to a large reduction in insecticide use with no significant adverse effects on non-target arthropod communities (Navasero et al., 2016). In India, under controlled conditions, the trials are successful in managing the *L. orbonalis* (Shelton et. al., 2017). While conventional breeding for varietal resistance or tolerance is discussed in reviews, durable, field-scale resistant varieties remain limited, making the integration of other control tactics necessary even when using the best available conventional cultivars (Saraswathi et. al., 2024).

5.1. Novel biotechnologies

Reviews list promising approaches (RNA interference, neuropeptide disruptors, improved transgenics) as research priorities; these require regulatory and deployment pathways before wide adoption (Saraswathi et al., 2024). RNA interference (RNAi) is an emerging biotechnological tool for pest management that exploits a natural gene-silencing mechanism. In this process, double-stranded RNA (dsRNA) molecules are designed to target and silence essential genes in the insect pest, leading to developmental abnormalities or mortality. In the case of the *L. orbonalis*, RNAi can be employed to disrupt genes responsible for vital physiological functions such as digestion, growth, reproduction or detoxification. When larvae ingest dsRNA expressed in transgenic brinjal plants or delivered through artificial diets, the targeted mRNA transcripts are degraded, effectively knocking down the expression of those genes (Kim and Zhang, 2023). This results in reduced feeding, stunted growth, impaired reproduction or death of the larvae, thereby minimizing crop damage. Compared to conventional chemical insecticides, RNAi offers several advantages: high specificity against the target pest, reduced risk to non-target organisms, and compatibility with other components of IPM. However, challenges such as stability of dsRNA in the insect gut, efficient delivery systems and possible off-target effects need to be addressed before large-scale field application. Recent advancements in biotechnological approaches offer promising solutions for managing *L. orbonalis*. Hanamasagar et al. (2024) provide a comprehensive review of RNA interference (RNAi) as a targeted and eco-friendly pest control method, emphasizing its species-specific targeting and reduced off-target effects. Despite of disadvantages, RNAi represents a promising eco-friendly strategy for sustainable management of brinjal fruit and shoot borer.

6. CHEMICAL CONTROL STRATEGIES

Chemical tactics continue to play a vital role in managing *Leucinodes orbonalis* outbreaks, especially when pest populations cross the economic threshold. However, their use should remain selective, need-based and carefully integrated into an overall IPM strategy. Indiscriminate or repeated use of the same insecticide group accelerates resistance development and causes collateral damage to natural enemies **(**Dar et al., 2017**).** To overcome this, rotation of insecticides with different modes of action, combined with selective applications, helps prolong efficacy and preserve beneficial arthropods such as parasitoids and predators. Recent field-based IPM modules (Table 1) have shown that alternating selective insecticides with biopesticides and biorationals (such as neem-based formulations, *Bacillus thuringiensis* or insect growth regulators) provides not only effective suppression of shoot and fruit borer but also reduces production costs and improves benefit–cost ratios. This integrated approach minimizes pesticide residues, enhances ecological sustainability, and maintains long-term

Table 1: Field-validated IPM modules and their efficacy against Leucinodes orbonalis

Module or package	Key components	Reported field effect
Tripura M7	Neem cake soil incorporation, pher-omone traps, weekly clipping, Trichogramma releases, alternating Chlorantraniliprole and Novaluron from 70 DAT	Reduced shoot damage to ~10.6% and fruit damage ~11–12% with higher yields relative to control (Chakrabortyet al., 2023)
Bangladesh biorational IPM	Spinosad+removal of infested shoots/fruit (and other biorational combinations)	Spinosad+sanitation: ~73 per cent shoot protection and ~72.7% fruit protection; marketable yield 5.70 t ha-1 in trials (Sarker et al., 2020)
Sequential insecticide schedule	Chlorantraniliprole → Spinosad → Lufenuron → Bt (B. thuringiensis kurstaki)	Reported strong reduction in dam-age and favourable cost–benefit in recent trials (Udikeri et al., 2024)

productivity (Sarker et al., 2020).

In IPM systems, the strategic deployment of selective insecticides-such as Spinosad, emamectin benzoate, chlorantraniliprole, lufenuron and novaluron-in rational sequences or alternation with biorationals like *B. thuringiensis* (*Bt*) is critical for maximizing efficacy while mitigating selection pressure and managing the evolution of resistance (Sarker et al., 2020; Udikeri et al., 2024). Sustainable resistance management necessitates the rotation of active ingredients with distinct modes of action and the integration of non-chemical control tactics to minimize application frequency (Saraswathi et al., 2022; Sharma et al., 2024). Furthermore, economic analyses frequently demonstrate that multi-component IPM modules—which strategically combine biological controls, sanitation, and judicious, selective chemical applications-are economically viable (e.g., yielding a high incremental cost-benefit ratio (ICBR) and consistently surpass traditional, calendar-based spray programs in terms of both marketable yield and profitability (Dabhade et al., 2024).

