



The Multifaceted Approach to Pod Borer Management: Ecological Insights and Future Directions

Priyakshi Buragohain¹, Bhabesh Deka^{2*} and Mumtak Tapak²

¹Assam Agricultural University-Zonal Research Station, Shillongani, Nagaon, Assam (782 002), India

²Dept. of Entomology, Faculty of Agricultural Sciences, Rajiv Gandhi University, Rono Hills, Arunachal Pradesh (791 112), India

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Corresponding Author

Bhabesh Deka

✉ bhabesh.deka@rgu.ac.in

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Abstract

Pod borers, predominantly lepidopteran pests (notably *Crambidae* and *Noctuidae*), are a major constraint to legume and other crop production because larvae penetrate pods, flowers and vegetative tissues, reducing seed quality, yield and marketability and increasing vulnerability to pathogens. This review aimed to consolidate the current understanding of the importance, biology, host use, environmental regulation, damage assessment and integrated management of pod borers, with an emphasis on economically robust decision-making and future-ready control. Pod borer population dynamics are tightly governed by developmental biology and environmental cues. Under climate change, temperature, humidity, rainfall and photoperiod interact to shape diapause, voltinism and range expansion. Effective management requires IPM combining monitoring (visual scouting; pheromone and light traps, with recommended trap spacing of ~10-110 m; systematic egg/larval sampling; and emerging automated image-based tools), economic thresholds adapted to crop, region, technology level and market prices and interventions integrating cultural tactics, biological control, selective/rotated insecticides and host plant resistance (including wild-relative introgression, metabolomics-guided trait discovery, *Bt* crops, RNAi and CRISPR/Cas9). Overall, locally adapted, farmer-participatory, climate-resilient IPM supported by advanced surveillance and judicious inputs are pivotal for sustainable pod borer suppression and stable crop productivity.

Keywords: *Helicoverpa armigera*, Integrated pest management, Lepidoptera, *Maruca vitrata*

Introduction

Pod borers, a group of insect pests primarily classified within the order Lepidoptera, particularly from the families *Crambidae* and *Noctuidae*, pose a significant threat to the pods of leguminous and other crops. Economically, pod borers are of considerable importance because of their potential to inflict substantial losses in legume production, which is a vital source of protein and nutrients in many global diets. The damage inflicted on essential crops, such as cowpea, chickpea, pigeonpea and other grain legumes, positions pod borers among the most critical pests in global agriculture, necessitating integrated pest management strategies to mitigate yield losses and economic impact

(Sharma *et al.*, 2010). Pod borers are distributed across tropical and subtropical regions, where they affect a diverse array of crops. The distribution of pests such as *Maruca vitrata* is pantropical, encompassing regions in Africa, Asia and beyond and causing significant damage to legumes (Ba *et al.*, 2019). Similarly, *Helicoverpa armigera* and other pod borers are found worldwide, affecting multiple crops, including cereals, pulses and vegetables (Sharma, 2014). Climate change is anticipated to influence their geographical distribution, potentially extending their range into temperate zones and thereby heightening the threat they pose to crops globally (Sharma, 2014). This shift highlights the global nature of pod borer infestations and the challenges they

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present to diverse agricultural systems. This objective of this review is to consolidate the current understanding of the importance, biology, host use, environmental regulation, damage assessment and integrated management of pod borers, with an emphasis on economically robust decision-making and future-ready control.

Significance of Pod Borer Management

Pod borer infestations substantially affect crop yield and quality, frequently resulting in severe reductions that threaten food security and farmers' livelihoods. For instance, the pod borer *Helicoverpa armigera* can inflict up to 90% damage on chickpea crops by attacking during the vegetative through pod formation stages, leading to significant yield losses if not effectively managed (Patil et al., 2017). Similarly, damage from pod borers, such as *Maruca vitrata* to cowpeas, a vital protein source in tropical regions, which results in compromised pod quality and diminished marketability (Ba et al., 2019). This damage not only reduces the quantity of the harvest, but also undermines seed integrity and quality, affecting subsequent planting and consumption of the harvested seeds. Economically, these crop losses translate into substantial financial setbacks for farmers and the agricultural industry as a whole. These losses highlight the urgent need for effective pod borer management to sustain agricultural profitability and food supply chains. The significance of integrated pest management (IPM) approaches in controlling pod borers is of paramount importance. IPM strategies, which integrate cultural practices, host plant resistance, biological controls and judicious use of chemical pesticides, have been demonstrated to significantly reduce pod borer damage and enhance sustainable crop production (Patil et al., 2017; Ba et al. 2019). Research has shown that IPM practices reduce the reliance on synthetic chemicals, thereby preserving populations of natural enemies and minimizing ecological disruption while achieving effective pest suppression (Picanço et al., 2007; Mohapatra et al., 2024). For instance, integrated modules implemented in okra cultivation have decreased infestation rates and increased yields and net returns compared to conventional chemical methods (Mohapatra et al., 2024). Similarly, IPM has been successful in minimizing losses across various crops while promoting environmental sustainability and economic viability (Wilson, 2020; Pecenka et al., 2021). Therefore, effective pod borer management through IPM is crucial not only for safeguarding crop yield and quality, but also for reducing economic losses and promoting sustainable agricultural practices that protect ecosystems and natural pest control agents.

