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Research Article

Integrated Management of Sugarcane Stem Borers (*Chilo* spp.): Distribution, Infestation Patterns and Control Approaches

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Abstract

Sugarcane cultivation across India is significantly threatened by infestations of *Chilo* species, which are among the most damaging stem borers affecting the crop. These pests are prevalent in major sugarcane-producing states such as Uttar Pradesh, Maharashtra, Tamil Nadu, Karnataka, and Andhra Pradesh. Their infestation leads to considerable reductions in stalk weight, juice quality, and sugar recovery. The borers penetrate and tunnel through the stalks, thereby compromising structural integrity, reducing sucrose content, impeding nutrient flow, and increasing the plant's vulnerability to diseases and secondary infections. Economic losses due to these infestations can range between 10% and 80% of the total yield, depending on the severity of infestation and the efficacy of pest management interventions. Integrated Pest Management (IPM) strategies are widely adopted for controlling sugarcane stem borers. These strategies combine cultural practices, chemical control, behavioral manipulation, biological agents, and the cultivation of pest-resistant varieties. However, the sustainability and effectiveness of these measures are increasingly challenged by issues such as pesticide residues, environmental heterogeneity, limited efficacy of formulations, labor shortages, and escalating production costs. In response, advances in biotechnology have led to the development of transgenic sugarcane lines expressing insecticidal proteins derived from *Bacillus thuringiensis* (Bt). These Bt sugarcane varieties hold promise for improving pest resistance, reducing chemical pesticide reliance, and promoting sustainable agricultural practices. This paper provides a comprehensive overview of the biology and distribution of *Chilo* species, assesses their economic impact on sugarcane production, evaluates the efficacy and limitations of existing IPM strategies, and examines the future prospects of biotechnological innovations such as Bt sugarcane in managing these persistent pests.

Keywords: Sugarcane, Sugarcane Borers, *Chilo*, Distribution, Damage, IPM, *Bacillus thuringiensis*.

Introduction:
Sugarcane (*Saccharum officinarum* L.) is a significant tropical and subtropical crop, recognized globally as one of the most economically important agricultural commodities. This tall, perennial grass, capable of reaching heights of 4 to 5 meters (13–16 feet), is primarily cultivated for the high sucrose content found in its stalks. The domestication of sugarcane traces back several millennia to the Indian subcontinent and Southeast Asia (Jaipal, 1996). In contemporary India, sugarcane cultivation spans over 5.01 million hectares, producing approximately 352.1 million tonnes, with an average productivity of 69.84 tonnes per hectare (Pasupathy, 2021). Beyond its economic significance, sugarcane cultivation has substantial social and environmental implications. It serves as a primary livelihood source for millions of farmers and agricultural laborers, while its by-products sustain several ancillary industries, particularly in rural contexts. Notably, sugarcane supports two major traditional sectors: jaggery production and the manufacturing of *khandsari* (unrefined raw-white sugar). Over the years, the area under cultivation, productivity, and total production of sugarcane in India have exhibited consistent growth, aligning closely with the expansion of the sugar industry. National estimates for the year 2013–14 indicated a cultivated area of 4.99 million hectares, an average yield of 70.50 tonnes per hectare, and a sugar recovery rate of 10.23% (Rju & Kumar, 2019).

Sugarcane yield is influenced by a multitude of factors, including soil fertility, climatic conditions, cultivar selection, agronomic practices, as well as the prevalence of diseases, insect pests, and environmental stressors. Among these, insect pest infestations constitute a major constraint, often resulting in substantial reductions in productivity. Given that sugarcane requires a prolonged growth cycle—ranging from 10 to 18 months—the crop remains vulnerable to both biotic and abiotic stresses throughout its developmental stages (Singh et al., 2022). In India, sugarcane is cultivated across two primary agro-climatic zones: the tropical and subtropical regions. The spectrum of pest incidence varies significantly between these zones. In subtropical regions, major pests include the top borer (*Scirpophaga excerptalis*), shoot borer (*Chilo infuscatellus*), and stalk borer (*Chilo auricilius*), whereas the tropical zones are predominantly affected by the internode borer and early shoot borer. Of particular concern is the stem borer genus *Chilo*, which comprises 41 known species. *Chilo infuscatellus* Snellen (Lepidoptera: Crambidae), a major pest in peninsular India, is especially destructive during the early growth stages of sugarcane, leading to considerable economic losses (Harris, 1990). In addition, species such as *Chilo tumidicostalis* have been reported to infest several members of the Poaceae (Gramineae) family. This pest, along with *Chilo auricilius* and *Chilo sacchariphagus*, is widely distributed and recognized for its destructive impact in India and Bangladesh (Rahman et al., 2013). The subtropical regions of India, characterized by extreme seasonal fluctuations, often experience moderate crop development but high levels of pest infestation. Consequently, sugarcane farmers must contend with a variety of major and minor pests, whose management necessitates an understanding of their taxonomy, life cycles, and economic implications. This study concentrates on the *Chilo* genus, examining its geographical distribution, the nature and extent of crop damage it causes, and the contemporary strategies employed for its management.

