REVIEW

Sugarcane borers: species, distribution, damage and management options

Ao-Mei Li[1] · Zhong-Liang Chen[1] · Fen Liao[1] · Yong Zhao[2] · Cui-Xian Qin[1] · Miao Wang[1] · You-Qiang Pan[1] · Shao-Long Wei[3] · Dong-Liang Huang[1]

Abstract

Lepidopteran borers stand out as the most destructive pests in sugarcane, leading to reductions in stalk weight, juice quality and sugar recovery. Presently, integrated pest management (IPM) systems are utilized for sugarcane borer management, employing diverse methods encompassing cropping system, chemical pesticides, behavioral manipulation, biological agents and the selection of resistant varieties. However, the effectiveness of this strategy remains controversial due to concerns about harmful residues, formulation limitations, environmental variability, labor shortages and increased input costs. Currently, multiple lines of transgenic sugarcane expressing insecticidal genes from the bacterium *Bacillus thuringiensis* (Bt) have been developed globally, offering the prospect of increases production with reduced pesticides application, thereby eliminating the negative effect of IPM. In Brazil, the first genetically modified sugarcane cultivars resistant to the sugarcane borer have been approved and released for commercial cultivation, shedding a bright light on a viable solution for sugarcane borers. This paper reviews borer species and distribution, the significant damage caused by sugarcane borers, current control approaches and the future effective control strategies. Additionally, this work provides comprehensive understanding on Bt sugarcane, serving as an additional tool to complement conventional sugarcane borers control resistance programs.

Keywords Major pests · Taxonomy · Sugarcane damage · Integrated pest management (IPM) · Genetically modified (GM)

Sugarcane borers species, distribution, damage worldwide

Sugarcane encounters a spectrum of biotic stressors, each with the potential to exert a substantial influence on its growth and yield. Among these stressors, lepidopteran borers are the foremost destructive pests in the major sugarcane-growing regions, including Brazil, India, China, the USA, South Africa, Indonesia, Reunion Island, Mexico, Iran, Colombia and Papua New Guinea (Nikpay et al. 2015). To better protect sugarcane from borer attacks, understanding the species, distribution and damage worldwide is of paramount importance.

Sugarcane borers species

Globally, sugarcane is susceptible to attacks by various insects from orders such as Lepidoptera, Homoptera, Coleoptera, Hemiptera, Orthoptera, and Isoptera (Yoseph and Desmond 2009). Lepidoptera borers represent

Ao-Mei Li and Zhong-Liang Chen have contributed equally to this work.

✉ Shao-Long Wei
nngt51578@126.com

✉ Dong-Liang Huang
hdl666@163.com

[1] Key Laboratory of Sugarcane Biotechnology and Genetic Improvement (Guangxi), Ministry of Agriculture and Rural Affairs, Guangxi Key Laboratory of Sugarcane Genetic Improvement, Sugarcane Research Institute, Guangxi Academy of Agricultural Sciences, Nanning 530007, China

[2] Sugarcane Research Institute, Yunnan Academy of Agricultural Sciences, Kaiyuan, Yunnan 661699, China

[3] Guangxi Subtropical Crops Research Institute, Guangxi Academy of Agricultural Sciences, Nanning 530007, China

significant pests in almost all sugarcane-planting countries. Approximately 50 species of Lepidoptera borers, including the genera *Chilo, Diatraea*, *Sesamia*, *Argyroploce*, *Tryporyza*, *Scirpophaga*, *Eoreuma*, *Telchin* and *Eldana*, have been documented attacking sugarcane (Fig. 1), mainly belonging to the Pyralidae, Crambidae, Noctuidae and Tortricidae families (Long and Hensley 1972; Kfir et al. 2002).

One notable sugarcane borers belongs to the genus *Chilo*, which is classified under the Crambidae and was previously categorized under Pyralidae. Species within the genus *Chilo* initiate damaged by causing 'dead-heart' in sugarcane shoots and subsequently feed on the internal stem tissue. These damages result in a significant reduction in sugarcane yield, potentially leading to total crop failure (Guan et al. 2012). *Chilo infuscatellus*, commonly referred to as the early shoot borer, causes damage to the crop in its early stages, leading to a subsequent reduction in yield. This species can survive year-round in mild climates (David et al. 1986; Narasimhan et al. 2001; Srikanth et al. 2009; Omkar 2018). Another significant sugarcane borer in this genus is the internode spotted borer, *Chilo sacchariphagus*, known for typically attacking plants aged 3–7 months. It exerts a more substantial impact on cane yield than sucrose yield (Waterhouse 2007; Bezuidenhout et al. 2008). The third species, *C. venosatus,* is also a noteworthy sugarcane borer, contributing to substantial economic losses (Liu et al. 2012; Hu et al. 2017; Fang et al. 2018). The fourth species, *C. tumidicostalis,* primarily inflicts damage to the crop after internode formation (Long and Hensley 1972). The fifth species, stalk borer *C. auricilius*, has young larvae that bore into shoots and canes by cutting holes and forming galleries in the stalk (Jaipal

1996), impairing growth and causing losses in cane yield and sugar recovery (Nesbitt et al. 1986).

Concerning borers within the *Diatraea* genus, their primary impact is on sugarcane in the Americas. In this genus, *Diatraea saccharal* is a prominent pest prevalent in the Western Hemisphere (Box and Harold 1931; Long and Hensley 1972; Reagan et al. 1972; Cristofoletti et al. 2018). Additionally, species like *D. albicrinella*, *D. busckella*, *D. tabernella*, *D. centrella*, *D. indigenella*, *D. lineolata*, *D. considerate* and *D. magnifactella* have been documented as sugarcane attackers (Long and Hensley 1972; Vejar-Cota et al. 2008; Vargas et al. 2015; Solis and Metz 2016).

The pink borers species in the Sesamia genus lead to a significant reduction in sugar recovery (Okamoto et al. 1999; Nikpay et al. 2014). Among these species, *Sesamia cretica* and *S. nonagrioides* are widely distributed in all sugarcane-growing areas, infesting sugarcane at all stages of growth (Jamshidnia et al. 2010; Nikpay et al. 2017). *S. grisescens*, on the other hand, can cause substantial damage to sugarcane in a few countries (Young et al. 1992). Additionally, larvaes of *S. inferens* bore into the aboveground parts of sugarcane seedlings (Luo et al. 2014). *S. nonagrioides,* also known as the corn borer, is another species within the *Sesamia* genus that causes severe damage to sugarcane (Fantinou et al. 2003).

Apart from the borer species from *Chilo*, *Diatraea* and *Sesamia*, some species of other genera also attack sugarcane. For example, larvae of *Argyroploce schistaceana* inflict damage to both underground and surficial parts of sugarcane, causing a significant increase in population density and ultimately resulting in losses in cane yield and sugar (Luo et al. 2014; Zhang et al. 2019a). Larvaes of *Tryporyza*
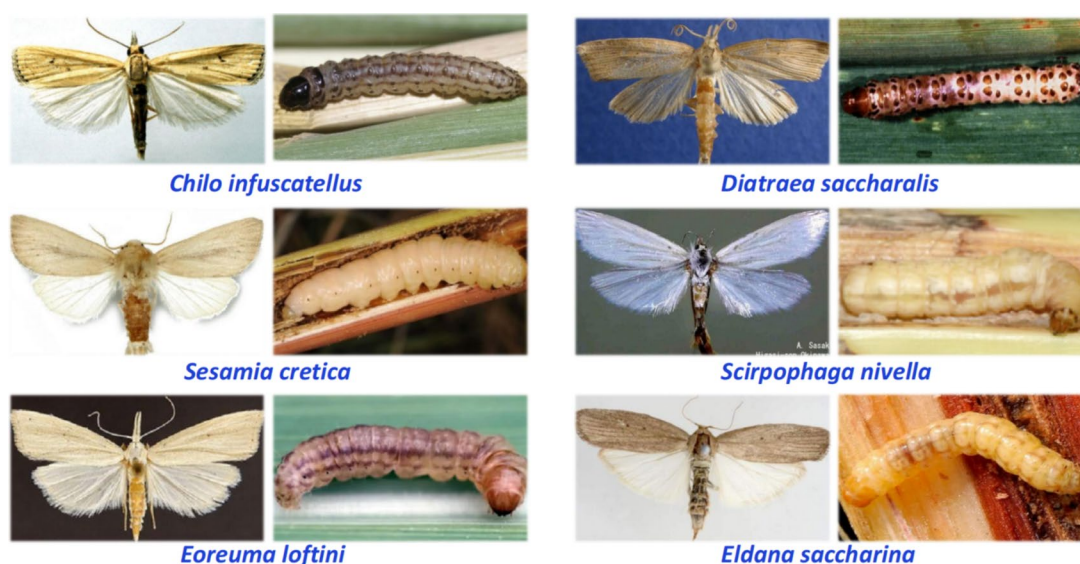

Fig. 1 The major sugarcane borers

intacta bore into the seedlings, causing 'dead-heart' and reducing the number of tillers (Wei et al. 2012, 2014). *Scirpophaga nivella* imparts a characteristic 'bunchy top' appearance to the plant (Long and Hensley 1972). The Mexican rice borer, *Eoreuma loftini*, is an invasive sugarcane borer causing severe damage (Meagher et al. 1994; Showler et al. 2011). The giant cane borer, *Telchin licus,* caused severe damage to sugarcane (Almeida et al. 2007; Triana et al. 2020), mainly in Central and South America. The African sugarcane stalk borer, *Eldana saccharina*, attacks mature sugarcane (Girling 1978) and is the most destructive pest in South African (Keeping 2006), with the first description dating back to 1865 from sugarcane in Sierra Leone (Atkinson and Carnegie 1989; Bosque-Pérez and Mareck 1991; Ngwuta 2015).

Sugarcane borers distribution

Sugarcane borers, particularly species within the genera *Chilo* and *Sesamia*, stand out as the predominant and highly damaging pests affecting sugarcane in cane-growing countries globally, with the exception of Australia and Fiji (Sallam 2006). Each geographical region possesses its distinctive pest fauna. Old World regions, including African and Asia, host a variety of *Chilo* and *Sesamia* species (Long and Hensley 1972). Conversely, New World regions, such as the Americas, are primarily populated by *Diatraea* species (Long and Hensley 1972).

The sugarcane internode spotted borer, *Chilo sacchariphagus*, originally emerged in Asia but has subsequently disseminated to various sugarcane-producing countries and islands worldwide, encompassing central Asia, India, Korea, China, Indonesia, Malaysia, Sri Lanka, Thailand, Vietnam, Madagascar, Mauritius, Mozambique and South Africa (Cao et al. 2011; Ghahari et al. 2009; Nibouche et al. 2019; CABI 2022). The early shoot borer, *C. infuscatellus*, constitutes a notable pest with an extensive range spanning from the Philippines to Afghanistan, encompassing central Asia, India, Korea, China, Indonesia, Malaysia, Thailand, Uzbekistan, Vietnam, Russia and Papua New Guine (Narasimhan et al. 2001; CABI 2022). Another destructive pest, the stalk borer *C. auricilius*, is present in Eastern and Southeastern Asia, including Bangladesh, Bhutan, China, India, Indonesia, Malaysia, Myanmar, and other regions, as well as, northern Australia (Khanna et al. 1957; Nesbitt et al. 1986; Jaipal 1996; CABI 2022). *C. tumidicostalis* is a serious pest in some states of India, such as Assam, West Bengal, and the eastern part of Bihar, as well as in Bangladesh and Nepal (Neupane 1990). *C. venosatus* is primarily distributed in South China, Swaziland, Australia, Brazil, India, the Antilles, and Central and South America (He 2009; Liu et al. 2012 Fang et al. 2018).

Borers belonging to the genus *D.* are acknowledged as severe pests of sugarcane in the Americas (White et al. 2001). *D. saccharalis*, in particular, is a significant sugarcane pest across the American continent, spanning Antigua and Barbuda, Barbados, Belize, Costa Rica, Cuba, Haiti, Honduras, Mexico, Montserrat, Argentina, Bolivia, Brazil, Colombia, Ecuador, Guyana, Peru, Suriname, Uruguay and Venezuela (CABI 2022). This borer has posed a significant and enduring threat to the sugar industry in Brazil and America (Box and Harold 1931; Reagan et al. 1972 Vargas et al. 2015; Almeida et al. 2007; Sidhu 2013). It also represents a significant challenge in Cuba, Peru, Puerto Rico, Jamaica, Trinidad, Mexico, Colombia and America (Long and Hensley 1972; Solis and Metz 2016). *Crambid* stalk borer species, including *Diatraea considerata*, *D. magnifactella*, are distributed in Mexico (Vejar-Cota et al. 2008). In Colombia, various *Diatraea* species, including *D. albicrinella*, *D. busckella*, *D. tabernella D. centrella*, *D. indigenella* and *D. lineolata*, have been reported to attack sugarcane (Solis and Metz 2016). *D. centralla* is the primary sugarcane borer in Guyana and Trinidad (Long and Hensley 1972).

The pink borer, *Sesamia inferens*, has been identified as a sugarcane borer in various countries, including Bangladesh, Bhutan, Cambodia, China, India, Indonesia, Japan, Nepal, Pakistan, the Philippines, Singapore, Thailand, Papua New Guinea, the Solomon Islands and others (Young et al. 1992; Okamoto et al. 1999; CABI 2022). The other two species from the *Sesamia* genera, *S. cretica* and *S. nonagrioides*, are distributed in all sugarcane-growing areas (Jamshidnia et al. 2010). The corn borer, *S. nonagrioides*, is found throughout southern Europe, North Africa, and the Middle East (Fantinou et al. 2003; CABI 2022). *S. calamistis* and *E. saccharina* are the two major sugarcane borers found exclusively in South Africa (Long and Hensley 1972; CABI 2022). The pink stem borer, *Sesamia* spp., is also the most destructive pest of sugarcane in Southwest Iran (Nikpay et al. 2014; CABI 2022). *S. cretica* is an important borer of sugarcane, maize and sorghum in Africa, the Middle East, Southern Europe, Egypt, and Mediterranean, including Sudan, Somalia, Kenya, Cameroon and Ethiopia (Temerak and Negm 2009; Goftishu et al. 2016; CABI 2022). *S. grisescens* is exclusively distributed in Papua New Guinea (Young et al. 1992; CABI 2022).

Apart from the three aforementioned genera of sugarcane borers, there are additional generas specific to Asia, Africa and Americas. In Asia, the white borer *A. schistaceana* is prevalent in sugarcane-growing areas in China and is considered highly detrimental in Mauritius (Young et al. 1992) and also distributed in Madagascar, Indonesia, Japan, Malaysia, Philippines, Sri Lanka and Vietnam (CABI 2022). *S. excerptalis* is identified as a prominent sugarcane borer in Thailand (Young et al. 1992) and is frequently found across various regions, including

Bangladesh, China, India, Indonesia, Japan, Malaysia, Myanmar, Nepal, Pakistan, the Philippines, Singapore, South Korea, Thailand, Vietnam, Australia, Papua New Guinea and the Solomon Islands (CABI 2022). *S. nivella* is identified as a species that inflicts significant economic damage in India, Java and Indonesia (Long and Hensley 1972; Angerilli et al. 1998). Moreover, it is commonly found across several regions, including Bangladesh, Brunei, China, India, Indonesia, Malaysia, Myanmar, Nepal, Pakistan, the Philippines, Singapore, Sri Lanka, Thailand, Vietnam, Australia, Fiji, New Caledonia and Papua New Guinea (CABI 2022). The Guangxi sugarcane area hosts various sugarcane borers, including *A. schistaceana* and *T. intact* Snellen (Li et al. 2016a, b). In the Americas, the Mexican rice borer, *E. loftini*, was initially discovered on sugarcane in the Lower Rio Grande Valley of Texas, USA, in the early 1980s and has subsequently spread to sugarcane-growing regions in Louisiana (Showler et al. 2011; Vanweelden et al. 2015; Wilson et al. 2015a). The sugarcane borer, *T. intacta*, is a severe pest in Southeast Asian countries and South China, causing significant damage, particularly in recent years (Wei et al. 2014). In 2008, the giant cane borer *T. licus* was initially recorded in Sao Paulo, the largest sugarcane-growing state in Brazil. It has

subsequently spread across all sugarcane areas and is currently invading the central and southern regions of this country (Almeida et al. 2007). The African sugarcane stalk borer, *E. saccharina*, is acknowledged as the most destructive pest in South Africa, where it not only infests numerous wetland sedges (Atkinson and Carnegie 1989; Keeping 2006), but is also widely distributed in Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Chad, Congo, Equatorial Guinea, Eswatini, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Liberia, Madagascar, Malawi, Mali, Mozambique, Niger, Nigeria, Rwanda, Senegal, Seychelles, Sierra Leone, Somalia, Sudan, Tanzania, Togo, Uganda, Zambia, Zimbabwe and Saudi Arabia (CABI 2022).

In the major sugarcane production regions, namely Asia, South America, and their neighboring areas, a greater variety of borer species indicate a significant occurrence of pests. In contrast, Australia and Europe exhibit fewer borer species (Fig. 2). This phenomenon is partly attributed to the relatively small total area of sugarcane in these two regions. However, it may also be linked to their effective pest control measures. The diversity of borer species in various regions may also be influenced by the local climate, ecological environment, and insect species composition. To prevent
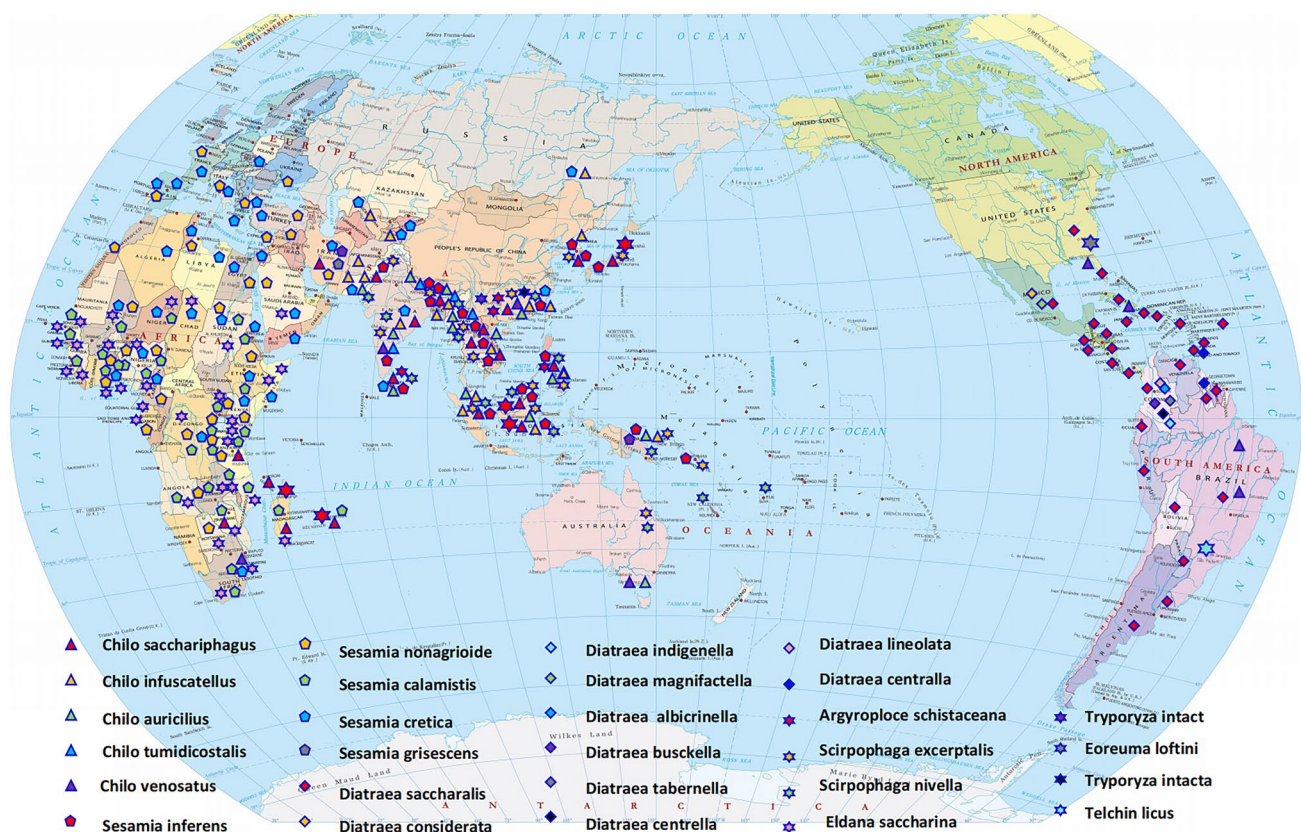

Fig. 2 The distribution of sugarcane borers around the world

the spread and proliferation of insect pests, effective control of invasive species is a crucial strategy for every country, particularly those with border regions.