Biology and Ecology of Pod Borers

The biology and ecology of pod borers encompass distinct developmental stages, each characterized by specific traits and time durations (Figure 1). During the egg stage, pod borer eggs exhibit specific morphological features that vary by species and their duration is influenced by environmental conditions (Smithers, 1960). The female moths of *Helicoverpa armigera* lay eggs on the tender parts of the plant and its fecundity ranges from 500 to 890 eggs. The freshly laid eggs are yellowish-white in colour. The apical

area of egg is smooth and the rest of the surface sculptured in the form of longitudinal ribs (Ali et al., 2009). The eggs of *Maruca vitrata* are laid singly or in batches of 2-6 on the under surface of leaves, terminal shoots and flower buds (Naveen et al., 2009). The freshly laid eggs are milky white in color, oval in shape, dorsoventrally flattened and stuck to its substrate (Ashigar and Umar, 2016). The eggs hatch into larvae in synchrony with host plant phenology, which is crucial for optimal larval growth and development, especially in species that feed on foliage (Holliday, 1985). The larval stage consists of multiple instars, typically ranging from four to seven, depending on the species (Wang et al., 2010). Larval feeding habits vary but generally involve boring into pods, stems or seeds, depending on host plant tissue specificity. Early instars may have limited feeding capacity but are critical for establishing developmental trajectories, whereas later instars consume more tissue and can cause significant crop damage (Jones and Despland, 2006; Montezano et al., 2014). The larval stage is strongly influenced by synchronization with host phenology, as delayed hatching can reduce growth rates and increase larval instar numbers due to lower food quality (Jones and Despland, 2006). There are five larval instars in *Maruca vitrata* lasting between 8-16 days, depending on climatic condition and the host plants. Larval feed component also affects the biology of the insect and it preferentially feed on the reproductive organs of the host plant for about three weeks and then migrates to the pods before pupation. Larval body is semi-transparent and spotted on each segment and the spotting intensity varies and the spots fade before pupation (Ashigar and Umar, 2016). The average time duration of first, second, third, fourth, fifth and sixth instars of *Helicoverpa armigera* varied 2.60 ± 0.08 , 3.40 ± 0.10 , 4.40 ± 0.13 , 3.80 ± 0.11 , 4.40 ± 0.13 and 5.40 ± 0.16 days, respectively (Kumar et al., 2022). Following larval development, the pupal stage occurs in concealed locations, such as within plant tissues or soil. Pupal duration is species- and temperature-dependent (Wang et al., 2010). There were differences in the measurements of male and female pupae. Female pupae measured 22.50 ± 0.67 mm in length and 7.37 ± 0.22 mm in width. Similar to female pupae, male pupae measured 21.86 ± 0.66 mm in length and 7.06 ± 0.21 mm in width (Kumar et al., 2022). The early pupal stage of *Maruca vitrata* in legumes is greenish, but when fully grown, it turns brown and is hidden in a cocoon made of dry leaves, flowers and other dead plant matter. Normally, the pupal cycle lasts one to two weeks (Pandit and Dwivedi,

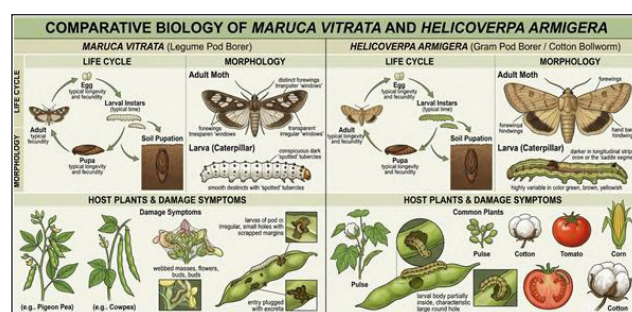


Figure 1: Relative abundance of insect pollinators on rapeseed

2021). Adults often emerge conservatively from the pupal case, sometimes remaining temporarily within the pupal cells before emerging into the environment (Wang *et al.*, 2010). The adult of *Maruca vitrata* are medium sized and both sexes are morphologically alike. The forewings are brown having white spot and black-edged while the hind wings are semi-hyaline (Ashigar and Umar, 2016). In terms of body length and breadth, it was found that females were larger than males in case of *Helicoverpa armigera* (Kumar *et al.*, 2022).