Sugarcane Stem Borers and their distributions:

Sugarcane is attacked by insects from various orders, including Lepidoptera, Homoptera, Coleoptera, Hemiptera, Orthoptera, and Isoptera (Geetha *et al*, 2018). Among them, Lepidoptera borers are significant pests in almost all sugarcane-producing regions, with around 50 species from the Pyralidae, Crambidae, Noctuidae, and Tortricidae families.

The genus *Chilo*, formerly classified under Pyralidae and now under Crambidae, includes major sugarcane borers (Fig 1). These species cause 'dead-heart' in young shoots and damage inner stem tissues, leading to yield loss and potential crop failure (Guan *et al*., 2012). Other important borers belong to the *Sesamia*, *Diatraea*, *Eldana*, *Tryporyza*, *Scirpophaga*, and *Eoreuma* genera (Table 1). These borers pose serious threats to sugarcane, impacting both yield and quality.

Table 1: Major borer species affecting sugarcane

Species	Common Name	Reference
Chilo infuscatellus	Early shoot borer	David *et al*., 1986
Chilo sacchariphagus	Sugarcane Internode borer	Waterhouse, 2007
Chilo venosatus	-	Liu *et al*., 2012
Chilo tumidicostalis	spotted sugarcane stem borer	Long & Hensley, 1972
Chilo auricilius	Stalk borer	Nesbitt *et al*., 1986
Sesamia cretica	Pink borer	Okamoto *et al*., 1999
Sesamia nonagrioides	Corn borer	Fantinou *et al*., 2003
Sesamia inferens	Asiatic pink stem borer	Luo *et al*., 2014
Eldana saccharina	African stalk borer	Girling, 1978
Scirpophaga excerptalis	White top borer	Zhang *et al*., 2012
Scirpophaga nivella	White rice borer	Long & Hensley, 1972
Eoreuma loftini	Mexican rice borer	Meagher *et al*., 1994

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Fig 1: A. *Chilo infuscatellus*, B. *Chilo sacchariphagus*, C. *Chilo auricilius*

Distribution:

An important and highly destructive insect affecting sugarcane worldwide, with the exception of Australia and Fiji, is sugarcane borers, particularly those belonging to the genera *Chilo* and *Sesamia* (Sallam, 2006). Numerous species of *Chilo* and *Sesamia* are found in Old World regions such as Africa and Asia. On the other hand, *Diatraea* species dominate populations in New World locations like the Americas.

Numerous borers belonging to the genus Chilo are major pests of sugarcane in India. Three species of *Chilo*, *Chilo infuscatellus*, *Chilo sacchariphagus indicus* and *Chilo auricilius*—are the main ones that affect sugarcane plantations in India. Different parts of the nation have varied distributions and effects from them (Table 2).

Table. 2: Sugarcane Borer Distribution in India

Species	Distribution	Impact	Reference
Chilo infuscatellus	**Northern India**: Uttar Pradesh, Bihar, Punjab, Haryana **Southern India:** Karnataka, Tamil	"Dead heart" in young sugarcane shoots, caused by *Chilo infuscatellus*, leads to central leaf drying, reduced tillering, stunted growth, and lower yield. The pest also causes leaf yellowing and stem boreholes, weakening the plant.	Mann *et al*. 2006; Jasmine *et al*. 2012, Pasupathy 2011