Economic loss caused by borers

Yield losses linked to most borers species are primarily attributed to reductions in crop before the formation of young shoots and to reductions in stalk weight and juice quality after internodes formation has commenced (Long and Hensley 1972). The infestation index, represented by the percentage of bored internodes, stands as a reliable parameter for predicting yield losses (Milligan et al. 2003). Ellis et al. (Ellis et al. 1960) concluded that the occurrence of internodes bored per unit weight of cane consistently correlates with sugar loss more effectively than estimates of the number of bored internodes or stalks. However, some researchers have also highlighted the impact of borer damage on juice quality (Holloway and Haley 1928). Thus, the damage caused by different species of borers has been assessed based on various methods of measurement. For example, *Chilo infuscatellus* can survive the winter in mild climates, and attacks the ratooning seedlings, resulting in the occurrence of 28.6 percent dead hearts (Srikanth et al. 2009), determined by the ratio of damaged seedlings to total seedlings. Meanwhile, larvaes of *C. venosatus* feed inside the sugarcane stem, resulting in a production loss of 25 percent (w/w) (Liu et al. 2012), measured by assessing the bored rate of the sugarcane and estimating the sugar production loss.

Based on various calculations, the losses attributed to borers were estimated. In Brazil, *D. saccharalis* larvae bored an average of 25.77 percent and 19.01 percent of the internodes during the sugarcane-growing seasons of 2010 and 2011, respectively. Percentage of bored internodes (*D. saccharalis*) ranged from 3.7 to 27.7% in the 2018 plant cane and 2019 first ratoon trials in in Louisiana, the USA (Salgado et al. 2022). Sucrose yield significantly decreased with the increasing internodes infestation, resulting in estimated sugar yield losses of 8.83 percent and 19.80 percent per 1 percent bored internodes for the first and second seasons, respectively (Rossato et al. 2013). Additionally, an approximately 0.5 percent reduction in sugar yield per acre was observed for each 1 percent of bored internodes after *D. saccharalis* infestation (Long and Hensley 1972).

In India, losses in sugarcane yield and sucrose content due to *C. tumidicostalis* have been estimated to range from 8.2 to 12.6 percent and 10.7 to 48.6 percent, respectively, in Bihar (Khanna et al. 1957). And these borers result in cane yield losses of 8 to 10 percent at the farmer's level and sugar recovery losses of 10 to 15 percent in sugar processing (Jasmine et al. 2012).

In China, about 40 percent of sugarcane is annually damaged by borers, leading to yield losses ranging from 10 to 25 percent (Li et al. 2016a, b). In China, researches observed that sugarcane borer could cause cane loss of 2625–7950 kg/ha, representing 3.2–9.4% of cane production when borer damage rate was 5–20% and 9960–13,537.5 kg/ha, accounting for 11.7–15.9% when borer incidence was 25–35% (Zhang et al. 2019b). Pests occurred significantly in Xianggui sugarcane area of China, where the average borer-damaged strain was 46.54%, the average yield loss was 14.89%, and the average sucrose content loss was as high as 1.12%. The estimated results of economic damage caused by pests revealed that the agricultural losses amounted to 467 million yuan (about 60.31 million dollars), industry losses reached 856 million yuan (about 119.72 million dollars), and the national financial losses were 51million yuan (Xie et al. 2020).

In Louisiana, damages caused by *D. saccharalis* were estimated to cause losses of up to 28 percent of cane weight per acre in a susceptible cultivar ('CP 44–101') (Hensley and Long 1969). However, it is crucial to note that economic losses associated with *E. loftini* in Louisiana sugarcane may reach as high as 220 million US dollars when the insect becomes fully established in the state (Meagher et al. 1994). The crambid stalk borer, *D. considerata*, causes annual losses of up to 10 million US dollars in Mexico (Vejar-Cota et al. 2008). Mexican rice borers, *E. loftini*, damage 20 percent of sugarcane internodes in that region, resulting in losses of 575 USD/ha (Meagher et al. 1994), and the total annual losses throughout the region are estimated to be between 10 and 20 million USD (Hardke et al. 2011). These diverse instances underscore the significant economic impact. Under the conditions of the Cauca River Valley in Colombia, economic losses attributed to *Diatraea* spp are estimated at 143 kg of sucrose for each percent of bored internodes (Vargas et al. 2013). In Papua New Guinea, between January and June 1987, 70 percent of the total commercial planting in Ramu suffered moderate-to-severe damage by *S. grisescens*, leading to an 18 percent loss in sugar production (Young et al. 1992). The crop losses caused by *E. saccharina* in South African sugarcane have been estimated at a 0.1-percent yield loss for every 1 percent of damaged stalks (Smaill and Carnegie 1979).

In Indonesia, the economic losses of sugarcane caused by *S. nivella* can amount to as much as 50 percent (Angerilli et al. 1998). Simultaneously, the proportion of stalks damaged by *C. sacchariphagus* and *C. auricilius* reached 40 percent, leading to an approximate biomass yield reduction of 12.5 t/ha (19.2 percent) (Goebel et al. 2014).

Moreover, the damage inflicted by its larvaes is pervasive, manifesting at all stages of plant development. In addition, the entrance holes crafted by these borers not only serve as gateways for their but also provide avenues for secondary

phytopathogenic fungi, thereby intensifying the potential impact on the crop (Rossato et al. 2013).

In general, bores damage results in 10–30% reduction in sugarcane yield, corresponding to the losses of one-fifth (calculated as an average of 20%) of the land allocated for sugarcane cultivation annually, thereby representing a substantial and noteworthy losses. Consequently, the developed and implementation of novel technologies to mitigate borer damage represent a critically important and formidable undertaking for sugarcane-producing economies worldwide.

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

Integrated pest management (IPM) is an ecological strategy for pest control designed to suppress pest populations below the economic threshold level (ETL). Presently, IPM systems for managing the sugarcane borer encompass the manipulation of cropping system, the use of chemical pesticides, behavioral manipulation, biological control, and the selection of resistant varieties (Fig. 3).

Cropping system

The cropping system have long been acknowledged as the fundamental line of defense against pests in sugarcane cultivation practices. These practices encompass intercropping, planting clean seed canes, the removal of crop residues and damaged plants, fertilization, the manipulation of planting dates, and other specific tillage methods (Hensley 1971; Jaipal 2000; Kfir et al. 2002) (Fig. 4).

Intercropping is a valuable cultivation practice that can reduce pest damage, while simultaneously increasing income. However, it is important to avoid intercropping sugarcane with similar crops from the same family, Graminae, such as maize, sorghum and rice, to prevent the spread of pests between these crops. Alternatively, intercropping sugarcane with legumes such as soybean, mung bean, green manure crops, peanut, as well as vegetables such as tomatoes, hot peppers and cabbage, can establish an ecological balance conducive to the survival of natural enemies, thereby enhancing pest control (Zeng 2004).
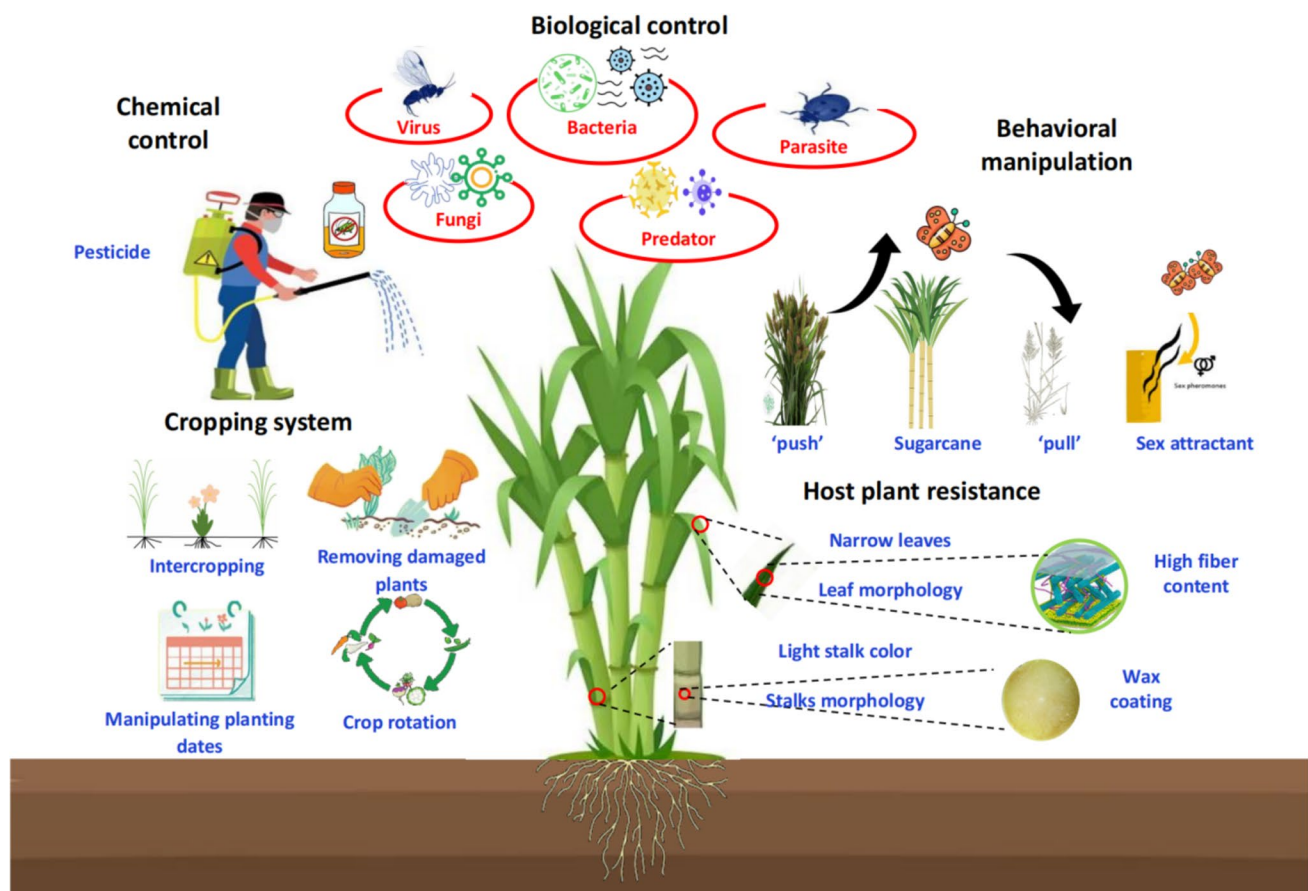

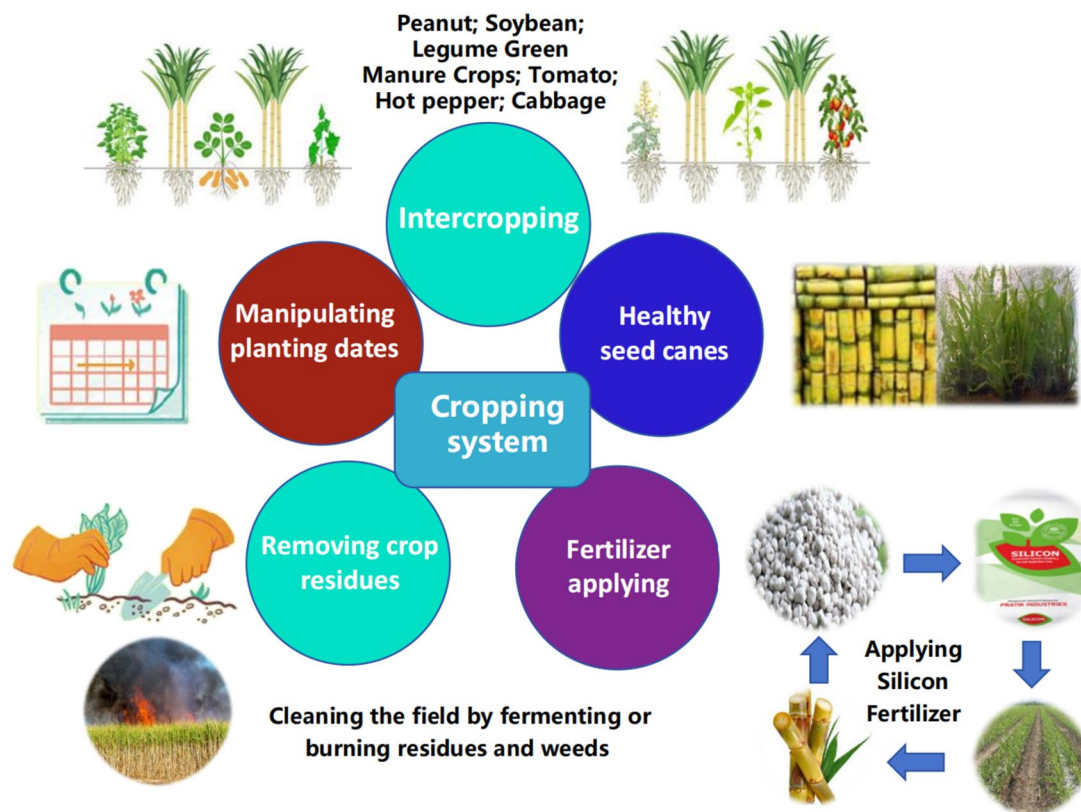**Fig. 3** Integrated pest management strategy on sugarcane bores control

Fig. 4 Cropping systems for control of sugarcane bores

The use of clean seed canes is instrumental in reducing the risk of pest infestation and enhancing both cane yield and quality. It is imperative to refrain from using canes sourced from fields severely impacted by pests (Tan et al. 2003). Moreover, common practices such as pre-harvest burning and the timely mechanical removal of borer-infested shoots or egg masses have been widely employed to curtail in-field pest populations and minimize damage (Jaipal 2000; Ma et al. 2014). The application of silicon (Si) fertilizer has proven effective in mitigating borer infestations by delaying the penetration of early instar larvaes into the stalks, resulting in increased larval mortality and reduced weight lost (Kvedaras and Keeping 2007). Additionally, the choice of planting date can significantly impact *D. saccharalis* populations in sugarcane, with early-planted sugarcane displaying greater susceptible to borers, consequently leading to heightened infestations (Beuzelin et al. 2011).

Moreover, performing low cutting during cane harvest proves effective in eliminating the majority of overwintering pests. Conversely, continuous sugarcane cultivation in the same field can result in an overabundance of overwintering borers, asynchronous borer development, and ultimately, substantial damage (Tan et al. 2003). Additional practices such as earthing up and propping cane stalks prevent lodging

have been demonstrated to be effective measures in reducing stalk borer (Jaipal 2000).

However, it is essential to acknowledge that certain cultivation practices have been abandoned due to their low control efficiency, labor shortages and escalating input costs (Hensley 1971). Despite these challenges, the integration of a combination of cultivation control practices, tailored to the specific conditions of each sugarcane cultivation area, remains crucial for effective and sustainable pest management.

Chemical pesticide control

When the level of economic injury reaches 6–12% of damaged internodes for *D. saccharalis*, the necessity for action and the application of insecticides is recommended (White et al. 2008). Novaluron, an inhibitor of chitin synthesis, has demonstrated noteworthy reductions in *D. saccharalis* infestations, resulting in a 6.3–14.5-fold decrease in bored internodes. Moreover, the pyrethroid gamma-cyhalothrin has proven effective in safeguarding sugarcane against *D. saccharalis* infestations (Beuzelin et al. 2010). In studies conducted in Louisiana, insecticides such as Esfenvalerate, Cyfluthrin + Azinphos-methyl, Lambda-cyhalothrin,

Tebufenozide and Esfenvalerate + Acephate have demonstrated efficacy against *D. saccharalis*. Particularly, they have shown a strong fit for the chemical management of the pest (Rodriguez et al 2001; Cherry et al. 2015). Similarly, insecticides such as Flubendiamide, ß-cyfluthrin, Novaluron and Chlorantraniliprole have proven effective in reducing *D. saccharalis* injury, achieving reductions ranging from 39.1 to 99.4% (Reay-Jones et al. 2005). Chlorantraniliprole and Flubendiamide have demonstrated high effectiveness in the management of *E. loftini* (Wilson et al. 2017). In China, insecticides including Carbofuran granules and Bisalfap granules have been extensively employed for controlling sugarcane borer (Chen 1998). Granular pesticides such as Sevidol granules, Lindane and Carbofuran have been utilized for controlling of the early shoot borer, *C. infuscatellus*, a significant pest in the sugarcane fields of Tamil Nadu, India (Narasimhan et al. 2001).

Despite the demonstrated effectiveness of numerous insecticides in mitigating sugarcane borer infestations, the indiscriminate application of these chemicals has resulted in adverse outcomes. These include the persistence of harmful residues, the development of pest resistance, resurgence of pests, environmental damage and the emergence of secondary pests (Reagan et al. 1972; Singh et al. 2015). Challenges such as inadequate penetration of insecticides, the protection of later instars and pupae within stalks, and the inability to apply foliar treatments in a timely manner during peak periods of adult emergence or oviposition pose substantial obstacles to the effectiveness of insecticide treatments (Bennett 1971; Reagan et al. 1972). To address these issues, novel application techniques and formulations need to be explored and implemented.

Behavioral manipulation

Considering the potential adverse effects of pesticides, behavioral management and biological control are regarded as alternative supplementary technologies for controlling sugarcane borer.