Host Range and Preferences

Pod borers exhibit a diverse range of host preferences influenced by evolutionary, ecological and environmental factors. The primary host plants for pod borers are typically species within specific plant families that offer suitable nutritional and chemical conditions for insect development. The gram or noctuid pod borer, *H. armigera* (Hübner) (Lepidoptera: Noctuidae), is a voracious feeder pest that infests over 100 plant species including widespread and economically important crops such as cotton, maize, tobacco, pigeonpea, chickpea and tomato (Talekar *et al.*, 2006). The ability of *H. armigera* to feed on the harvestable parts of host plants, along with its high polyphagy and mobility, broad geographical variety, migratory potential, facultative diapause, high fecundity and tendency to develop resistance to insecticides lead to its status as an economically important crop pest (Hemati *et al.*, 2012). The legume pod borer, *Maruca vitrata* has been reported to feed on over 39 host plants, the most frequent host plants include *Cajanus cajan*, *Vigna unguiculata*, *Phaseolus lunatus* and *Pueraria phaseoloids* (Sharma, 1998; Ramasamy *et al.*, 2021).

The primary hosts tend to be major hosts, providing optimal conditions for reproduction and larval development. Secondary hosts and alternative food sources play significant roles, particularly when primary hosts are scarce or are seasonally unavailable. These secondary hosts typically share taxonomic proximity or chemical traits with primary hosts but may be less optimal for feeding or oviposition than primary hosts. Various studies have emphasized that many phytophagous insects incorporate secondary or alternative host plants into their diet or life cycle, including collateral hosts within the same plant family or even unrelated plants serving as refuges or secondary food sources (Kumar *et al.*, 2021; Ong'Amo *et al.*, 2006). Additionally, herbivorous insect generalists often utilize an extended suite of secondary hosts with lower attractiveness cues, supporting their survival and reproduction beyond that of primary hosts (Jones *et al.*, 2022). Seasonal variations also influence the host selection of pod borers. Synchronization with the phenology of host plants is critical because the timing of egg hatching, larval emergence and host plant growth must align for successful feeding and development. Insects often seasonally select hosts that are at the appropriate developmental stages, which may involve switching between hosts as availability changes. Some species modulate host choice based on seasonal growth, with larval feeding and oviposition behaviours adapted to the host's phenological stage (Stastny

et al., 2006). The evolutionary and ecological processes that govern host preference also include the insect's sensory and genetic mechanisms, which enable the detection and utilization of host-specific chemical cues, allowing adaptation to diverse hosts where appropriate (Suzuki *et al.*, 2018; Jones *et al.*, 2022).

Environmental Factors Affecting Pod Borer Population

Temperature and humidity are pivotal environmental determinants that affect the development and survival of pod borers. Temperature modulates the developmental rate at all life stages. Elevated temperatures typically expedite larval growth and development, whereas reduced temperatures decelerate these processes and occasionally induce diapause. For instance, research on insects with intricate life cycles indicates that low temperatures coupled with short photoperiods induce diapause more effectively than either factor alone (Caporale *et al.*, 2017). Similarly, temperature affects the duration of the pupal stage and the timing of adult emergence, as evidenced by studies on various lepidopteran and beetle species (Lefevere and Kort, 1989; Wang *et al.*, 2021). Humidity impacts survival during dormancy by influencing desiccation risk; arid conditions can prolong dormancy and elevate mortality, whereas humid environments enhance the survival of overwintering stages (Tauber *et al.*, 1998; Rull *et al.*, 2019). Photoperiod serves as a primary cue for triggering diapause and altering the reproductive cycles of pod borers. A reduction in day length signals the onset of unfavorable conditions (*e.g.*, winter), inducing diapause in pupae or other life stages to enhance their survival (Dingle, 1974; Caporale *et al.*, 2017). Photoperiod interacts with temperature to regulate the induction and termination of diapause, with induction often occurring under short photoperiods and low temperatures (Wang *et al.*, 2021). Upon termination of diapause, increases in day length and temperature facilitate the completion of development and reproduction (Dingle, 1968). Photoperiod and temperature jointly influence voltinism (the number of generations year⁻¹), with populations in northern latitudes exhibiting extended diapause periods corresponding to shorter day lengths and cooler temperatures (Beck and Apple, 1961). Rainfall and moisture significantly affect pod borer population dynamics by affecting insect hydration, survival during dormancy and synchronization with host plant phenology. Seasonal humidity can serve as a cue for emergence timing and diapause regulation by indicating resource availability or unfavorable dry periods (Rull *et al.*, 2019). In arid environments, prolonged dormancy with higher mortality is more prevalent due to desiccation stress during overwintering. Rainfall patterns also influence host plant growth and, consequently, food availability, indirectly shaping pod borer population size and growth (Tauber *et al.*, 1998). Climate modeling and pest distribution modeling for pod borers use environmental and biological data to forecast population dynamics and shifting geographic ranges under global climate change. Yang *et al.* (2024) used the optimized MaxEnt model to predict the potential distribution of this pest with multiple variables associated with climate, land

use and host plant, at its recorded range and a globe scale. Data on thermal constant and developmental thresholds of different developmental stages of *H. armigera* could formulate a population simulation model of the pest that could be applied to investigate the impact of global warming on biological processes that are responsible for changes in population levels of the pest (Chander et al., 2023).