	Nadu, Andhra Pradesh **Western India:** Maharashtra, Gujarat		
Chilo sacchariphagus indicus	**Southern India**: Tamil Nadu, Karnataka, Andhra Pradesh. **Western India**: Maharashtra, Gujarat	The internode borer infests the internodal regions of the sugarcane stem, developing tunnels that reduce the quality and amount of juice extracted from the cane. This can cause reduced sugar content material and standard yield.	Hensley,1971; Pasupathy, 2011; Jaipal, 2014
Chilo auricilius	**Eastern India**: West Bengal, Assam **Northern India**: Uttar Pradesh, Bihar **Southern India**: Tamil Nadu	This is another important pest, affecting the internodes and on occasion the top shoots. The harm pattern is similar to that of different Chilo species, main to reduced crop quality and yield.	Neupane,1990; Jaipal 2000; Zeng 2004

The state of West Bengal is domestic to a big populace of sugarcane stem borers, which can be observed across the sugarcane cultivation zones. The numerals district, wherein sugarcane farming is highly-priced, has an infestation of pests. Variations inside the district's weather, farming practices, and the provision of natural predators can all have an effect on the prevalence and spread of sugarcane stem borers (Table 3).

Table 3: Sugarcane Borer Distribution in West Bengal

Species	Distribution in West Bengal	Damage	Reference
Chilo infuscatellus	North 24 Parganas, Hoogly, Murshidabad, Bardhaman	10-20%	Kumar, 2019
Chilo sacchariphagus	Nadia, Bardhaman, Midnapore, Hoogly	8-15%	Jaipal, 2016

Chilo auricilius	North 24 Parganas, Malda, Nodia	8-12%	Moneer *et al.*, 2022

Ecological Impact of Borer Infestation

Sugarcane borers represent a major entomological threat to sugarcane production, resulting in both economic and ecological detriment through considerable reductions in yield and crop quality. The principal modes of damage include the destruction of young shoots during the early stages of establishment, substantial losses in stalk biomass, and the deterioration of juice quality following internode development (Long and Hensley, 1972). A widely used metric for estimating crop losses is the percentage of bored internodes, commonly referred to as the infestation index, which serves as a reliable indicator for forecasting yield reduction (Milligan et al., 2003). Moreover, the qualitative aspects of sugarcane juice—critical for sugar extraction—are also adversely impacted by borer activity, as evidenced in earlier studies (Holloway and Haley, 1928). In response to the diverse manifestations of borer-induced injury, several methodologies have been devised to quantify and evaluate the extent of damage caused by various borer species. These approaches play a crucial role in understanding pest dynamics and formulating targeted management strategies aimed at mitigating ecological and economic losses.

On a global scale, sugarcane borers cause significant losses. In China, yearly yield losses range from 10 to 25%, affecting approximately 40% of the country's sugarcane crop (Li *et al.*, 2016). The sugarcane borer can lead to yield reductions of 2625–7950 kg/ha (3.2–9.4% of total production) when the damage rate is 5–20% and 9960–13,537.5 kg/ha (11.7–15.9%) when incidence increases to 25–35% (Zhang *et al.*, 2019). In Indonesia, *Scirpophaga nivella* can cause up to 50% economic loss in sugarcane production (Angerilli *et al.,* 1998). *Chilo sacchariphagus* and *Chilo auricilius* collectively lead to biomass yield losses of approximately 12.5 t/ha (19.2%) when 40% of stalks are damaged (Goebel *et al*., 2014).

In India, sugarcane borers are a major concern, with different species inflicting heavy losses in various regions. *Chilo tumidicostalis* leads to sugarcane yield and sucrose content losses ranging from 8.2 to 12.6% and 10.7 to 48.6%, respectively, in Bihar (Khanna *et al*., 1957). *Chilo infuscatellus* primarily infests sugarcane during the summer, causing extensive losses during early growth stages. In India, shoot losses range from 30 to 75% in different cane-growing regions (Avasthy and Tiwari, 1986). In crops yielding 100 tons per hectare with 10% sugar recovery, yield loss is estimated at 0.35 tonnes of sugar per 5% rise in stem borer incidence. Indian sugarcane can tolerate up to 15% damage from *C. infuscatellus* without significant reductions in cane population, cane sugar percentage, or overall production (Raja *et al*., 1990). North Bihar is identified as an endemic region for *C. infuscatellus* due to high infestation levels.