Insects respond to a variety of chemical cues, including pheromones employed for mate attraction and allelochemicals used to locate host plants and identify plants under attack by herbivores. The utilization of sex pheromones serves as a valuable method for monitoring moth population levels of borers, providing essential information for timing insecticide applications and diminishing the fertility of wild females through mating disruption techniques (Van Rensburg et al. 1985; Narasimhan et al. 2001). The complexity of insect pheromones necessitates careful consideration of the formulation employed, particularly for successful trapping. For instance, the pheromone of *C. infuscatellus* has been identified as Z-II hexadecenol and Z-II Hexadecenal

(Narasimhan et al. 2001). While the sex pheromones of *C. venosatus* consist of a mixture of major components (Z13–18:AC, Z11–16:AC, and Z13–18:OH), only one sex pheromone component (Z11–16:OH) has been identified from *C. infuscatellus* (Fang et al. 2018). Pheromone-trapping techniques have proven successfully in detecting the presence of *C. sacchariphagus* Bojer in sugarcane in Mozambique sugarcane fields (Way et al. 2004). The female sex pheromone of the sugarcane borer, *C. sacchariphagus*, comprises two compounds, (Z)-13-octadecenyl acetate (I) and (Z)-13-octadecen-l-ol (II). Traps baited with combinations of these components successfully captured male *C. sacchariphagus* moths, with the 7:1 ratio performing similar to a virgin female moth (Trials 1980). In field trials, a blend of (Z)-8-tridecenyl acetate, (Z)-9-tetradecenyl acetate and (Z)-10-pentadecenyl acetate in an 8:4:1 ratio proved highly attractive for trapping male *C. auricilius* (Nesbitt et al. 1986). Studies have showed that a combination of (Z)-9-tetradecenol with (Z)-9-tetradecenyl acetate, with the most effective composition being 75:25, as an enticing attractant for male *S. cretica* (Donegani 1977). In Guangxi, China, control experiments utilizing the sex pheromone of *C. infuscatellus* on 5333 ha of sugarcane fields achieved a control effect of 82.48%, with the rate of attacked plants being less than 5% (Zeng 2004). Synthetic pheromone blends for *C. suppressalis*, *C. indicus* and *C. auricilius* have demonstrated satisfactory attractiveness to male moths in the field (Beevor et al. 1990). Three potential pheromone components, hexadecenal (l6Ald), (E)-l1-hexadecenal (E11-l6Ald) and (Z)-l1-hexadecenal (Zl1-16Ald), have been identified from *Scirpophaga nivella* and *Diatraea saccharalis* (Angerilli et al. 1998; Dam et al. 2023). Field tests using traps baited with a 3-component blend revealed it as the most attractive synthetic pheromone combination (Angerilli et al. 1998). The sex pheromone produced by females of *Sesamia nonagrioides* is a blend comprising Z-l1-hexadecenyl acetate (Z-11-16: Ac), Z-11-hexadecenal (Z-11-16: Ald), Z11-hexadecenol (Z-11-16: OH) and dodecyl acetate (12: AC) (Babilis and Mazomenos 1992). Despite the absence of recorded pheromone traps for *Sesamia nonagrioides* in the field, studies have identified. (Z)-13-octadecenyl acetate (I), (Z)-ll-hexadecenyl acetate (II) and (Z)-13-octadecenal (III) in an approximate ratio of 8:1:1.3 as equally attractive to the natural pheromone extracted from the female *E. loftini* moths (Shaver et al. 1988). Likewise, a two-component blend of (9Z, 11E)-hexadeca-9,1-dienal and (11Z)-hexadec-11-enal, in an approximate ratio of 10:1, has demonstrated comparable attractiveness to the natural pheromone extracted from the female *D. saccharalis* pheromone glands (Kalinová et al. 2005). The effectiveness of the *D. saccharalis* pheromone in reducing sugarcane borer damage has also been reported (Hensley 1973).
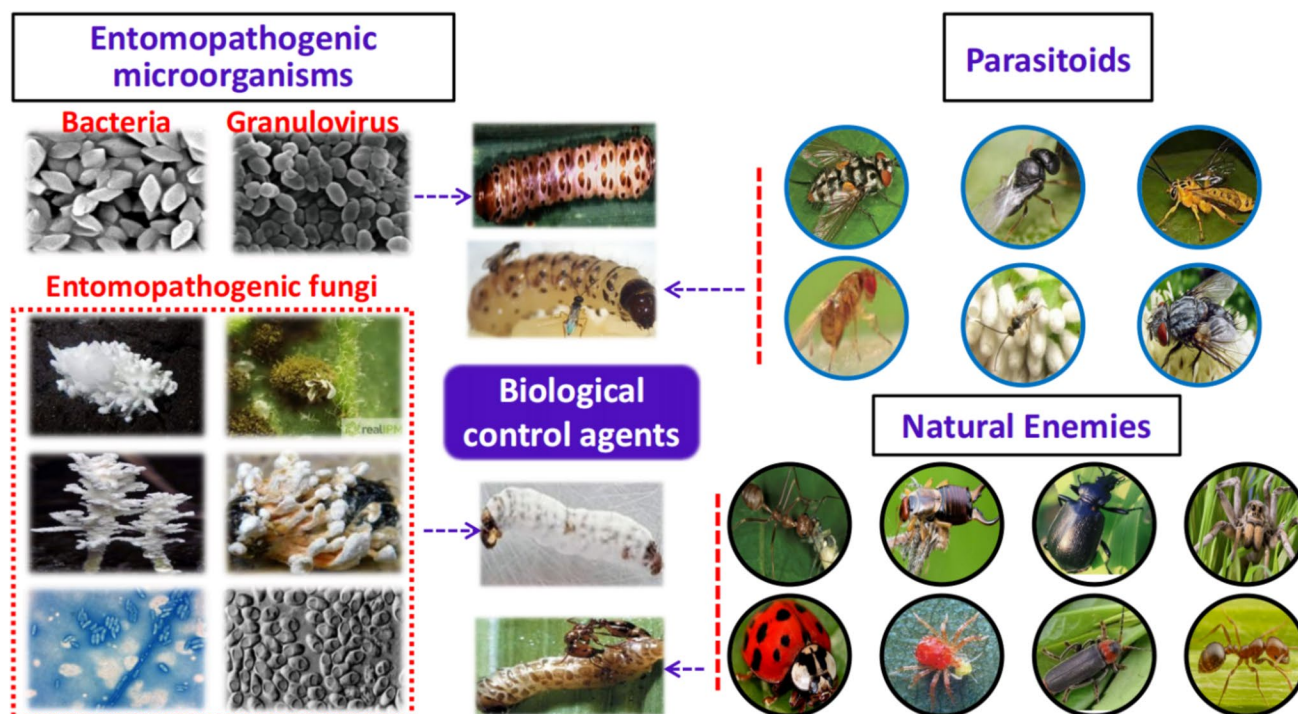
Fig. 5 Biological control of sugarcane bores

Trap crops are plant strategically cultivated to attract insects, serving as a protective measure for target crops against pest attacks. Extensive testing have been conducted on trap crops, with numerous instances of successful commercial application in various crops documented (Hokkanen and T 1991; Shelton and Nault 2004; Jacob et al. 2021). The utilization of trap crops extends to sugarcane borer management. In field conditions, small sugarcane plots surrounded by a row of *Erianthus arundinaceus* (Retz.) Jeswiet have demonstrated reduced stalk borer damage, leading to decreased larval survival and development compared to sugarcane (Hokkanen and T 1991; Shelton and Badenes-Perez 2006; Nibouche and Tibère 2010), and *E. arundinaceus* 28NG7 has been identified as a potential trap crop for controlling *C. sacchariphagus*, and larger commercial field trials have substantiated its efficiency in diminishing *C. sacchariphagus* damage on sugarcane (Nibouche et al. 2012).

Push–pull strategies encompass the manipulation of insect pests and their natural enemies by incorporating stimuli that render the protected target unattractive or unsuitable to the pests (push), while simultaneously exert a pulling force on the pest, guiding it toward an alternative crop or trap (pull), from which the pests are subsequently removed (Cook et al. 2007). Maize (*Zea mays*) is identified as a suitable attractive plant (Schexnayder et al. 2001), while *Melinis minutiflora* and *Cyperus dives* serve as repellent plant for certain borers (Conlong and Rutherford 2009) and are also attractive to parasitoids of these pests, such as *Xanthopimpla stemmator* (Conlong and

Kasl 2000). When intercropped with sugarcane, *M. minutiflora* can reduce *E. saccharina* populations in sugarcane by up to 50% and diminish damage to sugarcane by up to 75% (Barker et al. 2006). Additionally, Bt maize functions as a 'dead-end trap crop' due to the toxic effect of the *cry1Ab* protein on *E. saccharina* larvae, potentially mitigating borer damage on sugarcane (Keeping et al. 2010). Recently, MON 95379 Bt maize as a new tool to manage sugarcane borer (*D. saccharalis*) in South America (Horikoshi et al. 2022).

Regrettably, the utilization of pheromone to diminish stem borers infestation and enhance sugarcane crop production has made little progress thus far (Campion and Nesbitt 1983). The advancement of semiochemical components is frequently impeded by constraints in formulation and delivery technology, mainly stemming from the small and specialized market. Inadequate knowledge and components may result in control breakdowns, jeopardizing the robustness and reliability of pest management approaches. Attaining a comprehensive understanding of the behavioral and chemical ecology of host-pest interactions and the impacts of these strategies on beneficial organisms necessitate substantial research efforts.

Biological control

In Integrated Pest Management (IPM) strategies for sugarcane borers, biocontrol plays a pivotal role. Biocontrol agents mainly encompass entomopathogenic microorganisms, parasitoids and natural enemies (Fig. 5).

Entomopathogenic microorganisms, encompassing bacteria, viruses, fungi, have found commercially applications as biological agents. Notably, among bacteria, Bt (*B. thuringiensis*) stands out as a well-known classical biological agent (Sanahuja et al. 2011). Diverse Bt strains (HD133 *cryAa*, *cry1Ab*, *cry1C*; HD559; GM7 *cry1Aa*, *cry1Ab*, and *cry1B*; GM10 *cry1Aa*, *cry1Ab*, *cry1Ac*, and *cry1C*; GM34 *cry1Aa*, *cry1Ab*, and *cry1Ac*; S76 *cryAa*, *cry1Ab*, *cryAc*, *cry2Aa*, and *cry2Ab*) and pure proteins have demonstrated efficacy in killing *D. saccharalis* (Hernández-Velázquez et al. 2012; Daquila et al. 2021). In South Africa, novel control strategies for *E. saccharina* have been developed using the sugarcane endophyte *Gluconacetobacter diazotrophicus* carrying Bt *cry1Ac* genes (Theo and Gustav 2013). Glasshouse trials revealed that sugarcane treated with *Pseudomonas fluorescens* carrying the Bt gene exhibited increased resistance to *E. saccharina* damage compared to untreated sugarcane (Herrera et al. 1994). In field trials, *B. thuringiensis* Berliner reduced *D. saccharalis* damage by up to 75%, although it has not yet been adopted for commercial production (Legaspi et al. 2000; Showler 2016).

Viruses infecting insects have garnered great attention as biological control agents, owing to their specificity toward insect populations and minimal impact environment impact. An endemic granulovirus (GV) extracted from larvae of the sugarcane borer, *Diatraea saccharalis* (DisaGV), originally discovered in the USA, was introduced to Brazil as an effort to control sugarcane borers (Alves 1986). In India, natural occurrences of two GVs infecting larvae of *C. infuscatellus* (ChinGV) and *C. sacchariphagus* (ChsaGV) were widely distributed in Tamil Nadu (Easwaramoorthy and Jayaraj 1987). Additionally, viruses such as *Anticarsia gemmatalis* MNPV (AgMNPV), *Trichoplusia ni* MNPV (TnMNPV) and AgMNPV-D10 have demonstrated lethal effects on *D. saccharalis* (Hernández-Velázquez et al. 2012). These viruses provide potential insights for practical use in the biological control of sugarcane borer.

The field of entomopathogenic fungi has emerged as a promising avenue for researching the biological control of insect pests in sugarcane plants. The entomopathogenic fungi *Beauveria bassiana* and *Metarhizium anisopliae* have displayed significant potential as biocontrol agents against the sugarcane borer, *D. saccharalis*. Field experiments conducted in Brazil showed that the application of *M. anisopliae* resulted in a commendable mortality rate of above 50% for *D. saccharalis*. Similarly, in India, *M. anisopliae* exhibited efficacy against *C. indicus* (Easwaramoorthy et al. 2001). Eight strains of *M. anisopliae* displayed high virulence against *C. venosatus* in China (Liu et al. 2012). Furthermore, *M. anisopliae* has demonstrated potential as a pathogen for *S. inferens* (Varma and Tandan 1996). In India, *B. bassiana* caused mortality rates of 69% to 76% in *C. infuscatellus* larvae (Sivasankaran et al. 1990). Laboratory studies have also indicated the pathogenicity of *B. bassiana* against *S. inferens and S. grisescens* (Varma and Tandan 1996; Sweet 1994). Other entomopathogenic fungi such as *Hirsutella nodulosa*, *Isaria tenuipes*, and *I. farinosa,* Cordyceps species have been studied on *D. saccharalis, S. inferens* and *C. indicus, E. saccharina* (Varma and Tandan 1996; Assefa et al. 2010; Hernández-Velázquez et al. 2012). Moreover, *Fusarium oxysporum* has exhibited pathogenicity against *S. inferens* (Varma and Tandan 1996). Additionally, *Nosema* sp., a microsporidium causing 'white larvae' disease, has impeded large-scale production of borers on sugarcane (Inglis et al. 2015).

Table 1 Parasitoids on sugarcane borers

Parasitoid	Borer species	Borer life stage	Reference
Billaea claripalpis	*Diatraea* spp.	Larvae	Vargas et al. (2015)
Cotesia flavipes	*Diatraea* spp.	Egg and larvae	Fuchs et al. (1979; Parra et al. (2014); Molter et al. (2023)
Goniozus natalensis	*Eldana saccharina*	Larvae	Hearne et al. (1994)
Lixophaga diatraeae	*Diatraea saccharalis*	Larvae	Posnock (2016)
Lydella minense	*Diatraea* spp.	Larvae	Vargas et al. (2015)
Sturmiopsis inferens	*Chilo infuscatellus, C. auricilius, Acigona steniellus, Sesamia inferens*	Larvae	David et al. (1988), Srikanth et al. (2009)
Telenomus busseolaes	*S. Intacta, C. sacchariphagus*	Egg	Nagarkatti and Nair (1973), Jamshidnia et al. (2010), Qin et al. (2018)
Trichogramma galloi	*Diatraea* spp.	Egg and larvae	Goebel et al. (2014), Parra et al. (2014), Molter et al. (2023)
Xanthopimpla stemmator	*E. saccharina, C. sacchariphagus*	Pupa	Conlong (1994), Conlong and Goebel (2002)

Biocontrol programs have also utilized parasitoids on egg, larva and pupa, to manage sugarcane borers (Table 1). Sixteen known species of parasitoids target the larva-pupa stage of the sugarcane borer (Chen 1998). Insect parasitoids such as *Trichogramma* spp. and *Cotesias* spp. have demonstrated effectiveness in controlling the egg and larval stages of moth borers (Goebel et al. 2014; Roldán et al. 2020; Molter et al. 2023). For example, in Brazil, releases of *Trichogramma galloi* Zucchi and *Cotesia flavipes* have been employed to handle *Diatraea* spp. infestations, resulting in a substantial 60% reduction in pest populations (Parra et al. 2014). *C. flavipes* is also a pivotal agent in managing *D. saccharalis* in South Texas (Fuchs et al. 1979; Parra et al. 2014). *Lixophaga diatraeae* has demonstrated effectiveness in controlling *D. saccharalis* in Louisiana, with a noteworthy 75% parasitization rate recorded in the 1954 season (Posnock 2016). In Colombia, the tachinid flies *Lydella minense* or *Billaea claripalpis* are released when previous crop damage exceeds 2.5–5% (Vargas et al. 2015). *Sturmiopsis inferens*, a tachinid fly, serves as a crucial larval parasitoid of shoot borer (*C. infuscatellus*), stalk borer (*C. auricilius*), Gurdaspur borer (*Acigona steniellus*) and pink borer (*S. inferens*) (David et al. 1988). Releases of *S. inferens* against *C. infuscatellus* in India resulted in parasitism rates of 23.3% to 21.0% (Srikanth et al. 2009). *T. busseolae*, an egg parasitoid wasp, has demonstrated high parasitism rates of approximately 50% on the eggs of sugarcane borers, *S. intacta* and *C. sacchariphagus* (Nagarkatti and Nair 1973; Jamshidnia et al. 2010; Qin et al. 2018). *Goniozus natalensis* shows promise as a parasitoid for biologically controlling *E. saccharina* infestations in sugarcane, resulting in a 60% reduction in crop damage (Hearne et al. 1994). The pupa parasitoid *Xanthopimpla stemmator* Thunberg has been widely reared and released against *E. saccharina* in South African (Conlong 1994). In Açucareira de Moçambique, releases of *X. stemmator* led to reductions in *C. sacchariphagus* populations ranging from 31.3 to 90% across different trial sites (Conlong and Goebel 2002) (Table 1).

Biological control through predation by natural enemies plays a significant role in managing sugarcane borers (Meagher et al. 1998). Predators such as ants, earwigs, ground beetles, spiders, wireworms, lady beetles, mites and soldier beetles are considered crucial in controlling sugarcane borers in Louisiana (Negm and Hensley 1969). The red imported fire ant (*Solenopsis invicta*) emerges as a dominant natural enemy of *D. saccharalis* in Louisiana sugarcane fields (Beuzelin et al. 2010). *Pheidole* spp. ants also serve as abundant predators on sugarcane borers (Cherry et al. 2015). Spiders (*Araneae*) play a significant role as egg predators of *D. saccharalis* and hold second importance within the natural enemy complex (Ali and Reagan 1986). Among the spiders, *Lycosa poonaensis* and *Palystes* sp. stand out as the most voracious species, consuming 1.6 borer larvae and 2.2 borer adults per day respectively, indicating their effectiveness in controlling sugarcane borer (Technol 2001a). Ground beetles (Coleoptera: Carabidae), tiger beetles (Coleoptera: Carabidae: Cicindelinae), rove beetles (Coleoptera: Staphylinidae), click beetles (Coleoptera: Elateridae), and earwigs (*Dermaptera*) are also acknowledged as important natural enemies on *D. saccharalis* in Louisiana (Negm and Hensley 1967, 1969).

Fluctuations in biological control can arise due to geographical and seasonal variations, along with the presence of hyperparasitoids, which may undermine the effectiveness of this strategy (Gitahy et al. 2007). Moreover, the environmental instability of entomopathogenic microorganisms hinders their augmentative use in controlling sugarcane borers. Therefore, further in-depth research is still required in this field to achieve widespread application.

Host plant resistance

In the realm of diseases and pests' control, the paramount approach is plant resistance, prove to be both highly and economically prudent. The selection of resistant sugarcane varieties is commonly achieved through the application of conventional breeding techniques. Resistance to borers in sugarcane manifests in leaves or stems, impeding or retarding larval ingress into the stalks (Kvedaras et al. 2007). Traits linked to leave, such as narrow leaves, leaf shedding, erect leaves, long leaf spindles, low leaf senescence, and those related to stems, including high fiber content, light stalk color, heavy wax coating, thin stalks, high vigor, high juice content, and rind hardness and epicuticular wax composition, have served as criteria for ranking entries based on their resistance to borers (Long and Hensley 1972; Ngwuta 2015; Reagan and Mulcahy 2019; de Mello et al. 2020; Wartha et al. 2022; Penn and Read 2023). The selection of numerous resistant sugarcane cultivars has been facilitated by these pivotal resistance traits. Exemplary varieties, including N21, N24, L 99-226, L 01-299, HoCP 04-838, L 01-283, Ho 12-615, SP803280, SP813250, RB867515 and SP891115, have exhibited resistance traits in either the stem or leaves, leading to a diminished rate of borer larvae and substantial height gain in stalks (Kvedaras et al. 2009; Tomaz et al. 2017; Reagan and Mulcahy 2019). In India, varieties such as Co 243, 281, 285, 312, 356, 421, 449, 453, 527, 617, 650, 775, 853, 975, 1007, 1048, 1049, 1157, 6239, 6402, 6403, 6507, 6508, 6510, 6610, Cos 673, 729, BO17, 54, 70 and 99 have demonstrated a low incidence of infestation by *C. infuscatellus* (David et al. 1986). Among these, Co 1007, 1236, 7302, 7303, S-5/75, S-38/76, E 92 and E 168 (David et al. 1986), as well as Co 356 and 513 are acknowledged for their resistance to *Chilo auricilius* in India. Additionally, Co 243, 453 and 617 display a lower

susceptible to *Chilo tumidicostalis* (Negm and Hensley 1969). Furthermore, the determination of the percentage of bored internodes and the relative survival of larval within the stalk have been employed to select sugarcane varieties exhibiting resistance to the Mexican rice borer, *Eoreuma loftini* (Wilson et al. 2015b; Salgado et al. 2022). The evaluation of sugarcane resistance to the African sugarcane borer, *E. saccharina*, involves the measurement of the length of bored stalks, the count of bored internodes, and the quantification of surviving larvae and pupae in terms of both number and weight (Keeping 2006).

The incorporation of introgressions from wild relatives species plays a pivotal role in enhancing resistance and tolerance to various biotic and abiotic stresses, as well as obtaining desirable agronomic traits, including increased yields (Prescott-Allen 1986; Singh et al. 2020; Meena et al. 2020). Nevertheless, the effective selection of elite varieties with resistance to borers through introgression poses challenges, given the highly time-consuming and labor-intensive nature of the selection process. The selection of desired clones necessitates three stages on a large population before they can proceed to regional evaluation trials (Meena et al. 2020). To confer resistance to Lepidopteran stalk borers, transgenic sugarcane lines expressing genes like the Cry protein, proteinase inhibitor, or lectin have been successfully developed (Srikanth et al. 2011). This approach holds promise in effectively suppressing borers, offering substantial benefits to sugarcane production.

Status of transgenic sugarcane

Genes used for GM sugarcane

Significant endeavors have been devoted to the development of genetically modified sugarcane harboring desired traits. For example, transgenic sugarcane plants have been employed for the production of sorbitol, gentiobiose, and gentiobiitol (Chong et al. 2010a,b), cellobiohydrolases (*CBH I* and *CBH II*) (Harrison et al. 2011), bacterial endoglucanase (Harrison et al. 2014), 2G ethanol (Bewg et al. 2016), and other valuable alternative products (Petrasovits et al. 2012; Barros et al. 2013; Zale 2016). Furthermore, numerous genetically modified sugarcanes exhibiting resistance to both biotic and abiotic stresses have been successfully developed. Diverse genes have been integrated into sugarcane genomes, encompassing a bacterial toxin degradation gene (Zhang et al. 1999), virus resistance genes (Ingelbrecht et al. 1999; Butterfield et al. 2002; McQualter et al. 2004; Gilbert et al. 2005, 2009; Zhu et al. 2011; Guo et al. 2015), bovine pancreatic trypsin inhibitor gene (Christy et al. 2009), several insect resistance genes (Arencibia et al. 1997; Enríquez and G. 2000; Falco and Silva-Filho 2003;

Weng et al. 2006; Kalunke et al. 2009; Arvinth et al. 2010; Weng et al. 2011; de Oliveira et al. 2022), herbicide resistance genes (Enríquez-Obregón et al. 1998; Christell et al. 2013), and tolerance to drought and salinity genes (Molinari et al. 2010; Reis et al. 2014; Kumar et al. 2014) (Table 2).