Damage Assessment and Monitoring

Pod borers inflict substantial damage on crops by affecting multiple plant parts, resulting in diminished yield and quality degradation of the crop. Feeding damage caused by pod borers predominantly affects pods, flowers and vegetative components, such as leaves and stems. The larvae penetrate the pods to consume the developing seeds, leading to direct seed loss and compromising pod integrity. Flower feeding by certain species diminishes reproductive success by destroying the floral tissues crucial for fruit set. Furthermore, larval feeding on vegetative parts debilitates plants by disrupting nutrient transport, reducing photosynthetic capacity and creating entry points for pathogens (Shanower et al., 1999; Okosun et al. 2021). Secondary effects on plant health include reduced vigor, stunted growth and increased susceptibility to secondary infections and pests. This damage disrupts physiological processes and can lead to heightened plant stress, resulting in decreased overall productivity. Additionally, multiple pest attacks on various plant parts may interact in a non-additive manner, sometimes exacerbating yield losses or, conversely, inducing compensatory growth in plants, thereby complicating the damage-yield loss relationships (Gagic et al., 2016). Quality deterioration of harvested crops is a critical consequence of pod borer infestations. Damaged pods and seeds result in poor grain quality, reduced marketability and post-harvest losses due to increased susceptibility to pests and fungal infections. Effective pest management strategies, including integrated pest management approaches that combine host resistance, biological control and judicious pesticide use, are essential for minimizing such damage and maintaining crop health and quality (Abate and Ampofo, 1996; Mohapatra et al., 2024).

1. Monitoring Techniques

Monitoring pod borer populations necessitates employing various techniques tailored to the pest's distinct life stages, including visual scouting, pheromone and light traps for adults and sampling protocols for immature stages of the pest. Visual scouting involves direct field inspections to evaluate the presence and extent of damage caused by pod borer larvae and adults. This method aids in identifying damage thresholds, which are levels of infestation or injury at which pest control becomes economically justified. These thresholds inform targeted management decisions and minimize unnecessary pesticide application (Patil et al., 2017; Furlan et al., 2020). Pheromone traps are extensively used to monitor adult pod borer populations, particularly males attracted to species-specific sex pheromones. Proper trap placement and spacing are crucial for avoiding interference and ensuring representative sampling. Studies have recommended trap distances ranging from

approximately 10 m to 110 m, depending on the species and environmental factors (Bacca et al., 2006; Jactel et al., 2018). Light traps may complement pheromone traps, especially for species attracted to light, thereby enhancing overall adult monitoring. Sampling protocols for eggs and larvae typically involve systematic field surveys in which a predetermined number of plants or pods are inspected for early life stages. Egg mass counts and larval presence on pods and flowers assist in anticipating damage and optimally timing control measures. Recent advancements include automated detection techniques, such as image processing algorithms on mobile devices for pests, such as the cacao pod borer, facilitating rapid on-site monitoring even in remote areas (Hacinas et al., 2024). Artificial intelligence and digital technologies are transforming crop protection with automated pest surveillance, predictive forecasting and precision decision-making for agricultural operations. Its integration with IPM principles could minimize unnecessary pesticide applications, without any negative impact on yield. Foundation models trained on large-scale agricultural datasets could improve pest identification, disease diagnosis and decision support by learning general representations that can be transferred across crops, geographical regions and pest species (Bommasani et al., 2021). Recent advances in artificial intelligence (AI), computer vision, sensors, wireless communication and the Internet of Things (IoT) are transforming traditional traps into smart traps. These systems can automatically detect, photograph, identify and count insects while transmitting data to farmers or researchers in near real time. Such technology can support early pest detection, improve decision-making and reduce unnecessary pesticide applications (Sapna, 2026).