Scirpophaga excerptalis is another major pest in India, reducing yield by up to 51% and sugar levels by 2.0 units. *Chilo auricilius*, introduced in 1954, has become a serious pest in western Uttar Pradesh. It infests both plant and ratoon crops, serving as a source of infestation for subsequent cycles. Kumar and Pal, 2019 reported that sugar recovery in uninfected canes was 9.85%. Sharma *et al.* (2010) found that *C. auricilius* causes severe losses in India's sugar sector, reducing cane yield by 17–33% with a 29% internode infestation rate. For every 1% increase in stem infestation, cane sugar production declines by 0.65%.

Sugarcane borers cause widespread damage through their feeding activities, leading to weakened vascular systems, secondary infections, and increased susceptibility to breakage. The wounds created by borers serve as entry points for pathogens, including bacteria and fungi, exacerbating crop losses. Red rot and other fungal diseases spread rapidly under these conditions.

Current integrated pest management (IPM) strategy on control of sugarcane bores:

The ecological pest control method known as integrated pest management, or IPM, aims to reduce pest populations below the economic threshold level (ETL). Currently, integrated pest management (IPM) strategies for controlling the sugarcane borer include cropping system modification, chemical pesticide application, behavioural modification, biological control, and resistant variety selection. Two major issues that should be monitored are Economic Injury Level (EIL) and Economic Threshold Level (ETL) (Table 4). EIL, denotes as the lowest pest population density that will cause economic damage to the cane. Whereas, ETL is when the pest population is larger enough to trigger an action to prevent the increasing pest population reaching an optimum level. The economic threshold levels for *Chilo* borers in sugarcane vary: *C. infuscatellus* at 15–22% incidence (Fang *et al*., 2018), *C. sacchariphagus* at 6.2–28.5 larvae per 6m row (Nesbitt *et al*., 1986), and *C. auricilius* at 5% dead hearts in the second brood by June end (Trials, 1980).

Cultural Control:

In sugarcane production, cropping practices play a key role in pest management. Effective strategies include intercropping, using clean seed canes, residue removal, fertilization, and adjusting planting dates (Hensley, 1971). Intercropping with non-Graminae crops like legumes and vegetables enhances ecological balance, promoting natural pest control (Zeng, 2004). Clean seed canes improve yield and reduce pest risks, while pre-harvest burning and mechanical removal of infested shoots help limit pest populations (Tan *et al*., 2003; Jaipal, 2000). Silicon fertilizers have also shown effectiveness against borer infestations (Kvedaras & Keeping, 2007).

Early planting increases borer susceptibility, and continuous sugarcane farming can lead to pest build up (Beuzelin *et al*., 2011; Tan *et al*., 2010). Methods like earthing up and supporting stalks help prevent lodging and borer damage (Jaipal, 2000). Despite challenges, integrating multiple cultivation practices remains essential for sustainable pest control (Table 4).

Table 4: Cultural control of borers

Species	Cultural Control	Reference
Chilo infuscatellus	1. Deep Summer ploughing 2. Inter culture and hand weeding 3. Timely irrigation 4. Light earthing up of crops three months after planting 5. Grow onion/ garlic/ coriander as intercrop 6. In ratoon crop mulching with trash reduce shoot borer attack.	Kvedaras and Keeping, 2007
Chilo sacchariphagus	1. Proper water management to avoid lodging. 2. De-trashing of canes and removal of water shoots once in a month from 5th month onwards 3. Balanced dose of fertilizer	Raja *et al.*, 1990, Beuzelin *et al.*, 2011
Chilo auricilius	1. Proper water management. 2. Use of silicon fertilizer	Zeng, 2004; Jaipal 2000

Chemical pesticide control:

Controlling sugarcane borers with chemical pesticides involves the use of insecticides that target the larvae and adults of the pests. Using pesticides like Organophosphates (Chlorpyrifos, Malathion) effecting against variety of pests, Pyrethroids (Cypermethrin, Permethrin) disrupt the function of sodium channels in nerve cells of the pest, Neonicotinoids (Imidacloprid, Thiamethoxam) bind to nicotinic acetylcholine receptors in the nervous system, causing paralysis and death of the pest, Insect Growth Regulators (IGRs) (Methoprene, Diflubenzuron) disrupt the normal development of insects, preventing them from reaching adulthood, are seen to be used.