The prosperous commercialization of transgenic crops hinges on the stable and uniform expression of introduced traits across successive generations, coupled with their agronomic performance comparable to elite commercial cultivars (Anderson and Birch 2012). Prominent transgenic crops, including soybean (Padgette et al. 1995), rice (Duan et al. 1996) and corn (Fearing et al. 1997; Chen et al. 2008; Paz et al. 2010), have exhibited these characteristics. Nonetheless, transgenic sugarcane populations manifest considerable genetic variability (Joyce et al. 1998; Gilbert et al. 2005; Vickers et al. 2005a), and somaclonal variation may occur to varying degrees in transgenic sugarcane due to the prolonged period in tissue culture during the transformation process. Hence, a comprehensive field assessment of transgenic events is imperative to identify elite and commercially valuable events. However, there have been limited field assessments of transgenic sugarcanes, as evidenced by studies conducted by several scientists (Arencibia et al. 1999; Leibbrandt and Snyman 2003; Lakshmanan et al. 2005; Vickers et al. 2005a; Gilbert et al. 2009; Weng et al. 2011; Basnayake et al. 2012).

Gallo-Meagher and Irvine presented the initial documentation of stable expression of a transgenic trait-herbicide resistance in successive generations of sugarcane (Gallo-Meagher and Irvine 1996). Subsequent to that milestone, stable transgene expression has been observed in relation to virus and insect resistance (Joyce et al. 1998; Gilbert et al. 2009; Weng et al. 2011), herbicide resistance (Weng et al. 2011), polyphenol oxidase activity (Vickers et al. 2005b), sorbitol (Chong et al. 2010b) and isomaltulose accumulation (Basnayake et al. 2012). Contradictory results have emerged from certain analyses of the agronomic performance of transgenic sugarcane. Arencibia et al. (1999) demonstrated that majority of transgenic events resistant to stalk borers exhibited agronomic traits akin to those of the untransformed parent clone. In field trials spanning three years, Leibbrandt and Snyman (2003) and Gilbert et al. (2005) similarly concluded that stable transgene expression and agronomic performance equivalent to that of parent clones were attained. Nonetheless, Vickers et al. (2005a) observed that the majority of transgenic events exhibited substantial yield reduction in contrast to the parent clone, with no impact on sugar content and purity. In summary, numerous beneficial genes have been successfully integrated into sugarcane, yielding the desired traits. No significant technical bottlenecks impede the generation of transgenic sugarcane. Nevertheless, more key tools are necessary to make transgenic events more efficient and available for commercial use.

Table 2 List of transgenic sugarcane engineered for desired traits

Type of explant	Promoter	Method of transformation	Exogenous gene	Target trait	Variety	References
Embryogenic callus	Ubi-1 promoter	Microprojectile bombardment	s6pdh	Hexose-phosphate sink	Q117	Chong et al. (2010b)
Embryogenic callus	–	Microprojectile bombardment	Sorbitol-6-phosphate dehydrogenase gene	Synthesize sorbitol	Q117	Chong et al. (2010a)
Callus clumps	Zm-Ubi1	Microprojectile bombardment	nptII	Accumulation of recombinant cellobiohydrolase and endoglucanase	Q117	Harrison et al. (2011)
embryogenic callus	maize phosphoenolpyruvate carboxylase promoter (Zm-PepC) w	Microprojectile bombardment	Cellulase enzyme	Cellulase accumulation	Q117	Harrison et al. (2014)
callus	ZmUbi	Microprojectile bombardment	Caffeoyl-CoA O-methyltransferase (CCoAOMT), ferulate 5-hydroxylase (F5H) and caffeic acid O-methyltransferase (COMT)	Lignin content and/or composition	KQ228	Bewg et al. (2016)
callus	Maize Ubi promoter, the maize and rice polyubiquitin promoters, the maize chlorophyll A/B-binding protein promoter and a Cavendish banana streak badnavirus promoter	Microprojectile bombardment	phaA, phaB and phaC	Polyhydroxybutyrate production	Q117	Petrasovits et al. (2012)
callus	35S promoter	Microprojectile bombardment	WRINKLED1 (WRI1), diacylglycerol acyltransferase1-2 (DGAT1-2) and oleosin1 (OLE1), ADP-glucose pyrophosphorylase (AGPase), peroxisomal ABC transporter1 (PXA1)	Triacylglycerols content	CP-88–1762	Zale et al. (2016)
embryogenic callus	Ubi promoter from the maize ubi-1 gene	Microprojectile bombardment	Albicidin detoxifying gene	Confers resistance against a pathogenic bacterium	Q63 and Q87	Zhang et al. (1999)
Embryogenic callus	Maize ubiquitin promoter	Microprojectile bombardment	Putative SCYLV resistance gene	resistance to sugarcane yellow leaf virus	CP 92–1666	Gilbert et al. (2009)
Embryogenic callus	Maize ubiquitin promoter	microprojectile bombardment	coat protein (CP) gene	Sorghum mosaic potyvirus resistance	CP65-357 and CP72-1210	Ingelbrecht et al. (1999)
Embryogenic callus	The maize polyubiquitin (Ubi) promoter	Microprojectile bombardment	Fiji disease virus (FDV) S9 ORF 1	Resistance to Fiji disease	Q124	McQualter et al. (2004)

Table 2 (continued)

Type of explant	Promoter	Method of transformation	Exogenous gene	Target trait	Variety	References
Leaf explants	35S promoter	Agrobacterium-mediated transformation	coat protein (CP) genes	Resistant to Sorghum mosaic virus	ROC22	Guo et al. (2015)
Cell cultures	Maize ubiquitin promoter (ubi)	Microprojectile bombardment	Untranslatable coat protein gene	Sugarcane yellow leaf virus resistance	H62-4671	Zhu et al. (2011)
–	UBI	–	Virus and herbicide resistance gene	Herbicide resistance and Sorghum mosaic virus resistance	CP72-1210	Butterfield et al. (2002)
Embryogenic cultures	Ubi	Microprojectile bombardment	SCMV entage, coat protein gene	Resistance to Sugarcane mosaic virus Strain E	CP 84–1198 and CP 80–1827	Gilbert et al. (2005)
Embryogenic calli	Maize ubiquitin promoter	Microprojectile bombardment	Aprotinin gene	Resistant to top borer Scirpophaga excerptalis Walker	CoC 92061 and Co 86,032	Christy et al. (2009)
meristematic explants	Cauliower Mosaic virus (CaMV) 35S promoter	Agrobacterium-mediated transformation	bar gene	Herbicide-resistant	Ja 60–5,	Enríquez-Obregón et al. (1998)
Embryogenic callus explants	ubiquitin promoter region	microprojectile bombardment	acetolactate synthase	Herbicide-resistant sugarcane	NCo310	Christell et al. (2013)
Embryogenic calli	Minimum rice actin 1 gene promoter	Microprojectile bombardment	P5CS gene	Stress-inducible production of proline	RB855156	Molinari et al. (2010)
Embryogenic calli	stress-inducible promoter Rab17	microprojectile bombardment	AtDREB2A CA	drought tolerance	RB855156	Reis et al. (2014)
Apical meristematic buds	35SCaMV promoter	Agrobacterium-mediated transformation	Arabidopsis Vacuolar Pyrophosphatase (AVP1) Gene	Drought and Salinity Stress Tolerance	CP77-400	Kumar et al. (2014)
embryogenic calli	maize ubiquitin-l(Ubi-1) promoter	microprojectile bombardment	bar gene	Herbicide resistant	NCo 310	Gallo-Meagher and Irvine (1996)

Sugarcane transformation methods

The production of transgenic sugarcane depends on reliable genetic transformation techniques. Presently, the two predominant methods for sugarcane transformation are biolistic and agrobacterium-based approaches (Manickavasagam et al. 2004; Zhangsun et al. 2007; Joyce et al. 2014; Mayavan et al. 2015). These methods involve the use of embryogenic callus induced from immature top stalks (Taparia et al. 2012a; Fouad et al. 2015). The regeneration of transformed plants has been accomplished through diverse approaches, including direct and indirect organogenesis or somatic embryogenesis (Arencibia et al. 1998), (Manickavasagam et al. 2004; Attia et al. 2005; Lakshmanan 2006), (Eldessoky et al. 2011; Taparia et al. 2012b). Various methods have demonstrated differing efficiencies in generating regenerative embryogenic calli. The application of a biolistic-based transformation approach, coupled with a bioreactor-based micro-propagation system, has proven successful in transforming twelve elite cane genotypes, achieving transformation efficiencies of up to 39% (Ramasamy et al. 2018). Nevertheless, these methods may be time-consuming and labor-intensive. In addressing these challenges, researchers have investigated tissue culture-free plant transformation methods mediated by *A. tumefaciens*, involving sugarcane axillary buds, stem cuttings, or seeds (Manickavasagam et al. 2004; Mayavan et al. 2013, 2015).

The promoter stands out as the most important element influencing the expression of transformed genes. To mitigate the risk of transgene silencing in multigene transformations and attain superimposed traits in transgenic crops, employing promoters with diverse expression patterns is highly desirable (Peremarti et al. 2010; Zeevi et al. 2012). Among several promoters, ubiquitin promoters have surfaced as a promising option for the constitutive expression of transgenes in sugarcane (Lakshmanan et al. 2005). These promoters have demonstrated a significant enhancement in transgene expression levels compared to other promoters, including the *CaMV 35S* promoter, rice *actin Act1* promoter, and synthetic *Emu* promoter (Mcelroy et al. 1991; Last et al. 1991). Ubiquitin promoters encompass those derived from Cauliflower mosaic virus (*CaMV*), Rice tungro bacilliform virus (RTBV), Commelina yellow mottle virus, Taro bacilliform virus, Banana streak virus (BSV), and Sugarcane bacilliform virus (SCBV) (Kay et al. 1987; Medberry and Olszewski 1992; Bhattacharyya-Pakrasi et al. 1993; Chen et al. 1996; Peer et al. 2001; Tzafrir et al. 1998; Schenk et al. 1999). The Ubi-1 promoter has proven effective in producing stable transgenic sugarcane lines (Falco and Silva-Filho 2003). In a recent development, transgenic sugarcane plants expressing two genes encoding proteinase inhibitors under the control of the maize ubiquitin promoter (*pUbi-1*) were created, leading to a substantial retardation of *Diatraea saccharalis* feeding on the transgenic sugarcane leaf tissues (Falco and Silva-Filho 2003). Similar to *Ubi-1*, sugarcane *ubi4* has demonstrated heat shock inducibility in stable transformed sugarcane callus lines, whereas sugarcane *ubi9* did not exhibit such inducibility in transgenic sugarcane plants (Wei et al. 2003). In contrast, another promoter, *SCBV21*, exhibited 1.8- and 2.4-fold higher transient expression of *EYFP* (Enhanced Yellow Fluorescent Protein) compared to the standard maize ubiquitin 1 (*Ubi1*) and Cauliflower mosaic virus 35S promoters, respectively, in sugarcane young leaf segments (Gao et al. 2017). Additional functional promoters in sugarcane encompass sugarcane dirigent and o-methyltransferase from putative defense and fiber biosynthesis-related genes, maize phosphoenolpyruvate carboxylase, and sugarcane loading stem gene (Damaj et al. 2010; Harrison et al. 2011; Moyle and Birch 2013).

Another critical factor influencing exogenous gene expression and performance is the GC content and codon usage pattern of target gene (Estruch et al. 1997). Earlier studies have shown that GC-rich regions are more transcriptionally active in plants and animals, whereas AT-rich regions can hinder transcription (Scott et al. 1998; Herbert and Rich 1999; Vinogradov 2003). Hence, designing synthetic copies of exogenous genes with elevated GC contents has the potential to enhance translational efficiency (Rocher et al. 1998 Rouwendal et al. 1997; Liu 2009; Jackson et al. 2013; Mudge et al. 2013). In the development of strongly insect-resistant sugarcane, the *cry1Ac* gene underwent modification to create a synthetic version, referred to as *s-cry1Ac*. This involved increasing the GC content of the coding region from the original 37.4% to 47.5% based on the sugarcane codon usage pattern. Consequently, this modification enhances the protein expression level of *s-cry1Ac* in transgenic sugarcane plants by twofold to threefold (Weng et al. 2006). Transgenic sugarcane lines harboring the modified *cry1Ac* gene with an evaluated GC content (54.8%) yielded approximately fivefold higher levels of *cry1Ac* protein (up to 50 ng *cry1Ac* protein per mg soluble proteins) compared to those expressing the partially modified *s-cry1Ac* (GC% = 47.5%) (Weng et al. 2011). These *m-cry1Ac* transgenic sugarcane lines demonstrated enhanced resistance to insect attacks compared to *s-cry1Ac* transgenic sugarcane plants (Weng et al. 2011).

The creation of transgenic plants with stacked multiple genes is typically accomplished through the cross between different transgenic plants (Cao et al. 2002; Datta et al. 2002; Zhao et al. 2003) or by retransformation with multiple genes (Jobling et al. 2002; Carlo et al. 2003; Singla-Pareek et al. 2003; Qi et al. 2004). However, researchers have devised a fast and cost-effective method that entails inserting a single

transferred DNA (T-DNA) containing multiple genes into a plant at the same site of the genome within one transformation cycle (Slater et al. 1999; Bohmert et al. 2000, 2002). Despite its advantages, the T-DNA approach has its limitations, including the size of the T-DNA and potential uneven gene expression among different genes (Jones et al. 1987; Peach and Velten 1991).

Besides, various studies have reported that factors, including the transgene copy number, developmental regulation, and transcriptional or post-transcriptional mechanisms, can influence transgene stability in transgenic sugarcane plants (Wei et al. 2003; Robert et al. 2010; Mudge et al. 2009). Hence, further improvements are necessary to overcome these limitations (Poirier et al. 2000; Goderis et al. 2002; Thomson et al. 2002). Encouragingly, long-term transgene expression consistency and the T-DNA insert stability have been successfully achieved in multiple cycles of field-propagated sugarcane (Caffall et al. 2017). Moreover, transgenic sugarcane parents that exhibit stable inheritance of transgenes can be effectively utilized in breeding programs (Butterfield et al. 2002), indicating a high likelihood of successful commercialization of transgenic sugarcane.

Progress, advantages and limitations of Bt sugarcane

The status of Bt crops

Bacillus thuringiensis (Bt) *Cry* toxins, recognized biological agents employed for insect pests control (Gómez 2007), are synthesized as crystal inclusions, hence acquiring the designation Cry toxins. Presently, a total of 166 *cry* genes have been documented, classifying their respective cry proteins divided into 30 groups and several subgroups (Barboza-Corona 1998).

Genetically modified (GM) plants incorporating Bt genes have undergone swift adoption since their commercial introduction in 1996 (Dively et al. 2016). Various crops, such as maize, cotton, soybean, rice, potato, brinjal, tomato and sugarcane, have been genetically modified with *Bt* genes (Xiao and Wu 2019). The global cultivation area of Bt crops has witnessed a substantial surge, escalating from 1.1 million hectares in 1996 to approximately 178 million hectares annually across 28 countries at present (Venugopal and Dively 2017). Bt corn, cotton and soybean collectively constitute over 99% of this total area (Venugopal and Dively 2017), with a cumulative surpassing of 830 million hectares planted with Bt crops globally up to the present moment.

Cry toxins exhibit toxic activity against various insect species (Miyasono et al. 1994; Bradley et al. 1995; Schnepf et al. 1998). Their mode of action involves solubilization and proteolytic processing in the insect midgut. The proteins bind to receptor molecules located in the apical cells of the brush border membrane, leading to their insertion and the formation of a pore (Hfte and Whiteley 1989; Bravo 1997; Schnepf et al. 1998). The specificity of these crystals to insects relies on the proteins' affinity to binding receptor molecules and the environmental conditions within the insect midgut (Van et al. 1990; Bravo et al. 1992) (Fig. 6). *Cry* toxins have exhibited substantial insecticidal
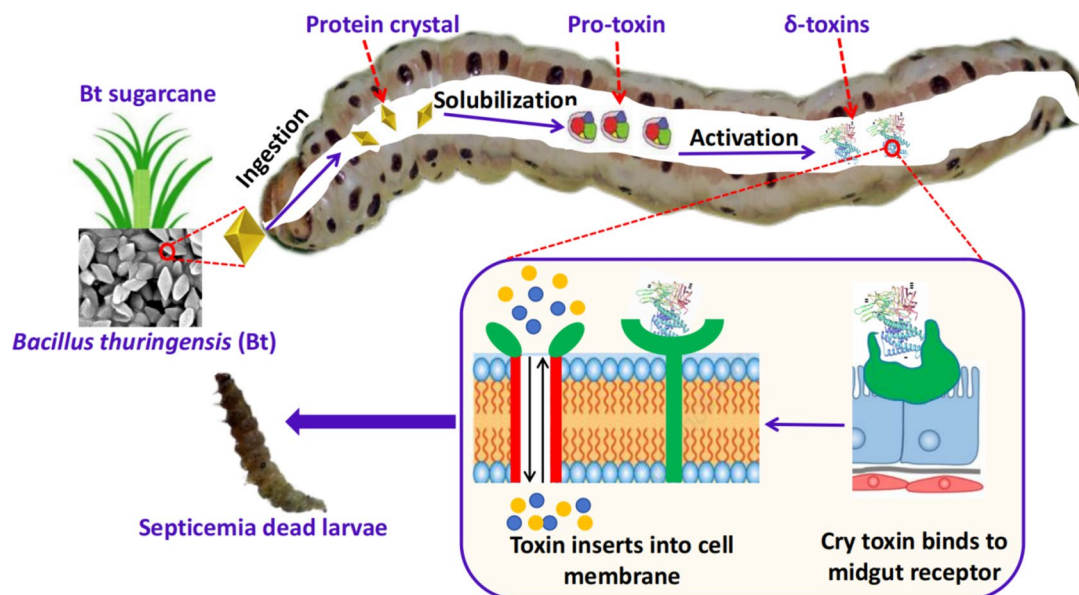

Fig. 6 The model of Bt mechanism. The Bt toxin dissolves in the high pH insect gut and become active. The toxins then bind to the gut cells of the insect, punching holes in the lining. The Bt spores spill out of the gut and ultimately leading to the death of the insect

activity against Lepidopterans, Coleopterans and mosquitoes (Gómez et al. 2007).

In addition to *Cry* proteins, different types of Bt crops have been engineered to produce vegetative insecticidal proteins (*Vip*) (Mahon et al. 2012; Bernardi 2015; Chakroun et al. 2016; Sharon et al. 2016; Wei et al. 2017). The increasing adoption of Bt crops reflects growers' high satisfaction with their performance. Bt crops have demonstrated outstanding effectiveness in controlling Coleopteran, Lepidopteran and some Hemipteran insect pests (Carrière et al. 2003; Wu et al. 2008; Hutchison et al. 2010; Downes et al. 2017; Xiao and Wu 2019; Girón-Calva et al. 2020). By diminishing reliance on conventional chemical pesticides, Bt crops provide an alternative and sustainable strategy for pest management (Betz et al. 2000).