2. Economic Threshold Levels

Economic threshold levels in agriculture are critical values of pest density or injury, beyond which the cost of pest damage exceeds the cost of pest control, thereby informing sustainable pest management decisions. Economic injury levels (EILs) denote the minimum pest density that results in economic losses. These thresholds are specific to both crops and pests and are influenced by various biotic and abiotic factors (Figure 2). Establishing economic injury levels for different crops necessitates an understanding of the pest-crop interactions and yield loss attributable to pests at varying infestation levels. For instance, in wheat, economic thresholds have been determined based on specific damaging pests, incorporating crop physiology to evaluate the crop's tolerance to damage, which can vary significantly depending on the pest species and crop developmental stages (Leybourne et al., 2024). On the basis of regression analysis and gain threshold, the Economic injury level (EIL) and Economic threshold level (ETL) of *H. armigera* in chickpea for both the years, 2016-17 and 2017-18 was determined as 2.08 and 1.56 larvae m⁻¹ row, respectively (Akansha and Singh, 2018). Similarly, in case of *M. vitrata*, the EIL and ETL in pigeonpea were determined as 5.58 and 4.19 webs plant⁻¹, respectively on the basis of regression analysis and gain threshold (Mahalle and Taggar, 2024). Several factors influence the determination of the economic thresholds. These include the crop's intrinsic tolerance or compensatory

ability to withstand pest damage, which can modulate the severity of yield loss. For example, some crops, such as certain potato cultivars, can overcompensate for herbivore damage, potentially doubling productivity under specific conditions, thus complicating threshold determination, as action levels may need to be adapted accordingly (Poveda *et al.*, 2018). Climate factors, such as temperature, CO₂ concentrations and precipitation patterns, affect not only crop growth but also pest population dynamics and pest damage potential, thereby influencing economic injury levels. The effects of climate vary regionally and seasonally, contributing to dynamic threshold levels over time and space (Hatfield *et al.*, 2011; Eitzinger *et al.*, 2012).

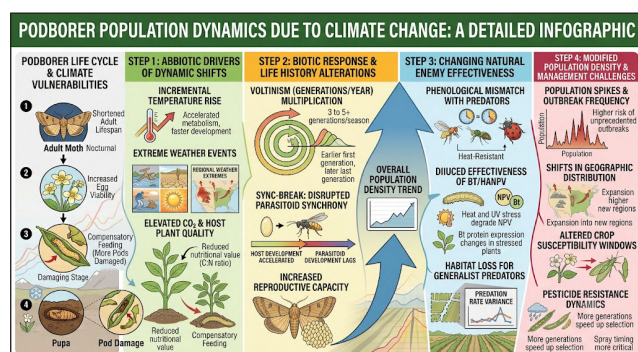


Figure 2: An infographic chart of population dynamics of Podborer due to climate change

Consequently, economic injury levels must be regionally adapted to local environmental factors, market prices and pest dynamics to ensure efficacy. Calculations of economic injury levels and thresholds involve formulas that consider pest density, crop value, control costs and yield loss rates. Modern approaches incorporate dynamic and multidimensional factors, including different pest life stages and temporal variations in pest density (Onstad, 1987).

Management Strategies

Management strategies for pest control in agriculture encompass cultural, biological and chemical methods, often integrated within the framework of Integrated Pest Management (IPM) to achieve sustainable and effective crop protection.

1. Cultural Control Methods

Cultural practices are essential components of pest management, as they modify the cropping environment to hinder pest establishment, reproduction and survival. Techniques such as crop rotation and intercropping effectively disrupt pest life cycles and reduce host availability, thereby decreasing pest populations (Tiwari, 2024). Adjusting planting dates can help avoid peak pest periods, whereas trap cropping involves planting a preferred host crop to attract pests away from the main crop, thus minimizing damage (Tiwari, 2024). Field sanitation, which includes the removal of crop residues and destruction of infested plant material, reduces pest refuges and breeding sites and post-harvest management ensures the minimization of pest carryover to subsequent crops (Zhou *et al.*, 2024). Collectively, these cultural strategies constitute an integral

part of Integrated Pest Management (IPM) approaches, reducing reliance on chemical inputs.

2. Biological Control

This method uses the natural enemies of pests to regulate their populations. In the case of pod borers, these natural adversaries include predators such as lady beetles and lacewings, as well as parasitoids such as certain wasps, which can effectively reduce pest populations (Tiwari, 2024). Conservation biological control focuses on preserving and enhancing habitats to support these beneficial insects, including reducing broad-spectrum insecticide use, which adversely affects non-target organisms (Galli *et al.*, 2024).

3. Chemical Control

Chemical insecticides continue to be a fundamental element of pest management strategies; however, their application should be judiciously integrated within Integrated Pest Management (IPM) frameworks to mitigate environmental and resistance-related concerns. Although conventional insecticides are effective in reducing pest populations, their excessive use can negatively impact beneficial organisms and the environment (Tiwari, 2024). In contrast, selective insecticides and insect growth regulators specifically target physiological processes in pests, providing precise control with minimal ecological disruption and reduced effects on non-target species (Galli *et al.*, 2024). The management of insecticide resistance is crucial and involves strategies such as rotating insecticide classes with distinct modes of action, employing economic thresholds to limit applications and incorporating non-chemical methods to alleviate the selection pressure (Zhou *et al.*, 2024). The development of innovative pesticide delivery systems, such as controlled-release formulations, enhances efficacy while minimizing environmental contamination (Mishra *et al.*, 2024). *Helicoverpa armigera* has developed resistance to many insecticides all over the world for, mainly to carbamates (MoA 1A), organo-phosphates (MoA # 1B), pyrethroids (MoA # 3A) families, or to *Bt* (*Bacillus thuringiensis*) compounds. Resistance to spinosyns (MoA 5), indoxacarb (MoA 22A), emamectin benzoate (MoA 6), has also been reported. More recent insecticides like diamides are still effective and no resistance has been reported so far (Ahmad, 2007).