The methods for applying these pesticides may include Foliar spray, aerial spray and soil treatment. Foliar spray which includes backpack sprayers, tractor-mounted sprayers, is directly spread on the leaves and stems where the borers are present. Aerial spraying that includes airplanes and drones is mainly effective for large scale fields. Another systemic treatment including soil drench, seed treatment in which the plant absorbs the pests therefore protects the entire crop. When the percentage of plants affected or visible damage increases above economic threshold levels, pesticides should be used. Although many insecticides have been shown to be beneficial in reducing sugarcane borer infestations, using them carelessly has had adverse effects.

Table 5: Chemical Control of Borers

Species	Chemical control	Reference
Chilo infuscatellus	• Fipronil 5% @ 600-800 ml in 200 I of water/acre. • Chlopyrifos 20% EC @ 500-600 ml in 200-400 l of water/acre • Chlorantraniliprole 18.5% SC@ 150 ml in 400 l of water. • Monocrotophos 36% SL@ 600-900 ml in 200-400 l of water/acre	Khanna *et al.,* 1957; Rodriguez *et al.,* 2001; Wilson *et al.* 2017 White et al. 2008
Chilo sacchariphagus	• Chlopyrifos 20% EC@ 500-600 ml in 200-400 l of water/acre • Monocrotophos 36% SL@ 750 ml in 200-400 l of water/acre	Wilson *et al.,* 2017, Singh *et al.,* 2015, Raja *et al*., 1990; Narasimhan *et al*., 2001
Chilo auricilius	• Cypermethrin 10% EC @ 260-304 ml in 200-280 l of water. • Monocrotophos 36% SL@ 750 ml in 200-400 l of water/acre	Zeng, 2004; Reay-Jones *et al*., 2005, Bennett, 1971

Behavioural manipulation:

Insects respond to chemical cues like pheromones for mate attraction and host plant identification. Sex pheromones are widely used for monitoring borer populations, optimizing insecticide application timing, and disrupting mating to reduce pest reproduction (Van Rensburg *et al*., 1985). Different borers respond to specific pheromones: *Chilo infuscatellus* is attracted to (Z)-11-Hexadecenal and (Z)-11-Hexadecen-1-ol acetate (Fang *et al*., 2018), *Chilo sacchariphagus* responds to (Z)-11-Hexadecenal, (Z)-13-Octadecenal, and (Z)-11-Hexadecenyl acetate (Trials, 1980), while *Chilo auricilius* is lured by (Z)-8-Tridecenyl acetate, (Z)-9-Tetradecenyl acetate, and (Z)-10-Pentadecenyl acetate (Nesbitt *et al*., 1986).

Apart from pheromone-based control, trap cropping is an effective strategy for managing sugarcane borers. *Erianthus arundinaceus* reduces stalk borer damage by limiting larval survival and growth (Hokkanen & T, 1991). The push-pull technique further enhances pest control by making sugarcane less attractive (push) while drawing borers to trap crops (pull), where they can be eliminated (Cook *et al*., 2007). Despite these strategies, the success of pheromone-based control remains limited due to the complexity of insect pheromones and challenges in large-scale implementation (Campion & Nesbitt, 1983).

Biological Control:

Biocontrol is essential to sugarcane borer Integrated Pest Management (IPM) techniques. Natural enemies, parasitoids, and entomopathogenic microorganisms are the three primary categories of biocontrol agents. As biological agents, entomopathogenic microorganisms—which include bacteria, viruses, and fungi—have found commercial usage. Bacillus thuringiensis (Bt) is a well-established biological control agent known for its specificity to insect pests and minimal environmental impact (Sanahuja *et al*., 2011). Among insect viruses, Granuloviruses (GVs) such as ChinGV and ChsaGV, naturally occurring in Tamil Nadu, India, have been effective against *C. infuscatellus* and *C. sacchariphagus* larvae (Easwaramoorthy, 1987). Additionally, AgMNPVD10, TnMNPV, and AgMNPV have demonstrated lethal effects on *D. saccharalis* (Hernández-Velázquez *et al*., 2012).

Entomopathogenic fungi, including *M. anisopliae* and *B. bassiana*, have shown significant efficacy in controlling sugarcane borers (Sivasankaran *et al*., 1990). Other fungi such as *Hirsutella nodulosa*, *Isaria tenuipes*, and *Cordyceps spp*. have also been tested on *D. saccharalis*, *S. inferens*, *C. indicus* and *E. saccharina* (Varma and Tandan, 1996). The microsporidium *Nosema* sp. has been reported to naturally suppress sugarcane borers by causing "white larvae" disease (Inglis *et al*., 2015).