Progress of Bt sugarcane

Due to the large and complex genome, selecting sugarcane cultivars with desired agronomic traits by conventional breeding program is a time- and labor-consuming procedure (Cheavegatti-Gianotto et al. 2011; Souza et al. 2011). Consequently, direct gene transformation is being employed as a promising approach to introduce important traits into sugarcane (Ye et al. 2016). The enhancement of insect resistance in transgenic sugarcane has been achieved through the transformation of *cry1A(b)* (Arencibia et al. 1997, 1999; Arvinth et al. 2010; Zhi et al. 2017), *GNA* (Sétamou et al. 2002; Zhangsun et al. 2007), *cry1Aa3* (Kalunke et al. 2009), *cry1Ac* (Weng et al. 2006, 2011; Gao et al. 2016a, b; Dessoky et al. 2021; Salgado et al. 2022), *cry2A* (Gao et al. 2018), *Vip3A* (Riaz et al. 2020), and *proteinase inhibitor* (Nutt et al. 2001; Falco and Silva-Filho 2003) (Iqbal et al. 2021)(Table 3). Field trials of insect-resistant transgenic sugarcane have revealed that most lines exhibit agronomic traits similar or less favorable than those of non-transgenic varieties (Arencibia et al. 1999; Zhi et al. 2017). Notably, concerning borer resistance, the creation of sugarcane cultivars ROC16 and YT79-177 by introducing of a modified *cry1Ac* gene through particle bombardment resulted in about 62% of transgenic plants being resistant to borer in both greenhouse and field trials (Weng et al. 2011). Furthermore, the Bt insecticidal gene *Cry1Ab* and the glyphosate-tolerant gene *EPSPS* were inserted into a single transferred DNA fragment along with the selection marker gene PMI and introduced into sugarcane using agrobacterium-mediated transformation, leading to the development of robust borer-resistant lines (Wang et al. 2017). Additionally, a gene encoding the *Bacillus thuringiensis Cry1a(b)* protein has been found to confer sugarcane resistance to *Diatraea saccharalis* under both laboratory and field conditions (Technol 2001b). Therefore, the insertion of insect-resistant genes into

sugarcane holds great promise as a strategy for controlling sugarcane borers.

It is worth noting that having low copy-number exogenous genes are considered to be beneficial for plant improvement (Dai et al. 2001). For example, a single copy of *Cry1Ab* or *Cry1Ac* in sugarcane can provide effective protection against borers (Arvinth et al. 2010; Weng et al. 2011). Additionally, transgenic sugarcane lines with a medium copy number of the *cry1Ac* gene have also shown significantly higher resistance to sugarcane borers while maintaining a similar yield to control lines (Gao et al. 2016a, b). However, there was a statistically significant negative correlation between the copy number of the *cry2A* gene and the percentage of borer-infested plants (Gao et al. 2018). The gene balance hypothesis suggests that a correlation between transgene copy number and gene expression levels, but in reality, the relationship is complex (Dai et al. 2001; Coate et al. 2016). Moreover, the correlation between the *cry1Ac* protein abundance and *cry1Ac* gene copies varied among different transgenic lines from various varieties(Zhou et al. 2018). Therefore, in practical plant improvement, it is necessary to screen a large population of transgenic lines to identify individuals with stable expression patterns that are appropriate for an aimed trait, while avoiding adverse agronomic changes that may arise from chance mutations or quasi-stable epigenetic changes during tissue culture (Graham et al. 2011; Yu et al. 2011).

Commercialized Bt sugarcane

During 2022, the total global area under GM crop cultivation reached approximately 202.2 million hectares, the planting area of GM crops accounted for about 12% of the total arable land area, reflecting an increase of 3.3%. The number of countries approved to cultivate GM crops increased to 29, and 71 countries and regions approved the commercial application of GM products (Li et al. 2023). Transgenic crops with herbicide tolerance (HT) and pest resistance (Bt) have been widely used in recent years. According to the statistics of the United States Department of Agriculture (USDA), in 2022, the share of Bt cotton accounted for about 89%, and Bt corn climbed to 84% of the GM crops. However, the plantation area of transgenic sugarcane is 100,000 hm^2. So far, a total of 7 GM sugarcane events, which confer insect resistance (against Lepidoptera), have been developed for approval (ISAAA 2019, 2022). In Brazil, the foremost sugarcane producer and primary sugar exporter, genetically modified (GM) sugarcane varieties resistant to the sugarcane borer (*Diatraea saccharalis*), have obtained approval and been introduced for commercial cultivation. Brazil stands as the sole and pioneering country to introduce Bt sugarcane to the market. These varieties CTC 20 Bt, CTC 9001 Bt and CTC 93309–4 Bt express not only the *cry1Ab* protein, but

Table 3 Transgenic sugarcane resistant to borers

Type of explant	Promoter	Method of transformation	Exogenous gene	Target trait	Variety	References
Embryogenic Calli	Ubiquitin promoter	Agrobacterium-mediated transformation/particle bombardment and regeneration	Cry1Ab	Shoot borer (Chilo infuscatellus) resistance	Co 86,032 and CoJ 64	Arvinth et al. (2010)
Embryogenic calli	CaMV 35S promoter	Electroporating	cryIA(b)	Borer resistance (Diatraea saccharalis)	Ja60-5	Arencibia et al. (1999)
Embryogenic calli	Ubi-1 promoter	*Agrobacterium-*mediated transformation	*Cry1Ab,* glyphosate-tolerant gene *EPSPS*	Insect Resistance and Herbicide Tolerance	ROC22	Zhi et al. (2017)
Embryogenic calli	CaMV35S promoter	Agrobacterium-mediated transformation	Cry 1Aa3	Borer resistance (Chilo sacchariphagus and Scripophaga excerptalis)	CoC671	Kalunke et al. (2009)
Embryogenic calli	Maize ubiquitin promoter	Microprojectile bombardment	S-Cry1Ac	Borer resistance	YT79-177 and ROC16	Weng et al. (2006)
Embryogenic calli	pUbimBt	Microprojectile bombardment	m-cry1Ac	Borer resistance	ROC16 and YT79-177	Weng et al. (2011)
Embryogenic calli	*35 s* promoter	Microprojectile bombardment	*cry1Ac*	Borer resistance -*Diatraea saccharalis*	FN15	Gao et al. (2016a, b)
Embryogenic calli	Maize ubiquitin promoter (*Ubi*-1)	Microprojectile bombardment	*cry1Ac*	Borer resistance- *Diatraea saccharalis*	–	Falco and Silva-Filho (2003)
Embryogenic calli	*cry1Ac p*	Agrobacterium tumefaciens transformation	*cry1Ac*	Borer resistance- Spodoptera litura	Salgado et al. (2022)	Salgado et al. (2022)
Young leaf explants	*35S promoter*	Agrobacterium transformation	cry1Ac	Mortality percentage of Sesamia cretica	GT54-C9	Dessoky et al. (2021)
Intact cells	CaMV 35S promoter	Microprojectile bombardment	cry1A(b)	Borer resistance	Ja 60–5	Arencibia et al. (1997)
–	–	–	–	Herbicide-Resistant	NCo310	Leibbrandt and Snyman (2003)
Embryogenic calli	Maize ubiquitin-1(*Ubi*-1) promoter	Microprojectile bombardment	*bar* gene	Herbicide resistant	NCo 310	Gallo-Meagher and Irvine (1996)
Embryogeniccalli		Agrobacterium-mediated transformation	CryIAC	Resistance against the Sesamia cretica	GT54–9(C9)	Ismail and Roba (2013)
Embryogenic calli	ST-LS1 promote	Particle bombardment	cry2A	Borer Resistance	ROC22	Gao et al. (2018)
Embryogenic calli	Ubi-1 promoter	Agrobacterium-mediated transformation	Cry1Ab, glyphosate-tolerant gene EPSPS,	Insect Resistance and Herbicide Tolerance	ROC22	Gao et al. (2018)
Embryonic calli	*35 s* promoter	Particle bombardment	cry1Ac	Resistance against sugarcane borer	FN15	Gao et al. (2016a, b)
Embryogenic calli	pGcry2A0229	Particle bombardment	cry2A	Resistance against sugarcane borer	ROC22	Gao et al. (2018)
Young leaf roll region with the apical meristem	Polyubiquitin	Particle bombardment	Vip3A	Resistance against sugarcane borer	CPF-246	Riaz et al. (2020)

also the neomycin phosphotransferase type II (*NptII*) protein used as a selection marker during the transformation process (Kennedy et al. 2018). Regarding health issue, the major concern for people is regarding GM crops. Investigations into the presence of foreign DNA and protein in sugar produced from these sanctioned GM sugarcane varieties have demonstrated the absence of heterologous DNA or Bt protein in the clarified juice, ethanol or raw sugar. This suggests their elimination or degradation during the processing of this GM variety (Cheavegatti-Gianotto et al. 2018).

Advantages of Bt crops

Biotechnology provides potent tools capable of substantially enhancing agricultural productivity and efficiency, concurrently tackling diverse challenges. Utilizing biotechnology enables the reduction of excessive insecticide use, leading to sustainable economic and ecological benefits (James 2010). For instance, Bt cotton has exhibited notable outcomes, including a 50% decrease in insecticide usage and a 31% surge in crop yields in China and India. This has resulted in a significant boost in cotton income, totaling US$11.9 billion (James 2011). In addition to direct economic benefits, reports indicate indirect advantages such as heightened employment, household income and diminished poverty (Subramanian and Qaim 2009; Raybould and Quemada 2010; Shankar and Thirtle 2010; Carpenter 2010). Substantial research suggests that the adoption of Bt crops has substantially decreased insecticide application in numerous countries (Carpenter 2010). On a global scale, genetically modified (GM) crops have augmented yields by 22%, diminished pesticide usage by 37%, and mitigated environmental impact, including an 18% reduction in insecticide and herbicide use (Raman 2017).

Cry proteins, expressed by Bt crops, have been shown to possess high specificity toward target pests, thereby presenting minimal risk to non-target species due to their narrow spectrum of activity (Romeis et al. 2006; Lareesa et al. 2008; Li et al. 2014). Reports confirm that the widespread adoption of Bt cotton has indeed yielded a positive impact on pest populations (Wu et al. 2008; Qiao et al. 2016; Qiao et al. 2017). Thus, Bt crops play a role in enhancing the overall sustainability and health of agroecosystems by fostering a more balanced and resilient ecosystem (Marvier et al. 2007); Naranjo et al. 2008; Naranjo 2011; Lu et al. 2012; Li et al. 2016a, b; Wei et al. 2018). As a result, this fosters more effective pest control and reduces reliance on broad-spectrum insecticides.

Bt crops contribute to food quality by mitigating pest damage, preventing not only yield losses but also preserving quality (Miller 2008), (Li et al. 2016a, b). Pesticide residues are a significant concern regarding food quality, given

their potential adverse effects on health through the direct consumption of foods containing toxic residues (Anilkumar et al. 2008; Usha et al. 2011; Nag and Raikwar 2011). Bt crops can decrease the dependence on chemical insecticides, thereby reducing pesticide residues in crops. This contributes to heightened food safety and quality by minimizing the potential health risks associated with pesticide exposure (Abedullah et al. 2014).

Due to its unique characteristics, such as vegetative propagation, sugarcane minimizes the likelihood of gene flow and potential environmental impacts associated with transgenic varieties. Additionally, sugar derived from sugarcane, undergoing high-temperature and crystallization processes, is considered a low-risk product in terms of both food and environmental safety (Qaiser et al. 2011). Several biosafety reports have been conducted on transgenic sugarcane lines to assess their safety and potential environmental effects (Gilbert et al. 2005). Specifically, studies on *Cry1Ac* transgenic sugarcane have demonstrated that it does not have a significant impact on microbial diversity in the rhizosphere soil and enzyme activities within a single crop season (Zhou et al. 2016). These findings suggest that Bt sugarcane has the potential to be utilized for effective insect pest management in sugarcane fields without significant adverse effects on the environment.

In summary, Bt crops function as a valuable tool for enhancing food and feed quality by decreasing pesticide residues, mitigating health risks linked to pesticide exposure, and advocating for safer and healthier agricultural practices.

Issues and solution of Bt crops

The emergence of pest resistance poses a significant challenge to the sustainability of Bt transgenic technology (Heckel 2012; Pardo-López et al. 2013; Dively et al. 2016; Sharon et al. 2016). The development of resistance in pest populations can lead to a reduction in the efficacy of Bt crops for pest control on a global scale (Tabashnik et al. 2013; Bruce et al. 2014). Additionally, there are reports of cross-resistance between Cry proteins in cotton pest insects (Anilkumar et al. 2008; Unnithan et al. 2015), emphasizing the urgency of resistance management (Mchughen 2012). To tackle these challenges, one commonly utilized approach is the high-dose refuge strategy. This approach involves planting Bt crops with high levels of toxin expression to suppress the population of resistant pests, while simultaneously growing 'refuge' plants that do not produce Bt toxins. These refuge plants offer a habitat for susceptible pests, allowing for their survival and mating with any resistant insects, thus maintaining a low frequency of resistant alleles (Roush 1997; Liu and Tabashnik 1997; Dively et al. 2016).

In addition to the high-dose refuge strategy, early detection of resistance is crucial. This involves conducting baseline susceptibility tests to determine the susceptibility of pest populations to Bt toxins and to identify the genetic basis underlying their resistance, (Paolino and Gassmann 2017; Wei et al. 2017). Identifying resistant individuals or populations early on enables the implementation of appropriate management strategies to mitigate resistance evolution and preserve the efficacy of Bt crops. Overall, these strategies are essential to delaying the evolution of resistance and maintaining the long-term effectiveness of Bt transgenic technology.

Conclusion and future perspectives

Lepidopteran borers, by causing reductions in stalk weight, juice quality and sugar recovery, are the most destructive pests in sugarcane. Currently, the use of chemical pesticides can severely damage human health and ecosystem functioning, compromising the sustainability of plant protection. Thus, the objective for scientists is reducing the use of chemical pesticides, thereby minimizing environmental impact without compromising crop yields. Biological agents, such as aphids and fungi, have been studied and other novel technologies, including application of cropping system, behavioral manipulation and the selection of resistant varieties, have been identified to effectively reduce sugarcane borer damages in laboratory conditions. However, the effectiveness of this strategy has been hampered by harmful residues, limitations in formulation, environmental variability, labor shortages, and increased input costs. Furthermore, the life cycle of the sugarcane borer typically lasts for two months, with 4–6 overlapping generations occurring each year. Given that the sugarcane borer primarily feeds within sugarcane stalks, managing it with foliar insecticides or other biological agents is challenging and requires careful timing to coincide with larval eclosion. Consequently, the effectiveness of biological control activities against the pest is impeded, and most of these technologies are challenging to implement in the field.

Transgenic Bt sugarcane, achieved through the introduction of genes encoding Cry proteins, has effectively enhanced sugarcane's resistance to insect damage, as evidenced by studies conducted by scientists (Kalunke et al. 2009; Arvinth et al. 2010; Wu et al. 2010; Weng et al. 2011; Gao et al. 2016a, b). A lot of successful commercial examples can be also found in Bt corn and Bt cotton, which have shown increased profits and decreased yield losses, so developing Bt sugarcane is a viable solution for sugarcane borers.

Further studies can focus on these aspects:

There is still a need for improvement in IPM strategy to control sugarcane borers. The development of innovative biological products, including microorganisms and metabolites, screening additional chemical pesticides, employing chemical ecology strategies, identifying novel cultural management approaches, and breeding resistant varieties, will enhance the resistance of sugarcane to attacks by borers. Investigating the effectiveness of various combinations of control strategies in 'IPM' is crucial for achieving effective control of sugarcane borers, albeit with significant challenges.

The implementation of these tactics depended on an enhanced understanding of the systematics, biology and ecology of the pests. Investigating the lifespan and feeding habits is crucial for determining the optimal timing of pesticide and other agent applications. Additionally, Geographic Information Systems (GIS), remote sensing, and semiochemicals for detecting damage and monitoring populations offer significant opportunities for IPM.

The success of this initiative relies on the collaborative efforts of researchers, technology-transfer specialists, and commercial partners to ensure the effective translation of research into practical use. Current practices in IPM should be evaluated within the context of IPM programs, with a focus on compatibility and consideration of ecological, environmental, and economic consequences. The efficacy of new control strategies should be assessed by farmers, ensuring consistent profitability and security for growers and sugarcane millers.

Promising biotechnological advances with excellent potential are poised to significantly enhance the control of sugarcane borers. Exploring the feasibility and advantages of stacking multiple genes within a single transferred DNA (T-DNA) fragment holds the potential to simplify genetic engineering and enhance the effectiveness of pest resistance (Xiao and Wu 2019). Thus, the future management of lepidopteran pests will encompass the integration of transgenic crops with various novel Bt genes. Additional research should concentrate on utilizing or developing more robust genetic modification techniques, including genome editing technology and efficient genetic transformation, for the development of crops with enhanced resistance traits against sugarcane borers.

Declarations

References

Abedullah KS, Qaim M (2014) Bt cotton, pesticide use and environmental efficiency in Pakistan. J Agric Econ 66:66–86. https://doi.org/10.1111/1477-9552.12072

Ali A, Reagan TE (1986) Influence of selected weed control practices on araneid faunal composition and abundance in sugarcane. Environ Entomol 15:527–531. https://doi.org/10.1093/ee/15.3.527

Almeida LCD, Dias FMM, Arrigoni EDB (2007) First occurrence of *Telchin licus* (Drury, 1773), the "giant sugarcane borer" in the State of São Paulo, Brazil. Rev Agric 82:223–230

Alves SB (1986) In: Controle Microbiano de Insetos. Manole, São Paulo, Brazil, PP. 407.

Anderson DJ, Birch RG (2012) Minimal handling and super-binary vectors facilitate efficient, agrobacterium-mediated, transformation of sugarcane (*Saccharum spp*. hybrid). Trop Plant Biol 5:183–192. https://doi.org/10.1007/s12042-012-9101-1

Angerilli NPD, Permana AD, Sasaerila Y et al (1998) Prospecting for insect pheromones in indonesia: finds, failures and the future. J Asia Pac Entomol 1:25–33. https://doi.org/10.1016/S1226-8615(08)60004-7

Anilkumar KJ, Rodrigo-Simon A, Ferre J et al (2008) Production and characterization of *Bacillus thuringiensis* Cry1Ac-resistant cotton bollworm *Helicoverpa zea* (Boddie). Appl Environ Microbiol 74:462–469. https://doi.org/10.1128/AEM.01612-07

Arencibia A, Vázquez RI, Prieto D et al (1997) Transgenic sugarcane plants resistant to stem borer attack. Mol Breed 3:247–255. https://doi.org/10.1023/A:1009616318854

Arencibia AD, Carmona ER, Tellez P et al (1998) An efficient protocol for sugarcane (*Saccharum spp*. L.) transformation mediated by *Agrobacterium tumefaciens*. Transgenic Res 7:213–222. https://doi.org/10.1023/A:1008845114531

Arencibia AD, Carmona ER, Cornide MT et al (1999) Somaclonal variation in insect-resistant transgenic sugarcane (Saccharum hybrid) plants produced by cell electroporation. Transgenic Res 8:349–360. https://doi.org/10.1023/A:1008900230144

Arvinth S, Arun S, Selvakesavan RK et al (2010) Genetic transformation and pyramiding of aprotinin-expressing sugarcane with *cry1Ab* for shoot borer (*Chilo infuscatellus*) resistance. Plant Cell Rep 29:383–395. https://doi.org/10.1007/s00299-010-0829-5

Assefa Y, Conlong DE, Berg JVB et al (2010) Distribution of sugarcane stem borers and their natural enemies in small-scale farmers' fields, adjacent margins and wetlands of Ethiopia. Pans Pest Artic News Summ 56:233–241. https://doi.org/10.1080/09670870903470223

Atkinson PR, Carnegie AJM (1989) Population dynamics of the sugarcane borer, *Eldana saccharina* Walker (Lepidoptera: Pyralidae), in Natal, South Africa. Bull Entomol Res 79:61–80. https://doi.org/10.1017/S0007485300018575

Attia AO, Mohamed AM, Hafez ME et al (2005) Establishment of regeneration and transformation systems of f144 sugarcane cultivar. Pakistan J Biotechnol 2:24–35

Babilis NA, Mazomenos BE (1992) Pheromone production in *Sesamia nonagrioides*: diel periodicity and effect of age and mating. J Insect Physiol 38:561–564. https://doi.org/10.1016/0022-1910(92)90106-N

Barboza-Corona JE, Ibarra J (1998) Proteínas insecticidas de *Bacillus thuringiensis*. Boletín De Educación Bioquímica-ISSN 1665–1995(17):3–10

Barker AL, Conlong D, Byrne MJ (2006) Habitat management using *Melinis minutiflora* (Poaceae) to decrease the infestation of sugarcane by *Eldana saccharina* (Lepidoptera: Pyralidae). Proc South Afr Sugar Technol Assoc 80:226–235

Barros GOF, Ballen MAT, Woodard SL et al (2013) Recovery of bovine lysozyme from transgenic sugarcane stalks: extraction, membrane filtration, and purification. Bioprocess Biosyst Eng 36:1407–1416. https://doi.org/10.1007/s00449-012-0878-y