Host Plant Resistance

Host plant resistance (HPR) is a crucial strategy for managing pod borer pests, offering a sustainable approach to crop protection by leveraging genetic variation within plants to mitigate pest damage. Sources of genetic resistance in crops frequently originate from wild relatives and landraces, which possess diverse resistance traits. For example, in chickpeas, germplasm accessions from wild species, such as *Cicer bijugum*, *C. judaicum* and *C. reticulatum*, provide valuable resistance genes against the *Helicoverpa armigera* pod borer (Sharma *et al.*, 2007). Resistance mechanisms in host plants are categorized into three types: antixenosis, antibiosis and tolerance mechanisms (Table 2). Antixenosis involves traits that deter pest colonization or feeding, thereby reducing pest preference or performance on plants. Antibiosis directly affects pest biology by impairing

development or survival through plant-produced toxins or adverse chemical profiles. Tolerance refers to a plant's capacity to withstand or recover from pest damage without significant yield loss (Stout et al., 2024). Understanding and integrating these mechanisms into breeding programs will enable the development of pod borer-resistant varieties. Breeding programs specifically targeting pod borer resistance have concentrated on introgressing resistance traits from wild relatives into elite cultivars and enhancing resistance using molecular approaches (Sharma et al., 2007). Similarly, maize breeding against pests, such as the fall armyworm, employs genome editing, marker-assisted selection and RNA strategies to enhance resistance and stability under field conditions (Woolfolk et al., 2025).

Biotechnological methodologies augment traditional breeding techniques by offering precise instruments for developing pest-resistant crops. Transgenic crops expressing insecticidal proteins, notably *Bacillus thuringiensis* (Bt) toxins, have proven effective against pod borers and other lepidopteran pests. Bt crops significantly reduce the need for insecticides by delivering targeted pest toxicity with minimal effects on non-target organisms (Kennedy, 2008; Li et al., 2024). RNA interference (RNAi)-based strategies are emerging as innovative methods that silence essential pest genes through the application of double-stranded RNA or transgenic expression, providing pest-specific control with environmental safety (Woolfolk et al., 2025). Recent progress has also been made in the technologies of clustered regularly interspaced short palindromic repeats (CRISPR) that present novel opportunities to develop insect resistant crop plants (Talakayala et al., 2020). One study has demonstrated that host-delivered dsRNA through RNAi can decrease *M. vitrata* larval feeding on pigeonpea leaves (Chatterjee et al., 2022). It is however important to focus on substantial research in this area before commercial application in crops like pigeonpea (Volp et al., 2025). Many molecular tools (markers systems, genetics maps, high-throughput genotyping and quantitative trait loci (QTL) analysis) are available to support breeding for Legume Pod Borer resistance in cowpea (Sodedji et al., 2020).

Integrated Pest Management (IPM) for pod borers combines host plant resistance, cultural practices, biological control and selective chemical use, adhering to ecosystem-based principles that prioritize sustainability (Figure 3). The components of IPM programs include monitoring pest populations using pheromone traps, cultural controls, such

as intercropping and planting adjustments, conservation of natural enemies and the deployment of resistant varieties, including transgenic ones (Patil et al., 2017; Green et al., 2020). IPM provides environmental benefits by reducing pesticide reliance and economic benefits through improved crop yields and reduced input costs (Tiwari, 2024). Successful region-specific IPM cases underscore the importance of local adaptation and farmer-participatory approaches. The lessons learned include the necessity for continuous farmer education, adaptive management in response to pest population changes and addressing challenges such as pesticide resistance and secondary pests (Patil et al., 2017).