A holistic summary of integrated pest management strategies against brinjal fruit and shoot borer (*Leucinodes orbonalis*) is presented in Figure 1, illustrating the complementary roles of cultural and mechanical practices, biological control agents, selective chemical applications, and emerging technologies such as *Bt* brinjal and RNA interference.

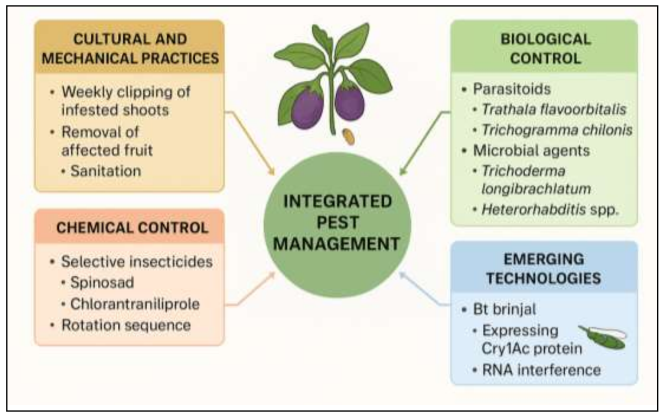

Figure 1: Components of Integrated Pest Management (IPM) for brinjal fruit and shoot borer (*Leucinodes orbonalis*)

7. WEATHER PARAMETERS INFLUENCING *L. ORBONALIS*

7.1. Temperature

It is the most critical meteorological factor governing *L. orbonalis* populations across geographic regions. The minimum temperature is consistently identified as the primary driver (Shah et al., 2023), showing a positive correlation where higher minimum temperatures lead to increased adult moth catches in pheromone traps and are the strongest predictor of pest abundance, particularly in South Asian locations (Anwar et al., 2017; Singh et al., 2024). The effects of maximum temperature are more variable, showing positive correlations with pest metrics in some regions and having physiological impacts that accelerate larval feeding and shorten development times, thus altering generation timing. Ultimately, peak infestation conditions are typically associated with moderate maximum temperatures (~27.8°C) combined with lower minimum temperatures (~12.4°C), demonstrating that temperature thresholds directly influence developmental rates and generation turnover (Haq and Rizvi, 2023). Recent studies by Shah et al. (2025) reported rising minimum temperatures strongly favor adult moth emergence and population growth, while maximum temperature and showed some positive influence.

7.2. Relative humidity (RH)

It exhibits a complex yet significant relationship with *L. orbonalis* populations. Evening relative humidity consistently shows a positive correlation with moth catches, as high evening RH (>60%) generally supports both population growth and adult activity (Shah et al., 2023). Conversely, the effect of morning relative humidity is more variable, often showing weak or even negative correlations with pest populations (Borkakati et al., 2021), with relationships varying significantly by region. Overall, the pest thrives under humid conditions, as peak infestation periods are typically associated with high relative humidity conditions, such as morning/evening RH around 85/61%, which generally support higher rates of population growth and survival (Haq and Rizvi, 2023).

7.3. Rainfall

Rainfall patterns exhibit season-dependent effects on *L. orbonalis* populations. During the *kharif* (monsoon) season, precipitation may show a positive association with pest numbers in some areas, while rainfall during the *rabi* (winter) season) often shows a negative correlation with pest abundance (Haq and Rizvi, 2023). Beyond these direct, regionally variable effects, rainfall has several important indirect effects: it modifies the host plant's vigor and susceptibility, influences the populations and effectiveness of natural enemies, and alters the field microclimate, all of which ultimately affect pest behaviour and population dynamics.

7.4. Other meteorological factors

The final two meteorological factors influencing *L. orbonalis* populations are Sunshine Hours and Wind Velocity. Bright sunshine hours often show a positive correlation with higher damage levels in regional surveys, as sunlight directly affects adult moth activity and mating behaviour ((Borkakati et al., 2021; Haq and Rizvi, 2023). Conversely, low wind velocity conditions typically correlate with increased pest incidence, while stronger wind affects adult moth dispersal and overall population distribution (Shah et al., 2023: Shah et al., 2025).

8. CONCLUSION

Effective management of brinjal fruit and shoot borer (*L. orbonalis*) required a cohesive IPM framework. This strategy integrated complementary tactics—cultural and mechanical practices like weekly clipping and pheromone trapping, biological control through native parasitoids and *Trichogramma chilonis* releases, microbial agents like Bt, and selective chemical applications (Spinosad, Chlorantraniliprole) rotated by mode of action. Emerging technologies, such as *Bt* brinjal expressing *Cry1Ac*, further reduced chemical use. Field-validated IPM modules enhanced yield, profitability, and environmental sustainability under key weather conditions.

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