Basnayake SWV, Morgan TC, Wu L et al (2012) Field performance of transgenic sugarcane expressing isomaltulose synthase. Plant Biotechnol J 10:217–225. https://doi.org/10.1111/j.1467-7652.2011.00655.x

Beevor PS, David H, Jones OT (1990) Female sex pheromones of Chilo spp. (Lepidoptera: Pyralidae) and their development in pest control applications. Int J Trop Insect Sci 11:787–794. https://doi.org/10.1017/S1742758400021354

Bennett FD (1971) Current status of biological control of the small moth borers of sugar cane Diatraea spp [Lep. Pyraeididae]. Entomophaga 16:111–124. https://doi.org/10.1007/BF02370694

Bernardi O, Bernardi D, Ribeiro RS et al (2015) Frequency of resistance to Vip3Aa20 toxin from Bacillus thuringiensis in *Spodoptera frugiperda* (Lepidoptera: Noctuidae) populations in Brazil. Crop Prot 76:7–14. https://doi.org/10.1016/j.cropro.2015.06.006

Betz FS, Hammond BG, Fuchs RL (2000) Safety and advantages of *Bacillus thuringiensis*-protected plants to control insect pests. Regul Toxicol Pharmacol 32:156–173. https://doi.org/10.1006/rtph.2000.1426

Beuzelin JM, Akbar W, Meszaros A et al (2010) Field assessment of novaluron for sugarcane borer, *Diatraea saccharalis* (F.) (Lepidoptera: Crambidae), management in Louisiana sugarcane. Crop Prot 29:1168–1176. https://doi.org/10.1016/j.cropro.2010.06.004

Beuzelin JM, Meszaros A, Akbar W, Reagan TE (2011) Sugarcane planting date impact on fall and spring sugarcane borer (Lepidoptera: Crambidae) infestations. Florida Entomol 94:242–252. https://doi.org/10.1653/024.094.0218

Bewg WP, Poovaiah C, Lan W et al (2016) RNAi downregulation of three key lignin genes in sugarcane improves glucose release without reduction in sugar production. Biotechnol Biofuels 9:270. https://doi.org/10.1186/s13068-016-0683-y

Bezuidenhout CN, Goebel R, Hull PJ et al (2008) Assessing the potential threat of *Chilo sacchariphagus* (Lepidoptera: Crambidae) as a pest in South Africa and Swaziland: realistic scenarios based on climatic indices. African Entomol 16:86–90. https://doi.org/10.4001/1021-3589-16.1.86

Bhattacharyya-Pakrasi M, Peng J, Elmer JS et al (1993) Specificity of a promoter from the rice tungro bacilliform virus for expression in phloem tissues. Plant J 4:71–79. https://doi.org/10.1046/j.1365-313x.1993.04010071.x

Bohmert K, Balbo I, Kopka J et al (2000) Transgenic Arabidopsis plants can accumulate polyhydroxybutyrate to up to 4% of their fresh weight. Planta 211:841–845. https://doi.org/10.1007/s004250000350

Bohmert K, Balbo I, Steinbuchel A et al (2002) Constitutive expression of the beta-ketothiolase gene in transgenic plants. A major obstacle for obtaining polyhydroxybutyrate-producing plants. Plant Physiol 128:1282–1290. https://doi.org/10.1104/pp.010615

Boobis AR, Ossendorp BC, Banasiak U et al (2008) Cumulative risk assessment of pesticide residues in food. Toxicol Lett 180:137–150. https://doi.org/10.1016/j.toxlet.2008.06.004

Bosque-Pérez NA, Mareck JH (1991) Effect of the stem borer *Eldana saccharina* (Lepidoptera: Pyralidae) on the yield of maize. Bull Entomol Res 81:243–247. https://doi.org/10.1017/S0007485300033496

Box HE (1931) The Crambine genera Diatraea and Xanthopherne (Lep., Pyral.). Bull Entomol Res 22:1–50. https://doi.org/10.1017/S0007485300029709

Bradley D, Harkey MA, Kim MK et al (1995) The insecticidal *CryIB* crystal protein of *Bacillus thuringiensis* ssp. thuringiensis has dual specificity to coleopteran and lepidopteran larvae. J Invertebr Pathol 65:162–173. https://doi.org/10.1006/jipa.1995.1024

Bravo A (1997) Phylogenetic relationships of *Bacillus thuringiensis* delta-endotoxin family proteins and their functional domains. J Bacteriol 179:2793–2801. https://doi.org/10.1128/jb.179.9.2793-2801.1997

Bravo A, Hendrickx K, Jansens S, Peferoen M (1992) Immunocytochemical analysis of specific binding of *Bacillus thuringiensis* insecticidal crystal proteins to lepidopteran and coleopteran midgut membranes. J Invertbr Pathol 60:247–253. https://doi.org/10.1016/0022-2011(92)90005-O

Bravo A, Gill SS, Soberón M (2007) Mode of action of *Bacillus thuringiensis* Cry and Cyt toxins and their potential for insect control. Toxicon 49:423–435. https://doi.org/10.1016/j.toxicon.2006.11.022

Bruce ET, David M, Mark E et al (2014) Defining terms for proactive management of resistance to Bt crops and pesticides. J Econ Entomol 107:496–507. https://doi.org/10.1603/EC13458

Butterfield MK, Irvine JE, Valdez Garza M et al (2002) Inheritance and segregation of virus and herbicide resistance transgenes in sugarcane. Theor Appl Genet 104:797–803. https://doi.org/10.1007/s00122-001-0830-z

CABI (2022) Sugarcane borer. CAB International, Wallingford, UK

Caffall KH, He C, Smith-Jones M et al (2017) Long-term T-DNA insert stability and transgene expression consistency in field propagated sugarcane. Plant Mol Biol 93:451–463. https://doi.org/10.1007/s11103-016-0572-6

Campion DG, Nesbitt BF (1983) The utilisation of sex pheromones for the control of stem-borers. Int J Trop Insect Sci 4:191–197. https://doi.org/10.1017/S1742758400004227

Cao J, Zhao JZ, Tang J et al (2002) Broccoli plants with pyramided *cry1Ac* and *cry1C* Bt genes control diamondback moths resistant to *Cry1A* and *Cry1C* proteins. Theor Appl Genet 105:258–264. https://doi.org/10.1007/s00122-002-0942-0

Cao AD, Diep DN, Hung HQ (2011) Survey of sugarcane moth borers in Southeast Vietnam. Int Sugar J 113:732–737

Carlo R, Philippe S, Dieter T et al (2003) Engineering of flower color in forsythia by expression of two independently-transformed dihydroflavonol 4-reductase and anthocyanidin synthase genes of flavonoid pathway. Mol Breed 12:197–208. https://doi.org/10.1023/A:1026364618719

Carpenter JE (2010) Peer-reviewed surveys indicate positive impact of commercialized GM crops. Nat Biotechnol 28:319–321. https://doi.org/10.1038/nbt0410-319

Carrière Y, Ellers-Kirk C et al (2003) Long-term regional suppression of pink bollworm by Bacillus thuringiensis cotton. Proc Natl Acad Sci USA 100:1519–1523. https://doi.org/10.1073/pnas.0436708100

Chakroun M, Banyuls N, Bel Y et al (2016) Bacterial vegetative insecticidal proteins (Vip) from entomopathogenic bacteria. Microbiol Mol Biol Rev 80:329–350. https://doi.org/10.1128/MMBR.00060-15

Cheavegatti-Gianotto A, de Abreu HMC, Arruda P et al (2011) Sugarcane (*Saccharum officinarum*): a reference study for the regulation of genetically modified cultivars in Brazil. Trop Plant Biol 4:62–89. https://doi.org/10.1007/s12042-011-9068-3

Cheavegatti-Gianotto A, Gentile A, Oldemburgo DA et al (2018) Lack of detection of Bt sugarcane *Cry1Ab* and *nptII* DNA and proteins in sugarcane processing products including raw sugar. Front Bioeng Biotechnol 6:24. https://doi.org/10.3389/fbioe.2018.00024

Chen TJ (1998) The outbreak and chemical control of sugarcane borers. Sugarcane 5:22–25

Chen G, Rothnie HM, He XY et al (1996) Efficient transcription from the rice tungro bacilliform virus promoter requires elements downstream of the transcription start site. J Virol 70:8411–8421. https://doi.org/10.1128/JVI.70.12.8411-8421.1996

Chen R, Xue G, Chen P et al (2008) Transgenic maize plants expressing a fungal phytase gene. Transgenic Res 17:633–643. https://doi.org/10.1007/s11248-007-9138-3

Cherry RH, Nuessly GS, Sandhu HS (2015) Insect Management in Sugarcane. Univ Florida 1–7

Chong BF, Abeydeera WPP, Glassop D et al (2010a) Co-ordinated synthesis of gentiobiitol and sorbitol, evidence of sorbitol glycosylation in transgenic sugarcane. Phytochemistry 71:736–741. https://doi.org/10.1016/j.phytochem.2010.01.014

Chong BF, Bonnett GD, Glassop D et al (2010b) Growth and metabolism in sugarcane are altered by the creation of a new hexosephosphate sink. Plant Biotechnol J 5:240–253. https://doi.org/10.1111/j.1467-7652.2006.00235.x

Christy LA, Arvinth S, Saravanakumar M et al (2009) Engineering sugarcane cultivars with bovine pancreatic trypsin inhibitor (aprotinin) gene for protection against top borer (*Scirpophaga excerptalis* Walker). Plant Cell Rep 28:175–184. https://doi.org/10.1007/s00299-008-0628-4

Coate JE, Song MJ, Bombarely A, Doyle JJ (2016) Expression-level support for gene dosage sensitivity in three glycine subgenus glycine polyploids and their diploid progenitors. New Phytol 212:1083–1093

Conlong DE (1994) A review and perspectives for the biological control of the African sugarcane stalkborer *Eldana saccharina* Walker (Lepidoptera: Pyralidae). Agric Ecosyst Environ 48:9–17. https://doi.org/10.1016/0167-8809(94)90070-1

Conlong D, Goebel F-R (2002) Biological control of *Chilo sacchariphagus* (Lepidoptera: Crambidae) in Moçambique : The firsts steps. Proc Annu Congr S Afr Sugar Technol Assoc 76:310–320

Conlong D, Kasl B (2000) Stimulo-deterrent diversion to decrease infestation in sugarcane by *Eldana saccharina* (Lepidoptera: Pyralidae). Proc Annu Congr S Afr Sugar Technol Assoc 74:212–213

Conlong DE, Rutherford RS (2009) Conventional and new biological and habitat interventions for integrated pest management systems: review and case studies using *Eldana saccharina* Walker (Lepidoptera: Pyralidae) In: Peshin R, Dhawan AK (eds) integrated pest management: innovation-development process. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-8992-3_10

Cook SM, Khan ZR, Pickett JA (2007) The use of push-pull strategies in integrated pest management. Annu Rev Entomol 52:375–400. https://doi.org/10.1146/annurev.ento.52.110405.091407

Cristofoletti PT, Kemper EL, Capella AN et al (2018) Development of transgenic sugarcane resistant to sugarcane borer. Trop Plant Biol 11:17–30. https://doi.org/10.1007/s12042-018-9198-y

Dai S, Zheng P, Marmey P et al (2001) Comparative analysis of transgenic rice plants obtained by Agrobacterium-mediated transformation and particle bombardment. Mol Breed 7:25–33. https://doi.org/10.1023/A:1009687511633

Dam MI, Ding B-J, Svensson GP et al (2023) Sex pheromone biosynthesis in the sugarcane borer *Diatraea saccharalis*: paving the way for biotechnological production. Pest Manag Sci 11:17–30. https://doi.org/10.1002/ps.7830

Damaj MB, Kumpatla SP, Emani C et al (2010) Sugarcane dirigent and O-methyltransferase promoters confer stem-regulated gene expression in diverse monocots. Planta 231:1439–1458. https://doi.org/10.1007/s00425-010-1138-5

Daquila BV, Dossi FC, Moi DA et al (2021) Bioactivity of *Bacillus thuringiensis* (Bacillales: Bacillaceae) on *Diatraea saccharalis* (Lepidoptera: Crambidae) eggs. Pest Manag Sci 77:2019–2028. https://doi.org/10.1002/ps.6230

Datta K, Baisakh N, Thet KM et al (2002) Pyramiding transgenes for multiple resistance in rice against bacterial blight, yellow stem borer and sheath blight. Theor Appl Genet 106:1–8. https://doi.org/10.1007/s00122-002-1014-1

David H, Easwaramoorthy S, Jayanthi R (1986) Sugarcane entomology in India. Indian Council of Agricultural Research, New York, pp 1986–2564

David D, Easwaramoorthy S, Nandagopal V et al (1988) Larvipositional behaviour of *Sturmiopsis inferens* tns. (Tachinidae: Diptera) on sugarcane shoot borer in India. Trop Pest Manag 34:267–270. https://doi.org/10.1080/09670878809371255

De REJ, Vargo-Gogola TC, Green DPJ (1998) Direct evidence for rapid degradation of Bacillus thuringiensis toxin mRNA as a cause of poor expression in plants. Plant Physiol 117:1445–1461. https://doi.org/10.1007/10.1104/pp.117.4.1445

de Mello US, Vidigal PMP, Vital CE et al (2020) An overview of the transcriptional responses of two tolerant and susceptible sugarcane cultivars to borer (*Diatraea saccharalis*) infestation. Funct Integr Genomics 20:839–855. https://doi.org/10.1007/s10142-020-00755-8

de Oliveira WS, Sakuno CIR, Miraldo LL et al (2022) Varied frequencies of resistance alleles to *Cry1Ab* and *Cry1Ac* among Brazilian populations of the sugarcane borer, *Diatraea saccharalis* (F.). Pest Manag Sci 78:5150–5163. https://doi.org/10.1002/ps.7133

Dessoky ES, Ismail RM, Elarabi NI et al (2021) Improvement of sugarcane for borer resistance using Agrobacterium mediated transformation of cry1Ac gene. GM Crops Food 12:47–56. https://doi.org/10.1080/21645698.2020.1809318

Dively GP, Venugopal PD, Finkenbinder C (2016) Field-evolved resistance in corn earworm to cry proteins expressed by transgenic sweet corn. PLoS ONE 11:1–22. https://doi.org/10.1371/journal.pone.0169115

Donegani IRG (1977) (Z)-9-Tetradecen-l -ol and (Z)-9-tetradecenyl acetate: a potent attractant system for male *Sesamia cretica* Led. (Lep., Noctuidae) 1. 1073: 1973–1974

Downes S, Kriticos D, Parry H et al (2017) A perspective on management of *Helicoverpa armigera*: transgenic Bt cotton, IPM, and landscapes. Pest Manag Sci 73:485–492. https://doi.org/10.1002/ps.4461

Duan X, Li X, Xue Q et al (1996) Transgenic rice plants harboring an introduced potato proteinase inhibitor II gene are insect resistant. Nat Biotechnol 14(4):494–498. https://doi.org/10.1038/nbt0496-494

Easwaramoorthy S, Jayaraj S (1987) Survey of granulosis virus infection in sugarcane borers, *Chilo infuscatellus* Snellen and *C. sacchariphagus indicus* (Kapur) in India. Trop Pest Manage 33:200–201. https://doi.org/10.1080/09670878709371149

Easwaramoorthy S, Nirmala R, Santhalakshmi G (2001) Occurence of *Metarhizium anisopliae* Var. anisopliae on sugarcane internode borer, *Chilo Sacchariphagus* Indicus (kapur). J Biol Control 15:81–84

Eldessoky DS, Ismail RM, Abdel-Hadi AHA, Abdallah NA (2011) Establishment of regeneration and transformation system of sugarcane cultivar GT54-9 (C9). GM Crops 2:126–134. https://doi.org/10.4161/gmcr.2.2.17288

Ellis TO, RÖHRIG PE, Arceneaux G (1960) Stalk borer damage as affecting available sucrose in mill cane. Conference paper: Pro.10th Congr int Soc Sugar Cane Tech, Hawaii, 1960 pp.924–36 pp.

Enriquez GA, Trujillo LE, Menendez C et al (2000) Sugarcane (Saccharum hybrid) Genetic transformation mediated by *Agrobacterium tumefaciens*: production of transgenic plants expressing proteins with agronomic and industrial value. Dev Plant Genet Breed 5:76–81. https://doi.org/10.1016/S0168-7972(00)80011-0

Enríquez-Obregón GA, Vázquez-Padrón RI, Prieto-Samsonov DL et al (1998) Herbicide-resistant sugarcane (*Saccharum officinarum* L.) plants by Agrobacterium-mediated transformation. Planta 206:20–27. https://doi.org/10.1007/s004250050369

Estruch JJ, Carozzi NB, Desai N et al (1997) Transgenic plants: an emerging approach to pest control. Nat Biotechnol 15:137–141. https://doi.org/10.1038/nbt0297-137

Falco MC, Silva-Filho MC (2003) Expression of soybean proteinase inhibitors in transgenic sugarcane plants: effects on natural defense against *Diatraea saccharalis*. Plant Physiol Biochem 41:761–766. https://doi.org/10.1016/S0981-9428(03)00100-1

Fang NN, Yuwei Hu YW, Mao B et al (2018) Molecular characterization and functional differentiation of three pheromone-binding proteins from *Tryporyza intacta*. Sci Rep 8:10774. https://doi.org/10.1038/s41598-018-29164-5

Fantinou AA, Perdikis DC, Chatzoglou CS (2003) Development of immature stages of *Sesamia nonagrioides* (Lepidoptera : Noctuidae) under alternating and constant temperatures. Environ Entomol 32:1337–1342. https://doi.org/10.1603/0046-225X-32.6.1337

Fearing PL, Brown D, Vlachos D et al (1997) Quantitative analysis of *Cry1A(b)* expression in Bt maize plants, tissues, and silage and stability of expression over successive generations. Mol Breed 3:169–176. https://doi.org/10.1023/A:1009611613475

Fouad WM, Hao W, Xiong Y et al (2015) Generation of transgenic energy cane plants with integration of minimal transgene expression cassette. Curr Pharm Biotechnol 16:407–413

Fuchs TW, Huffman FR, Smith JW (1979) Introduction and establishment of *Apanteles flavipes* [Hym.: Braconidae] on *Diatraea saccharalis* [Lep.: Pyralidae] in texas. Entomophaga 24:109–114. https://doi.org/10.1007/BF02375123

Gallo-Meagher M, Irvine JE (1996) Herbicide resistant transgenic sugarcane plants containing the bar gene. Crop Sci 36:1367–1374. https://doi.org/10.2135/cropsci1996.0011183X003600050047x

Gao S, Yang Y, Wang C et al (2016a) Transgenic sugarcane with a *cry1Ac* gene exhibited better phenotypic traits and enhanced resistance against sugarcane borer. PLoS ONE 11:1–16. https://doi.org/10.1371/journal.pone.0153929

Gao SW, Yang YY, Wang CF et al (2016b) Transgenic Sugarcane with a cry1Ac gene exhibited better phenotypic traits and enhanced resistance against sugarcane borer. PLoS ONE 11:e0153929. https://doi.org/10.1371/journal.pone.0153929

Gao SJ, Damaj MB, Park JW et al (2017) A novel sugarcane bacilliform virus promoter confers gene expression preferentially in the vascular bundle and storage parenchyma of the sugarcane culm. Biotechnol Biofuels 10:1–14. https://doi.org/10.1186/s13068-017-0850-9

Gao S, Yang Y, Xu L et al (2018) Particle bombardment of the *cry2A* gene cassette induces stem borer resistance in sugarcane. Int J Mol Sci 19:1–16. https://doi.org/10.3390/ijms19061692

Ghahari H, Tabari M, Ostovan H et al (2009) Host plants of rice stem borer, *Chilo suppressalis* Walker (Lepidoptera: Pyralidae) and identification of Chilo species in Mazandaran province. Iran J New Agric Sci 5:65–74

Gilbert RA, Gallo-Meagher M, Comstock JC et al (2005) Agronomic evaluation of sugarcane lines transformed for resistance to strain E. Crop Sci 45:2060–2067. https://doi.org/10.2135/cropsci2004.0771

Gilbert RA, Glynn NC, Comstock JC, Davis MJ (2009) Agronomic performance and genetic characterization of sugarcane transformed for resistance to sugarcane yellow leaf virus. F Crop Res 111:39–46. https://doi.org/10.1016/j.fcr.2008.10.009

Girling DJ (1978) The distribution and biology of *Eldana saccharina* Walker (Lepidoptera Pyralidae) and its relationship to other stem-borers in Uganda. Bull Entomol Res 68:471–488. https://doi.org/10.1017/S0007485300009457