Future Directions in Pod Borer Management

Future directions in pod borer management should emphasize the integration of emerging technologies, adaptation to climate change impacts and the adoption of sustainable, eco-friendly approaches. Advanced pest monitoring technologies, such as pheromone traps, remote sensing and precision agriculture tools, enable the accurate and timely detection of pod borer populations, facilitating targeted interventions and reducing unnecessary pesticide applications (Patil et al., 2017; Tiwari, 2024). Innovations in storage pest management incorporate nanotechnology-based pesticides, controlled-release formulations and bioformulations that enhance pest control efficacy while lowering the environmental footprint, showing promise for future pod borer control advancements (Mishra et al., 2024). Climate change significantly influences pod borer dynamics by altering pest biology, distribution and interactions with the host plants. Rising temperatures and changing precipitation patterns can increase pest reproduction rates, expand geographic ranges and exacerbate outbreak intensity, thereby complicating pest management efforts (Kumar et al., 2024; Vala et al., 2024). These changes demand adaptive pest management strategies that incorporate climate resilience, such as breeding climate-tolerant crop varieties, dynamic pest forecasting models and flexible IPM protocols that respond to shifting pest pressures (Hajjar et al., 2023; Tiwari, 2024). Sustainable and eco-friendly pod borer management approaches are closely aligned with integrated pest management (IPM) principles. Emphasizing biological control through natural enemies, cultural practices such as crop rotation and intercropping and the prudent use of selective insecticides, these methods reduce chemical dependency and promote agro-ecosystem health (Patil et al., 2017; Tiwari, 2024). Harnessing beneficial microorganisms, such as endophytes, hold potential for enhancing plant resilience and pest suppression in an environmentally sound manner (Das et al., 2025).

Biopesticides are reported to be highly effective in managing the major pod borer complex, specially *Helicoverpa armigera* and *Maruca vitrata*. *Bacillus thuringiensis* (Bt. *kurstaki*) at 1 g L⁻¹, Azadirachtin at 1500 ppm (5 mL L⁻¹) and *Beauveria bassiana* at 5 g L⁻¹ are recommended for the effective and economic management of the pod borer complex. These biopesticides demonstrated comparable efficacy in controlling larval populations and achieving optimal grain yields. Therefore, they present viable alternatives to

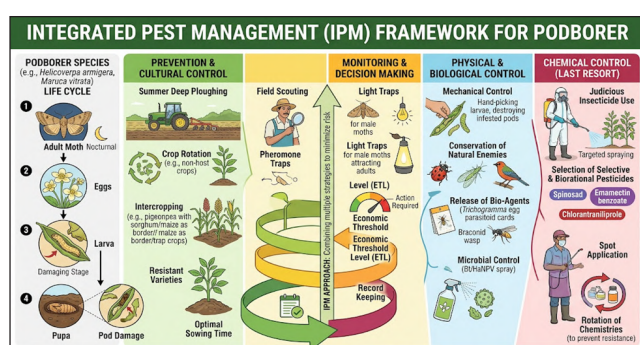


Figure 3: Integrated Pest Management (IPM) framework for pod borer

Table 1: Major pod borer species, host crops, distribution and damage symptoms

Podborer Species	Host Crops	Geographic Distribution	Nature of Damage & Key Symptoms	References/ Sources
Gram Pod Borer/ Old World Cotton Bollworm (<i>Helicoverpa armigera</i>)	Chickpea, pigeonpea, cotton, tomato, maize, soybean, cowpea, okra, sorghum.	Cosmopolitan; widely distributed across Europe, Asia, Africa, Australasia and South America.	Larvae bore into developing pods, fruits and bolls, feeding on seeds with their heads inside the pod and bodies hanging outside; causes massive yield drop and flower/fruit drop.	Devi <i>et al.</i> (2024); Pratisoli <i>et al.</i> (2015)
Spotted Pod Borer/ Legume Pod Borer (<i>Maruca vitrata</i>)	Cowpea, pigeonpea, mung bean, urdbean, soybean, lablab bean.	Pantropical; common across tropical and subtropical regions of Asia, Africa, the Americas and Oceania.	Larvae web together floral buds, flowers and young pods using silken threads; feed internally on floral organs and seeds, leaving prominent frass at entry holes.	Ramasamy <i>et al.</i> (2021); Singh and Singh (2021)
Lima Bean Pod Borer/ Etiella Moth (<i>Etiella zinckenella</i>)	Soybean, pigeonpea, cowpea, chickpea, lentil, green pea, lablab bean.	Widespread across southern/ eastern Europe, Africa, Asia, North America and Neotropics.	Larvae penetrate pods, web seeds together with silk and feed internally; infested pods often show dark brown necrotic spots, fecal accumulation and split pods.	ICAR-NBAIR, 2026; TNAU Agritech Portal, 2026.
Corn Earworm/ New World Bollworm (<i>Helicoverpa zea</i>)	Maize (sweet corn), cotton, tomato, soybean, bean varieties, sorghum.	Native to the Americas; ranges from southern Canada to Argentina.	Larvae bore into ears, bolls and pods, destroying developing kernels/seeds and predisposing tissues to secondary fungal rot.	Capinera (2002); Anonymous, (2025)