Studies on the predators of *Chilo* borers reveal diverse natural enemies across different species. For instance, *Chilo infuscatellus* is preyed upon by *Chrysoperla* spp. (green lacewings), spiders, and the seven-spotted ladybird beetle, as noted by Reagan and Mulcahy (2019), David *et al.* (1988), Liu *et al.* (2012), and Zeng (2004). Similarly, *Chilo sacchariphagus* faces predation from spiders, ants, ground beetles, birds, and even occasional attacks by parasitic wasps, according to de Mello *et al.* (2020), Varma and Tandan (1996), and Easwaramoorthy *et al.* (2001). In addition, *Chilo auricilius* is targeted by a range of predators including assassin bugs (Reduviidae), damsel bugs (Nabidae), spiders, and ants, as reported by Tomazet *et al.* (2017) and Inglis *et al.* (2015). Their larvae aggressively prey on borer eggs and young larvae, significantly reducing pest populations before they can cause economic damage.

Parasitoids play a key role in biological control programs targeting eggs, larvae, and pupae of sugarcane borers. *Trichogramma* spp. and *Cotesia* spp. effectively parasitize borer eggs and larvae, reducing pest populations (Goebel *et al*., 2014). *Trichogramma chilonis*, in particular, lays eggs inside borer eggs, preventing larval development. Its use in pest management reduces the need for chemical pesticides, lowering costs and minimizing environmental risks. By integrating *Trichogramma chilonis* into IPM strategies, sustainable farming practices are enhanced, improving crop resilience and ecosystem health.

Table 6: Various Parasitoids and Entomopathogenic microorganisms of Sugarcane borers (*Chilo*)

Species	Egg parasitoid	Larval parasitoid	Entomopathogenic bacteria	Entomopathogenic viruses	Entomopathogenic fungi	Reference
Chilo infuscatellus	*Trichogrammachilonis*	*Sturmiopsis inferens, Costesia flavipes*	*Bacillus thuringiensis* (Bt)	Neucleo polyhedron virus (NPV)	*Beauveria bassiana, Metarhizium anisopliae*	Reagan and Mulcahy 2019, David *et al*. 1988, Liu *et al.*, 2012, Zeng 2004
Chilo sacchariphagus	*Trichogrammaspp*	*Sturmiopsis inferens, Bracon hebetor*	*Bacillus thuringiensi, Bacillus cereus, Pseudomonas fluorescens, Serratia marcescens*	Baculo viruses, NPVs, Granulo viruses (GVs), Cytoplasmic Polyhedrosis virus (CPV)	*Lecanicillium lecanii, Isaria fumosorosea*	de Mello *et al*. 2020, Varma and Tandan 1996, Easwaramoorthy *et al*. 2001
Chilo auricilius	*Trichogrammaspp, Telenomus* spp, *Chelonus* spp	*Costesia flavipes, Xanthopimpla stemmator*	*Serratia marcescens, Bacillus cereus*	CPV	*Beauveria bassiana, Isaria fumosorosea*	Inglis *et al.*, 2015, Alves 1986

Host plant resistance:

Plant resistance is a crucial and cost-effective strategy for managing pests and diseases. In sugarcane, resistance against borers is exhibited through structural traits in stems and leaves that hinder larval entry (Kvedaras *et al*., 2007). Key resistance traits include erect leaves, high fibre content, rind hardness, and epicuticular wax composition, aiding in the selection of resistant cultivars (Long & Hensley, 1972). Resistant varieties such as L 99-226, L 01-299, N21, N24, and HoCP 04-838 have shown increased stalk height and reduced borer infestation (Kvedaras *et al*., 2009).

In India, varieties like Co 243, 281, 356, 449, 617, and BO17 exhibit low susceptibility to Chilo infuscatellus (David *et al*., 1986). Additionally, Co 1007, 1236, S-5/75, and E 168 are resistant to Chilo auricilius, while Co 243, 453, and 617 show reduced susceptibility to *Chilo tumidicostalis* (Negm & Hensley, 1969).

Enhancing resistance through wild species introgression is essential but labour intensive. To improve selection efficiency, a three-step evaluation process is recommended before field trials (Meena *et al*., 2020). Moreover, transgenic sugarcane expressing Cry proteins and proteinase inhibitors has shown promise in reducing borer damage and improving yield (Srikanth *et al*., 2011).