Girón-Calva PS, Twyman RM, Albajes R et al (2020) The impact of environmental stress on bt crop performance. Trends Plant Sci 25:264–278. https://doi.org/10.1016/j.tplants.2019.12.019

Gitahy PDM, De Souza MT, Monnerat RG et al (2007) A brazilian *Bacillus thuringiensis* strain highly active to sugarcane borer *Diatraea saccharalis* (Lepidoptera: Crambidae). Brazilian J Microbiol 38:531–537. https://doi.org/10.1590/S1517-83822007000300028

Goderis IJWM, De BMFC et al (2002) A set of modular plant transformation vectors allowing flexible insertion of up to six expression units. Plant Mol Biol 50:17–27. https://doi.org/10.1023/a:1016052416053

Goebel FR, Achadian E, Mcguire P (2014) The economic impact of sugarcane moth borers in Indonesia. Sugar Tech 16:405–410. https://doi.org/10.1007/s12355-013-0281-2

Goftishu M, Assefa Y, Fininsa C et al (2016) Phylogeography of *Sesamia cretica* Lederer (Lepidoptera: Noctuidae). Phytoparasitica 44:641–650. https://doi.org/10.1007/s12600-016-0556-8

Gómez I, Pardo-López L, Muñoz-Garay C et al (2007) Role of receptor interaction in the mode of action of insecticidal Cry and Cyt toxins produced by *Bacillus thuringiensis*. Peptides 28:169–173. https://doi.org/10.1016/j.peptides.2006.06.013

Graham MW, Mudge SR, Sternes PR, Birch RG (2011) Understanding and avoiding transgene silencing. Wiley-Blackwell. https://doi.org/10.1002/9780470958988.ch12

Guan CX, Xu HL, Lin MJ (2012) Prediction and forecasting of sugarcane stem borer and integrated control measures. Chin J Trop Agric 32:42–46

Guo JL, Guo S et al (2015) Transgenic Sugarcane resistant to sorghum mosaic virus based on coat protein gene silencing by RNA interference. Biomed Res Int. https://doi.org/10.1155/2015/861907

Hardke JT, Temple JH, Leonard BR et al (2011) Laboratory toxicity and field efficacy of selected insecticides against fall armyworm (lepidoptera: noctuidae). Florida Entomol 94:272–278. https://doi.org/10.1653/024.094.0221

Harrison MD, Geijskes J, Coleman HD et al (2011) Accumulation of recombinant cellobiohydrolase and endoglucanase in the leaves of mature transgenic sugar cane. Plant Biotechnol J 9:884–896. https://doi.org/10.1111/j.1467-7652.2011.00597.x

Harrison MD, Geijskes RJ, Lloyd R et al (2014) Recombinant cellulase accumulation in the leaves of mature, vegetatively propagated transgenic sugarcane. Mol Biotechnol 56:795–802. https://doi.org/10.1007/s12033-014-9758-9

He HY (2009) Observations on sexual characteristics and mating behavior of *Chilo venosatus* Walker. Guangdong Agric Sci 3:97–99

Hearne JW, van Coller LM, Conlong DE (1994) Determining strategies for the biological control of a sugarcane stalk borer. Ecol Modell 73:117–133. https://doi.org/10.1016/0304-3800(94)90101-5

Heckel DG (2012) Ecology insecticide resistance after silent spring. Science 337:1612–1614. https://doi.org/10.1126/science.1226994

Hensley SD (1971) Management of sugarcane borer populations in Louisiana, a decade of change. Biocontrol 16:133–146. https://doi.org/10.1007/BF02370696

Hensley SD (1973) A comparison of pheromone and blacklight traps for attracting sugarcane borer (*Diatraea saccharalis* (F.)) adults from a natural population. J Agric Univ Puerto Rico 57:320–329

Hensley SD, Long WH (1969) Differential yield responses of commercial sugarcane varieties to sugarcane borer damage. J Econ Entomol 62:620–622. https://doi.org/10.1093/jee/62.3.620

Herbert A, Rich A (1999) Left-handed Z-DNA: structure and function. Genetica 106:37. https://doi.org/10.1023/a:1003768526018

Hernández-Velázquez VM, Lina-García LP, Obregón-Barboza V, et al (2012) Pathogens associated with sugarcane borers, Diatraea spp. (Lepidoptera: Crambidae): a review. Int J Zool, 1–12. https://doi.org/10.1155/2012/303589

Herrera G, Snyman SJ, Thomson JA (1994) Construction of a bioinsecticidal strain of *Pseudomonas fluorescens* active against sugarcane borer, *Eldana Saccharina*. Appl Environ Microbiol 60:682–690. https://doi.org/10.1128/aem.60.2.682-690.1994

Hfte H, Whiteley HR (1989) Insecticidal crystal proteins of *Bacillus thuringiensis*. Microbiol Rev 53:242–255. https://doi.org/10.1128/mr.53.2.242-255.1989

Hokkanen THM (1991) Trap cropping in pest management. Annu Rev Entomol 36:119–138. https://doi.org/10.1300/J064v05n01_09

Holloway TE, Haley WE (1928) A cooperative estimate of the loss caused by the sugar-cane moth borer. J Econ Entomol 21:852–854. https://doi.org/10.1093/jee/21.6.852

Horikoshi RJ, Ferrari G, Dourado PM et al (2022) MON 95379 Bt maize as a new tool to manage sugarcane borer (*Diatraea saccharalis*) in South America. Pest Manag Sci 78:3456–3466. https://doi.org/10.1002/ps.6986

Hu YW, Zhao DR, Li JH et al (2017) Study on pathogenicity of *Beauveria bassiana* on the larvae of two sugarcane borers. Sugarcane Canesugar 1:19–22

Hutchison WD, Burkness EC, Mitchell PD et al (2010) Areawide suppression of european corn borer with bt maize reaps savings to Non-Bt maize growers. Science 330:222–225. https://doi.org/10.1126/science.1190242

Ingelbrecht IL, Irvine JE, Mirkov TE (1999) Posttranscriptional gene silencing in transgenic sugarcane. Dissection of homology-dependent virus resistance in a monocot that has a complex

polyploid genome. Plant Physiol 119:1187–1197. https://doi.org/10.1104/pp.119.4.1187

Inglis GD, Lawrence AM, Davis FM (2015) Impact of a novel species of Nosema on the southwestern corn borer (Lepidoptera: Crambidae). J Econ Entomol 96:12–20. https://doi.org/10.1603/0022-0493-96.1.12

Iqbal A, Khan RS, Khan MA et al (2021) Genetic Engineering approaches for enhanced insect pest resistance in sugarcane. Mol Biotechnol 63:557–568

ISAAA (International service for the acquisition of agri-biotech applications). 2019. GM approval database. https://www.isaaa.org/gmapprovaldatabase/.

ISAAA (International service for the acquisition of agri-biotech applications). 2022. GM approval database. https://www.isaaa.org/gmapprovaldatabase/.

Ismail RM (2013) Evaluation of genetically modified sugarcane lines carrying Cry 1AC gene using molecular marker techniques. GM Crops Food 4:58–66. https://doi.org/10.4161/gmcr.24299

Jackson MA, Anderson DJ, Birch RG (2013) Comparison of Agrobacterium and particle bombardment using whole plasmid or minimal cassette for production of high-expressing, low-copy transgenic plants. Transgenic Res 22:143–151. https://doi.org/10.1007/s11248-012-9639-6

Jacob V, Tibère R, Nibouche S (2021) Few sensory cues differentiate host and dead-end trap plant for the sugarcane spotted borer *Chilo sacchariphagus* (Lepidoptera: Crambidae). J Chem Ecol 47:153–166. https://doi.org/10.1007/s10886-020-01240-z

Jaipal S (1996) Evaluation of the biological control agent (*Trichogramma chilonis*) against the stalk borer (*Chilo auricilius*) in sugarcane crops. Tests Agrochem Cultiv 17:102–103

Jaipal S (2000) An IPM module for the management of major insect pests of sugarcane in Indian subtropics. Sugar Tech 2:1–8. https://doi.org/10.1007/BF02945750

James C (2010) A global overview of biotech (GM) crops: adoption, impact and future prospects. GM Crops 1:8–12. https://doi.org/10.4161/gmcr.1.1.9756

James C (2011) Global Status of Commercialized Biotech/GM Crops: 2011. ISAAA Brief No.43. ISAAA: Ithaca, NY.

Jamshidnia A, Kharazi-Pakdel A, Allahyari H et al (2010) Functional response of *Telenomus busseolae* (Hym.: Scelionidae) an egg parasitoid of the sugarcane stem borer, *Sesamia nonagrioides* (Lep.: Noctuidae) at different temperatures. Biocontrol Sci Technol 20:631–640. https://doi.org/10.1080/09583151003695902

Jasmine RS, Rajendran B, Rani RK (2012) BIPM components for the management of borer complex in sugarcane. J Biopestic 5:209–211

Jobling SA, Westcott RJ, Tayal A et al (2002) Production of a freeze-thaw-stable potato starch by antisense inhibition of three starch synthase genes. Nat Biotechnol 20:295–299. https://doi.org/10.1038/nbt0302-295

Jones JDG, Gilbert DE, Grady KL, Jorgensen RA (1987) T-DNA structure and gene expression in petunia plants transformed by *Agrobacterium tumefaciens* C58 derivatives. Mol Gen Genet 207:478–485. https://doi.org/10.1007/BF00331618

Joyce PA, Mcqualter RB, Bernard MJ, Smith GR (1998) Engineering for resistance to SCMV in sugarcane. Acta Hortic 461:385–392

Joyce P, Hermann S, O'Connel A et al (2014) Field performance of transgenic sugarcane produced using Agrobacterium and biolistics methods. Plant Biotechnol J 12:411–424. https://doi.org/10.1111/pbi.12148

Kalinová B, Kindl J, Hovorka O et al (2005) (11Z)-hexadec-11-enal enhances the attractiveness of *Diatraea saccharalis* main pheromone component in wind tunnel experiments. J Appl Entomol 129:70–74

Kalunke RM, Kolge AM, Babu KH, Prasad DT (2009) Agrobacterium mediated transformation of sugarcane for borer resistance using *Cry1Aa3* gene and one-step regeneration of transgenic plants. Sugar Tech 11:355–359. https://doi.org/10.1007/s12355-009-0061-1

Kay R, Chan A, Daly M, Mcpherson J (1987) Duplication of CaMV 35S promoter sequences creates a strong enhancer for plant genes. Science 236:1299–1302. https://doi.org/10.1126/science.236.4806.1299

Keeping MG (2006) Screening of South African sugarcane cultivars for resistance to the stalk borer, *Eldana saccharina* Walker (Lepidoptera : Pyralidae). African Entomol 14:277–288

Keeping MG, Rutherford RS, Conlong DE (2010) Bt-maize as a potential trap crop for management of *Eldana saccharina* Walker (Lep., Pyralidae) in sugarcane. J Appl Entomol 131:241–250. https://doi.org/10.1111/j.1439-0418.2007.01147.x

Kennedy RD, Adriana CG, De OWS et al (2018) A general safety assessment for purified food ingredients derived from biotechnology crops: case study of brazilian sugar and beverages produced from insect-protected sugarcane. Front Bioeng Biotechnol 6:45. https://doi.org/10.3389/fbioe.2018.00045

Kfir R, Overholt WA, Khan ZR, Polaszek A (2002) Biology and management of economically important lepidopteran cereal stem borers in africa. Annu Rev Entomol 47:701–731. https://doi.org/10.1146/annurev.ento.47.091201.145254

Khanna KL, Nigam LN, Puri VD (1957) *Chilo tumidicostalis* Hampson–a serious stem borer pest of sugarcane in Bihar. Proc Indian Acad Sci–sect B 46:75–95. https://doi.org/10.1007/BF03053165

Kumar T, Uzma KMR et al (2014) Genetic improvement of sugarcane for drought and salinity stress tolerance using Arabidopsis vacuolar pyrophosphatase (*AVP1*) Gene. Mol Biotechnol 56:199–209. https://doi.org/10.1007/s12033-013-9695-z

Kvedaras OL, Keeping MG (2007) Silicon impedes stalk penetration by the borer *Eldana saccharina* in sugarcane. Entomol Exp Appl 125:103–110. https://doi.org/10.1111/j.1570-7458.2007.00604.x

Kvedaras OL, Keeping MG, Goebel FR, Byrne MJ (2007) Larval performance of the pyralid borer *Eldana saccharina* Walker and stalk damage in sugarcane: influence of plant silicon, cultivar and feeding site. Int J Pest Manag 53:183–194. https://doi.org/10.1080/09670870601110956

Kvedaras OL, Byrne MJ, Coombes N, Keeping MG (2009) Influence of plant silicon and sugarcane cultivar on mandibular wear in the stalk borer *Eldana saccharina*. Agric for Entomol 11:301–306. https://doi.org/10.1111/j.1461-9563.2009.00430.x

La PJL, Pla M, Papazova N et al (2010) Stability of the MON 810 transgene in maize. Plant Mol Biol 74:563–571. https://doi.org/10.1007/s11103-010-9696-2

Lakshmanan P, Geijskes RJ, Aitken KS et al (2005) Sugarcane biotechnology: the challenges and opportunities. Vitr Cell Dev Biol Plant 41:345–363. https://doi.org/10.1079/IVP2005643

Lakshmanan P, Geijskes RJ, Wang L et al (2006) Developmental and hormonal regulation of direct shoot organogenesis and somatic embryogenesis in sugarcane (*Saccharum* spp. interspecific hybrids) leaf culture. Plant Cell Rep 25:1007–1015. https://doi.org/10.1007/s00299-006-0154-1

Lareesa WL, Naranjo SE, Lundgren JG et al (2008) Bt Crop Effects on functional guilds of non-target Arthropods: a meta-analysis. PLoS ONE 3:e2118. https://doi.org/10.1371/journal.pone.0002118

Last DI, Brettell RIS, Chamberlain DA et al (1991) pEmu: an improved promoter for gene expression in cereal cells. Theor Appl Genet 81(5):581–588. https://doi.org/10.1007/BF00226722

Legaspi BC, Legaspi JC, Lauziere I et al (2000) Jalisco fly as a parasitoid of the Mexican rice borer on different host plants. Southwest Entomol 25:77–79

Leibbrandt NB, Snyman SJ (2003) Stability of gene expression and agronomic performance of a transgenic herbicide-resistant sugarcane line in South Africa. Crop Sci 43:671–677. https://doi.org/10.2135/cropsci2003.6710

Li YH, Romeis J, Wu KM, Peng YF (2014) Tier-1 assays for assessing the toxicity of insecticidal proteins produced by genetically engineered plants to non-target arthropods. Insect Sci 21:125–134. https://doi.org/10.1111/1744-7917.12044

Li Y, Hallerman EM, Liu Q et al (2016a) The development and status of Bt rice in China. Plant Biotechnol J 14:839–848. https://doi.org/10.1111/pbi.12464

Li YJ, Duan WX, Huang Z et al (2016b) Occurrence of major diseases and insect pests in medium-term growth period of sugarcane and the diseases resistance evaluation in Guangxi. Plant Dis Pests 7:15–19

Li HH, Liu CY, Zhang HW et al (2023) Global genetically modified crop industrialization trends in 2022. JAST 25:6–16

Liu D (2009) Design of gene constructs for transgenic maize. Methods Mol Biol 526:3–20. https://doi.org/10.1007/978-1-59745-494-0_1

Liu YB, Tabashnik BE (1997) Experimental evidence that refuges delay insect adaptation to Bacillus thuringiensis. Proc R Soc B Biol Sci 264:605–610. https://doi.org/10.1098/rspb.1997.0086

Liu L, Zhan R, Yang L et al (2012) Isolation and identification of *Metarhizium anisopliae* from *Chilo venosatus* (Lepidoptera: Pyralidae) cadaver. Afr J Biotechnol 11:7609–7617

Long WH, Hensley SD (1972) Insect pests of sugar cane. Annu Rev Entomol 17:149–176

Lu Y, Wu K, Jiang Y et al (2012) Widespread adoption of Bt cotton and insecticide decrease promotes biocontrol services. Nature 487:362–365. https://doi.org/10.1038/nature11153

Luo ZM, Shen K, Huang YK et al (2014) The ecological niches of *Sesamia inferens* Walker and *Argyroploce schistaceana* Snellen and their interspecific competition on sugarcane. Chin J Appl Entomol 51:1046–1051

Ma S, Karkee M, Scharf PA, Zhang Q (2014) Sugarcane harvester technology: a critical overview. Appl Eng Agric 30:727–739. https://doi.org/10.13031/aea.30.10696

Mahon RJ, Downes SJ, James B (2012) Vip3A resistance alleles exist at high levels in australian targets before release of cotton expressing this toxin. PLoS ONE 7:e39192. https://doi.org/10.1371/journal.pone.0039192

Manickavasagam M, Ganapathi A, Anbazhagan VR et al (2004) Agrobacterium-mediated genetic transformation and development of herbicide-resistant sugarcane (Saccharum species hybrids) using axillary buds. Plant Cell Rep 23:134–143. https://doi.org/10.1007/s00299-004-0794-y

Marvier M, Mccreedy C, Regetz J et al (2007) A meta-analysis of effects of bt cotton and maize on nontarget invertebrates. Science 316:1475–1477. https://doi.org/10.1126/science.1139208

Mayavan S, Subramanyam K, Arun M et al (2013) Agrobacterium tumefaciens-mediated in planta seed transformation strategy in sugarcane. Plant Cell Rep 32:1557–1574. https://doi.org/10.1007/s00299-013-1467-5

Mayavan S, Subramanyam K, Jaganath B et al (2015) Agrobacterium-mediated in planta genetic transformation of sugarcane setts. Plant Cell Rep 34:1835–1848. https://doi.org/10.1007/s00299-015-1831-8

Mcelroy D, Blowers AD, Jenes B et al (1991) Construction of expression vectors based on the rice actin 1 (Act1) 5′region for use in monocot transformation. Mol Gen Genet 231:150–160. https://doi.org/10.1007/BF00293832

Mchughen A (2012) Regulation of agricultural biotechnology: The United States and Canada. Springer, Netherlands

McQualter RB, Dale JL, Harding RM (2004) Production and evaluation of transgenic sugarcane containing a Fiji disease virus (FDV) genome segment S9-derived synthetic resistance gene. Crop Pasture Sci 55:139–145. https://doi.org/10.1071/ar03131

Meagher RL, Smith JW, Johnson KJR (1994) Insecticidal management of *Eoreuma Loftini* (Lepidoptera: Pyralidae) on texas sugarcane : a critical review. J Econ Entomol 87:1332–1344. https://doi.org/10.1093/jee/87.5.1332

Meagher RL, Smith JW, Browning HW et al (1998) Sugarcane stem borers and their parasites in southern Texas. Environ Entomol 27:759–766. https://doi.org/10.1093/ee/27.3.759

Medberry SL, Olszewski LNE (1992) The Commelina yellow mottle virus promoter is a strong promoter in vascular and reproductive tissues. Plant Cell 4:185–192. https://doi.org/10.1105/tpc.4.2.185

Meena MR, Kumar R, Chinnaswamy A et al (2020) Current breeding and genomic approaches to enhance the cane and sugar productivity under abiotic stress conditions. Biotech 10:1–18. https://doi.org/10.1007/s13205-020-02416-w

Miller JD (2008) Mycotoxins in small grains and maize: old problems, new challenges. Food Addit Contam 25:219–230. https://doi.org/10.1080/02652030701744520

Milligan SB, Balzarini M, White WH (2003) Broad-sense heritabilities, genetic correlations, and selection indices for sugarcane borer resistance and their relation to yield loss. Crop Sci 43:1729–1735. https://doi.org/10.2135/cropsci2003.1729

Miyasono M, Inagaki S, Yamamoto M et al (1994) Enhancement of δ-endotoxin activity by toxin-free spore of *Bacillus thuringiensis* against the diamondback moth, *Plutella xylostella*. J Invertebr Pathol 63:111–112. https://doi.org/10.1006/JIPA.1994.1021

Molinari HBC, Marur CJ, Daros E et al (2010) Evaluation of the stress-inducible production of proline in transgenic sugarcane (*Saccharum* spp.): osmotic adjustment, chlorophyll fluorescence and oxidative stress. Physiol Plant 130:218–229. https://doi.org/10.1111/j.1399-3054.2007.00909.x