Table 2: Mechanisms of host plant resistance of *Helicoverpa armigera*

Resistance Mechanism	Primary Function/ Action	Key Morphological & Biochemical Plant Traits	Impact on Pod Borer	Key References
Antixenosis (<i>Non-preference</i>)	Deters or prevents the borer from settling, feeding, or ovipositing (egg-laying) on the host plant.	1. <i>High Trichome Density</i> : Dense glandular/non-glandular leaf & pod hairs block female moths from laying eggs. 2. <i>Pod Wall Thickness</i> : Tough, thick pod outer shell prevents neonate larvae from boring inside. 3. <i>Exudates</i> : Surface secretion of organic acids (e.g., malic acid, oxalic acid) acts as a physical/chemical repellent. 4. <i>Volatiles</i> : Absence of key attraction-triggering floral and foliar Volatile Organic Compounds (VOCs).	a) Reduced oviposition rate by female moths. b) Larvae wander away from host plants. c) Higher larval exposure to natural predators and desiccation.	Painter (1951); Sharma (1998); Mishra <i>et al.</i> (2025)
Antibiosis	Adversely affects the metabolic, growth and survival dynamics of larvae post-ingestion.	1. <i>Secondary Metabolites</i> : High levels of total polyphenols, condensed tannins, flavonoids (quercetin, rutin) and stilbenes. 2. <i>Enzyme Inhibitors</i> : Proteinase Inhibitors (PIs) that block digestive trypsin and chymotrypsin enzymes in larval guts. 3. <i>Organic Acids</i> : High concentrations of malic and oxalic acids inside plant tissues disrupt larval gut pH. 4. <i>Low Nutritional Value</i> : Low sugar-to-protein ratio in pod walls.	a) High mortality rate among early larval instars. b) Prolonged larval/ pupal development times. c) Substantially lower body weight of larvae and pupae. d) Reduced adult fecundity and deformed adult wings.	Yoshida <i>et al.</i> (1995); Sharma <i>et al.</i> (2009); Vanambathina <i>et al.</i> (2021)

Table 2: Continue...

Resistance Mechanism	Primary Function/ Action	Key Morphological & Biochemical Plant Traits	Impact on Pod Borer	Key References
Tolerance	Enables the plant to withstand, repair, or recover from damage without significant yield loss.	1. Compensatory Growth: High capacity to regenerate secondary branches, late-season flower flushes and replacement pods. 2. Synchronous Podding: Rapid pod maturity window to escape peak borer density. 3. Structural Integrity: Strong, fibrous stem architecture and deep root networks to handle stress.	a) Pests survive, but yield loss is minimized. b) Does NOT apply selection pressure on pod borers, preventing pests from rapidly evolving counter-resistance.	Horber (1980); Sharma and Ortiz (2002); Smith (2005); Koch et al. (2016)

conventional chemical insecticides for managing pod borers (Veeranna et al., 2024). Moreover, continuous research and farmer education are crucial for effectively implementing these sustainable strategies and enhancing long-term management success.

Understanding how specific pests interact with different crops is fundamental for precision agriculture. AI models analyze vast datasets comprising crop types, growth stages, agronomic practices and pest presence to identify patterns and vulnerabilities. These interactions are modeled to reveal the critical points in the crop growth cycle when pest pressure is highest. Machine learning algorithms have been employed to determine that certain pests, such as *Maruca vitrata*, are more likely to affect legumes during the flowering phase under conditions of moderate humidity and temperature. Crop-specific forecasting also incorporates varietal resistance data, enabling differentiation between susceptible and tolerant cultivars (Ashick and Tamilvanan, 2025).

Conclusion

In conclusion, the biology and ecology of pod borer underscore its significant threat to various crops owing to considerable yield losses primarily caused by larval feeding from the vegetative to pod stages. Management strategies encompass cultural controls, host plant resistance, including biotechnological tools, biological control agents and carefully managed chemical interventions integrated within IPM frameworks. Despite decades of Integrated Pest Management (IPM) efforts, these pests cause massive yield losses ranging from 60% to 90% under favourable conditions. The webbing of *Maruca vitrata* creates a physical shield against contact chemical insecticides and biopesticides. Due to their quick resistance adaptation, farmers often increase spray frequency and dosages. This leads to pest resurgence, elimination of natural predators, chemical residues in food legumes and inflated production. Modern pest management requires weather-based forecasting models. While research proves that specific combinations of temperature and humidity dictate larval peaks, real-time data translation to smallholder farmers remains inadequate. An integrated approach is vital, combining diverse control tactics based on pest monitoring, economic thresholds and ecological understanding to achieve sustainable, environmentally responsible and economically viable pod borer control.

Embracing emerging technologies, adapting to climate change and prioritizing sustainable practices will be crucial for future progress in managing this pervasive pest and ensuring crop production and food security.

Ethical Statement

The authors declare that no generative artificial intelligence tools were used in drafting or preparing this manuscript. The manuscript was written, interpreted and revised solely by the authors, who take full responsibility for its content.

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