***Bacillus thuringiensis* (Bt Sugarcane)**

Bt sugarcane is a genetically modified cultivar designed to express Cry proteins derived from *Bacillus thuringiensis* (Bt), which are highly effective against certain insect pests, particularly the sugarcane borer, a major threat to sugarcane yield. Cry toxins have demonstrated significant insecticidal properties against various insect species, including sugarcane borers (Gómez *et al*., 2007). These proteins function by binding to receptor molecules in the brush border membrane of insect midgut cells, leading to pore formation and eventual cell disruption (Höfte & Whiteley, 1989; Van *et al*., 1990).

In addition to Cry proteins, Bt crops have been engineered to produce vegetative insecticidal proteins (Vip), enhancing their pest resistance (Mahon *et al*., 2012). The widespread adoption of Bt crops reflects growers' confidence in their effectiveness, as they provide strong protection against coleopteran, lepidopteran, and some hemipteran pests (Carrière *et al*., 2003). Bt sugarcane employs various Cry proteins for insect resistance. Cry1Ab and Cry1Fa bind to gut receptors, causing cell lysis and hole formation to control lepidopteran pests (Arvinth *et al*., 2010; Dessoky *et al*., 2021). Cry1Ac prevents digestion, offering broad-spectrum resistance (Kalunke *et al*., 2009). Cry2Ab, combined with Cry1 genes, enhances dual-gene resistance by forming holes in midgut cells (Mahon *et al*., 2012).

Conclusion and future perspectives

Lepidopteran borers represent some of the most destructive pests affecting sugarcane cultivation, contributing to significant losses in stalk biomass, deterioration of juice quality, and reduced sugar recovery. Conventional control measures have heavily relied on chemical insecticides, which, while temporarily effective, raise critical concerns regarding environmental sustainability, ecological imbalance, and human health risks. In response to these challenges, contemporary research is increasingly focused on developing sustainable alternatives aimed at minimizing dependence on synthetic pesticides without compromising agricultural productivity.

Among the promising alternatives are biological control agents, including entomopathogenic bacteria and fungi, alongside agronomic innovations such as cropping system modifications, behavioral control strategies, and the development of pest-resistant sugarcane varieties. However, the practical application of these methods often encounters constraints such as residual pesticide contamination, environmental variability, labor shortages, and high input costs, which collectively limit their effectiveness in large-scale agricultural settings.

The sugarcane stem borer exhibits a complex life cycle, with four to six overlapping generations annually. Larval feeding occurs predominantly within the sugarcane stalks, making external control measures—such as foliar pesticide applications and biological interventions—highly dependent on precise timing to target larval emergence. This challenge often results in the suboptimal performance of biological control under field conditions. Nevertheless, advancements in genetic engineering have shown considerable promise. Transgenic *Bt* sugarcane, incorporating *Cry* protein-expressing genes from *Bacillus thuringiensis*, has demonstrated significant resistance to borer infestation and associated damage (Kalunke et al., 2009).

Despite these innovations, integrated pest management (IPM) strategies for sugarcane borers require further development to enhance their field-level efficacy. Key areas for advancement include the formulation of novel biological products, the evaluation of newer and safer chemical agents, the application of chemical ecology techniques, and the implementation of advanced cultural practices. Furthermore, continued efforts in breeding and selecting resistant cultivars remain indispensable. A deeper understanding of pest biology, behavioral patterns, and ecological interactions is essential for optimizing insecticide application schedules and improving overall pest control outcomes.

The integration of modern technologies such as semiochemicals for monitoring pest populations, remote sensing for real-time surveillance, and Geographic Information Systems (GIS) for spatial analysis holds substantial potential to revolutionize pest management in sugarcane agriculture. Collaborative engagement among researchers, extension specialists, and industry stakeholders is crucial to ensure the successful translation of scientific innovations into practical, scalable solutions.

IPM frameworks must be evaluated not only for their technical efficacy but also for their ecological and socio-economic sustainability. It is imperative for farmers to assess the cost-effectiveness and long-term benefits of new pest control methods to ensure economic viability for both producers and sugar mill operators. Innovations in biotechnology, particularly the development of transgenic sugarcane with next-generation *Bt* genes, offer considerable promise for future pest management. Continued research should prioritize genome editing technologies and the refinement of transformation protocols to create sugarcane cultivars with enhanced resistance to borers and improved agronomic traits.

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