Molter A, Bezerra JIM, Rafikova E, et al (2023) Dynamics and biological control of the sugarcane borer with two parasitoids. Ecol Modell , Elsevier, vol. 481(C). https://doi.org/10.1016/j.ecolmodel.2023.110371

Moyle RL, Birch RG (2013) Sugarcane loading stem gene promoters drive transgene expression preferentially in the stem. Plant Mol Biol 82:51–58. https://doi.org/10.1007/s11103-013-0034-3

Mudge SR, Osabe K, Casu RE et al (2009) Efficient silencing of reporter transgenes coupled to known functional promoters in sugarcane, a highly polyploid crop species. Planta 229:549–558. https://doi.org/10.1007/s00425-008-0852-8

Mudge SR, Basnayake SWV, Moyle RL et al (2013) Mature-stem expression of a silencing-resistant sucrose isomerase gene drives isomaltulose accumulation to high levels in sugarcane. Plant Biotechnol J 11:502–509. https://doi.org/10.1111/pbi.12038

Nag SK, Raikwar MK (2011) Persistent organochlorine pesticide residues in animal feed. Environ Monit Assess 174:327–335. https://doi.org/10.1007/s10661-010-1460-1

Nagarkatti S, Nair KR (1973) The influence of wild and cultivated Gramineae and Cyperaceae on populations of sugarcane borers and their parasites in North India. Entomophaga 18:419–430. https://doi.org/10.1007/BF02371019

Naranjo SE (2011) Impacts of Bt transgenic cotton on integrated pest management. J Agric Food Chem 59:5842–5851. https://doi.org/10.1021/jf102939c

Naranjo SE, Ruberson JR, Sharma HC, et al (2008) The Present and future role of insect-resistant genetically modified cotton in ipM. In: Romeis J, Shelton AM, Kennedy GG. (eds) Integration of insect-resistant genetically modified crops within ipm programs. Progress in Biological Control, vol 5. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-8373-0_6

Narasimhan S, Partho PD, Kannan S (2001) Pheromone technology and management of sugarcane pest chilo infuscatellus snell. The early shoot borer: a case study. In: Upadhyay RK, Mukerji KG, Chamola BP (eds) Biocontrol potential and its exploitation in sustainable agriculture. Springer, Boston, MA. https://doi.org/10.1007/978-1-4615-1377-3_12

Negm AA, Hensley SD (1967) The relationship of arthropod predators to crop damage inflicted by the sugarcane borer. J Econ Entomol 60:1503–1506. https://doi.org/10.1093/jee/60.6.1503

Negm AA, Hensley SD (1969) Evaluation of certain biological control agents of the sugarcane borer in Louisiana. J Econ Entomol 62:1008–1013. https://doi.org/10.1093/jee/62.5.1008

Nesbitt BF, Beevor PS, Cork A et al (1986) The female sex pheromone of sugarcane stalk borer, *Chilo auricilius* identification of four components and field tests. J Chem Ecol 12:1377–1388. https://doi.org/10.1007/BF01012357

Neupane FP (1990) Status and control of *Chilo* spp. on cereal crops in Southern Asia. Int J Trop Insect Sci 11:501–534. https://doi.org/10.1017/S174275840002107X

Ngwuta A, Ajala S, Obi I et al (2015) Selection of maize genotypes resistant to pink stem borer and sugarcane borer. J Agric Sci and Technol A 5:14–182. https://doi.org/10.17266/2161-6256/2015.03.003

Nibouche S, Tibère R (2010) Genotypic variation of resistance to the spotted stalk borer *Chilo sacchariphagus* (Bojer) in sugarcane: evidence of two distinct resistance mechanisms. Plant Breed 128:74–77. https://doi.org/10.1111/j.1439-0523.2008.01554.x

Nibouche S, Tibère R, Costet L (2012) The use of *Erianthus arundinaceus* as a trap crop for the stem borer *Chilo sacchariphagus* reduces yield losses in sugarcane: preliminary results. Crop Prot 42:10–15. https://doi.org/10.1016/j.cropro.2012.06.003

Nibouche S, Tibère R, Costet L (2019) *Erianthus arundinaceus* as a trap crop for the sugarcane stem borer *Chilo sacchariphagus* : Field validation and disease risk assessment. Crop Prot 124:104877. https://doi.org/10.1016/j.cropro.2019.104877

Nikpay A, Kord H, Goebel FR et al (2014) Assessment of natural parasitism of sugarcane moth borers Sesamia spp. by *Telenomus busseolae*. Sugar Tech 16:325–328. https://doi.org/10.1007/s12355-013-0277-y

Nikpay A, Soleyman-Nejadian E, Goldasteh S et al (2015) Response of sugarcane and sugarcane stalk borers *Sesamia* spp. (Lepidoptera: Noctuidae) to calcium silicate fertilization. Neotrop Entomol 44:498–503. https://doi.org/10.1007/s13744-015-0298-1

Nikpay A, Nejadian ES, Goldasteh S et al (2017) Efficacy of silicon formulations on sugarcane stalk borers, quality characteristics and parasitism rate on five commercial varieties. Proc Natl Acad Sci India Sect B-Biol Sci 87:289–297. https://doi.org/10.1007/s40011-015-0596-8

Nutt KA, Allsopp P, Geijskes RJ et al (2001) Canegrub resistant sugarcane. Aust Soc Sugar Cane Technol. https://www.cabidigitallibrary.org/doi/full/10.5555/20023165649

Okamoto K, Tabei R, Fukushima M et al (1999) Seasonal changes in infestation level of sugarcane by the pink borer, *Sesamia inferens* (Lepidoptera: Noctuidae), in relation to a parasitoid, *Cotesia flavipes* (Hymenoptera: Braconidae), on Okinawa island. Appl Entomol Zool 34:429–434. https://doi.org/10.1303/AEZ.34.429

Omkar (2018) Pests and their management. Springer, Singapore. https://doi.org/10.1007/978-981-10-8687-8

Padgette SR, Kolacz KH, Delannay X et al (1995) Development, identification, and characterization of a glyphosate-tolerant soybean line. Crop Sci 35:1451–1461. https://doi.org/10.2135/cropsci1995.0011183X003500050032x

Paolino AR, Gassmann AJ (2017) Assessment of inheritance and fitness costs associated with field-evolved resistance to *Cry3Bb1*

maize by western corn rootworm. Toxins 9:159. https://doi.org/10.3390/toxins9050159

Pardo-López L, Soberón M, Bravo A (2013) *Bacillus thuringiensis* insecticidal three-domain Cry toxins: mode of action, insect resistance and consequences for crop protection. Fems Microbiol Rev 37:3–22. https://doi.org/10.1111/j.1574-6976.2012.00341.x

Parra JRP, Botelho PSM, Pinto ADS (2014) Biological control of pests as a key component for sustainable sugarcane production. In: Luis Augusto Barbosa Cortez (Coord.). Sugarcane bioethanol-R&D for Productivity and Sustainability, São Paulo: Editora Edgard Blücher. https://doi.org/10.5151/BLUCHEROA-SUGARCANE-SUGARCANEBIOETHANOL_41

Peach C, Velten J (1991) Transgene expression variability (position effect) of CAT and GUS reporter genes driven by linked divergent T-DNA promoters. Plant Mol Biol 17:49–60. https://doi.org/10.1007/BF00036805

Penn HJ, Read QD (2023) Stem borer herbivory dependent on interactions of sugarcane variety, associated traits, and presence of prior borer damage. Pest Manag Sci. https://doi.org/10.1002/ps.7843

Peremarti A, Twyman RM, Gómez-Galera S et al (2010) Promoter diversity in multigene transformation. Plant Mol Biol 73:363–378. https://doi.org/10.1007/s11103-010-9628-1

Petrasovits LA, Zhao L, Mcqualter RB et al (2012) Enhanced poly-hydroxybutyrate production in transgenic sugarcane. Plant Biotechnol J 10:569–578. https://doi.org/10.1111/j.1467-7652.2012.00686.x

Poirier Y, Ventre G, Nawrath C (2000) High-frequency linkage of co-expressing T-DNA in transgenic *Arabidopsis thaliana* transformed by vacuum-infiltration of *Agrobacterium tumefaciens*. Theor Appl Genet 100:487–493. https://doi.org/10.1007/s001220050063

Posnock R (2016) Part 5. Renunciation 264–282. https://doi.org/10.4159/9780674089181-006

Prescott-Allen C, Prescott-Allen R (1986) First resource: wild species in the north american economy christine prescott-allen and robert prescott-Allen. Yale University Press, 92A Yale Station, New Haven, CT 06520. 1986. 529 pp. https://doi.org/10.2307/j.ctt211qvck

Qaiser H, Liu Y, Zhang A et al (2011) Variation of bacterial and fungal community structures in the rhizosphere of hybrid and standard rice cultivars and linkage to CO_2 flux. Fems Microbiol Ecol 78:116–128. https://doi.org/10.1111/j.1574-6941.2011.01128.x

Qi B, Fraser T, Mugford S et al (2004) Production of very long chain polyunsaturated omega-3 and omega-6 fatty acids in plants. Nat Biotechnol 22:739–745. https://doi.org/10.1038/nbt972

Qiao FB, Huang JK, Zhang CP et al (2016) The sustainability of the farm-level impact of bt cotton in China. J Agric Econ 67:602–618. https://doi.org/10.1111/1477-9552.12182

Qiao F, Huang J, Wang X (2017) Fifteen years of Bt cotton in China: results from household surveys. World Dev 98:351–359. https://doi.org/10.1016/j.worlddev.2017.05.006

Qin ZQ, Goebel FR, Li DW et al (2018) Occurrence of *Telenomus dignus* (Gahan) on the Sugarcane Borers, *Scirpophaga intacta* Snellen and *Chilo sacchariphagus* Bojer in Guangxi province, China. Sugar Tech 20:725–729. https://doi.org/10.1007/s12355-018-0612-4

Raman R (2017) The impact of genetically modified (GM) crops in modern agriculture: a review. GM Crop Food 8:195–208. https://doi.org/10.1080/21645698.2017.1413522

Ramasamy M, Mora V, Damaj MB et al (2018) A biolistic-based genetic transformation system applicable to a broad-range of sugarcane and energycane varieties. GM Crop Food 9:211–227. https://doi.org/10.1080/21645698.2018.1553836

Raybould A, Quemada H (2010) Bt crops and food security in developing countries: realised benefits, sustainable use and lowering

barriers to adoption. Food Secur 2:247–259. https://doi.org/10.1007/s12571-010-0066-3

Reagan TE, Mulcahy MM (2019) Interaction of cultural, biological, and varietal controls for management of stalk borers in Louisiana sugarcane. InSects 10:305. https://doi.org/10.3390/insects10090305

Reagan TE, Coburn G, Hensley SD (1972) Effects of mirex on the arthropod fauna of a louisiana sugarcane field. Environ Entomol 1:588–591. https://doi.org/10.1093/ee/1.5.588

Reay-Jones FPF, Showler AT, Reagan TE et al (2005) Integrated tactics for managing the mexican rice borer (Lepidoptera: Crambidae) in sugarcane. Environ Entomol 34:1558–1565. https://doi.org/10.1603/0046-225X-34.6.1558

Reis RR, da Cunha BADB, Martins PK et al (2014) Induced over-expression of *AtDREB2A* CA improves drought tolerance in sugarcane. Plant Sci 221–222:59–68. https://doi.org/10.1016/j.plantsci.2014.02.003

Riaz S, Nasir IA, Bhatti MU et al (2020) Resistance to *Chilo infuscatellus* (Lepidoptera: Pyraloidea) in transgenic lines of sugarcane expressing *Bacillus thuringiensis* derived *Vip3A* protein. Mol Biol Rep 47:2649–2658. https://doi.org/10.1007/s11033-020-05355-0

Robert GB et al (2010) Highly efficient, 5′-sequence-specific transgene silencing in a complex polyploid. Trop Plant Biol 3:88–97. https://doi.org/10.1007/s12042-010-9047-0

Rodriguez LM, Ottea JA, Reagan TE (2001) Selection, egg viability, and fecundity of the sugarcane borer (Lepidoptera: Crambidae) with tebufenozide. J Econ Entomol 294:1553–1557. https://doi.org/10.1603/0022-0493-94.6.1553

Roldán EL, Beuzelin JM, VanWeelden MT, Cherry RH (2020) Abundance of the sugarcane borer (Lepidoptera: Crambidae) and foraging ants (Hymenoptera: Formicidae) in sugarcane grown on organic and mineral soils in Florida. Environ Entomol 49:473–481. https://doi.org/10.1093/ee/nvaa015

Romeis J, Meissle M, Bigler F (2006) Transgenic crops expressing *Bacillus thuringiensis* toxins and biological control. Nat Biotechnol 24:63–71. https://doi.org/10.1038/nbt1180

Rossato JADS, Costa GHG, Madaleno LL et al (2013) Characterization and impact of the sugarcane borer on sugarcane yield and quality. Agron J 105:643–648. https://doi.org/10.2134/agronj2012.0309

Roush RT (1997) Bt-transgenic crops: just another pretty insecticide or a chance for a new start in resistance management? Pestic Sci 51:328–334. https://doi.org/10.1002/(SICI)1096-9063(199711)51:3%3c328::AID-PS650%3e3.0.CO;2-B

Rouwendal GJA, Mendes O, Wolbert EJH et al (1997) Enhanced expression in tobacco of the gene encoding green fluorescent protein by modification of its codon usage. Plant Mol Biol 33:989–999. https://doi.org/10.1023/A:1005740823703

Salgado LD, Wilson BE, Villegas JM et al (2022) Resistance to the sugarcane borer (Lepidoptera: Crambidae) in Louisiana sugarcane cultivars. Environ Entomol 51:196–203. https://doi.org/10.1093/ee/nvab118

Sallam MNS (2006) A review of sugarcane stem borers and their natural enemies in Asia and Indian ocean islands: an Australian perspective. Ann La Soc Entomol Fr 42:263–283. https://doi.org/10.1080/00379271.2006.10697459

Sanahuja G, Banakar R, Twyman RM et al (2011) *Bacillus thuringiensis*: a century of research, development and commercial applications. Plant Biotechnol J 9:283–300. https://doi.org/10.1111/j.1467-7652.2011.00595.x

Schenk PM, Sagi L, Remans T et al (1999) A promoter from sugarcane bacilliform badnavirus drives transgene expression in banana and other monocot and dicot plants. Plant Mol Biol 39:1221–1230. https://doi.org/10.1023/a:1006125229477

Schenk PM et al (2001) Promoters for pregenomic RNA of banana streak badnavirus are active for transgene expression in monocot

and dicot plants. Plant Mol Biol 47:399–412. https://doi.org/10.1023/a:1011680008868

Schexnayder HP, Reagan TE, Ring DR (2001) Sampling for the Sugarcane Borer (Lepidoptera: Crambidae) on Sugarcane in Louisiana. J Econ Entomol 94:766–771. https://doi.org/10.1603/0022-0493-94.3.766

Schnepf E, Crickmore N, Van Rie J et al (1998) *Bacillus thuringiensis* and its pesticidal crystal proteins. Microbiol Mol Biol Rev 62:775–806. https://doi.org/10.1128/MMBR.62.3.775-806.1998

Scott HD et al (1998) Premature Polyadenylation at multiple sites within a *Bacillus thuringiensis* toxin gene-coding region. Plant Physiol 117:1433–1443. https://doi.org/10.1104/pp.117.4.1433

Sétamou M, Bernal JS, Legaspi JC et al (2002) Evaluation of lectin-expressing transgenic sugarcane against stalkborers (Lepidoptera: Pyralidae): effects on life history parameters. J Econ Entomol 95:469–477. https://doi.org/10.1603/0022-0493-95.2.469

Shankar B, Thirtle C (2010) Pesticide productivity and transgenic cotton technology: the south african smallholder case. J Agric Econ 56:97–116. https://doi.org/10.1111/j.1477-9552.2005.tb00124.x

Sharon DT et al (2016) Bt resistance in Australian insect pest species. Curr Opin Insect Sci 15:78–83. https://doi.org/10.1016/j.cois.2016.04.002

Shaver TN, Brown HE, Williams HJ et al (1988) Components of female sex pheromone of *Eoreuma loftini* Dyar. J Chem Ecol 14:391–399. https://doi.org/10.1007/BF01022554

Shelton AM, Badenes-Perez FR (2006) Concepts and applications of trap cropping in pest management. Annu Rev Entomol 51:285–308. https://doi.org/10.1146/annurev.ento.51.110104.150959

Shelton AM, Nault BA (2004) Dead-end trap cropping: A technique to improve management of the diamondback moth, *Plutella xylostella* (Lepidoptera: Plutellidae). Crop Prot 23:497–503. https://doi.org/10.1016/j.cropro.2003.10.005

Showler AT (2016) Selected abiotic and biotic environmental stress factors affecting two economically important sugarcane stalk boring pests in the United States. Agronomy 6:10. https://doi.org/10.3390/agronomy6010010

Showler AT, Beuzelin JM, Reagan TE (2011) Alternate crop and weed host plant oviposition preferences by the Mexican rice borer (Lepidoptera: Crambidae). Crop Prot 30:895–901. https://doi.org/10.1016/j.cropro.2011.02.006

Sidhu JK (2013) Development of integrated pest management for sugarcane borer, *Diatraea saccharalis* in Louisiana rice. Dissertations, Louisiana State University. https://doi.org/10.31390/gradschool_dissertations.772

Singh V, Godara AK, Kumar P, Singh N (2015) Sugarcane growers' knowledge level about integrated pest management practices in Haryana. Agric Sci Dig 29:16–19

Singh G, Singh I, Taggar GK et al (2020) Introgression of productivity enhancing traits, resistance to pod borer and Phytopthora stem blight from *Cajanus scarabaeoides* to cultivated pigeonpea. Physiol Mol Biol Plants 26:1399–1410. https://doi.org/10.1007/s12298-020-00827-w

Singla-Pareek SL, Reddy MK, Sopory SK (2003) Genetic engineering of the glyoxalase pathway in tobacco leads to enhanced salinity tolerance. Proc Natl Acad Sci USA 100:14672–14677. https://doi.org/10.1073/pnas.2034667100

Sivasankaran P, Easwaramoorthy S, David H (1990) Pathogenicity and host range of Beauveria nr. bassiana, a fungal pathogen of Chilo infuscatellus Snellen. J Biol Control 4:48–51. https://doi.org/10.18311/JBC/1990/15336

Slater S, Mitsky TA, Houmiel KL et al (1999) Metabolic engineering of Arabidopsis and Brassica for poly(3-hydroxybutyrate-co-3-hydroxyvalerate) copolymer production. Nat Biotechnol 17:1011–1016. https://doi.org/10.1038/13711

Smaill RJ, Carnegie AJM (1979) The situation regarding Eldana borer (*E. saccharina* Walker) during 1978/79 and assessments of crop loss. In: Proc. S. Afr. Sugar Technol. Ass. pp 108–110

Solis MA, Metz MA (2016) An illustrated guide to the identification of the known species of diatraea guilding (Lepidoptera, Crambidae, Crambinae) based on genitalia. Zookeys 565:73–121

Souza GM, Berges H, Bocs S et al (2011) The sugarcane genome challenge: strategies for sequencing a highly complex genome. Trop Plant Biol 4:145–156. https://doi.org/10.1007/s12042-011-9079-0

Srikanth J, Salin KP, Kurup NK, Bai KS (2009) Assessment of the tachinid *Sturmiopsis inferens* as a natural and applied biological control agent of sugarcane shoot borer (*Chilo infuscatellus*) in southern India. Sugar Tech 11:51–59. https://doi.org/10.1007/s12355-009-0009-5

Srikanth J, Subramonian N, Premachandran MN (2011) Advances in transgenic research for insect resistance in sugarcane. Trop Plant Biol 4:52–61. https://doi.org/10.1007/s12042-011-9077-2

Subramanian A, Qaim M (2009) Village-wide effects of agricultural biotechnology: the case of bt cotton in India. World Dev 37:256–267

Sweet LSKPM (1994) Management of *Sesamia grisescens* walker (Lep.: Noctuidae), a sugar-cane borer in Papua New Guinea. Crop Prot 13:488–493

Tabashnik BE, Brévault T, Carrière Y (2013) Insect resistance to Bt crops: lessons from the first billion acres. Nat Biotechnol 31:510–521

Tan XP, Lv D, Hong H (2003) Integrated control of insect pests and diseases of sugarcane in Panxi district. Sugarcane 2:20–25

Taparia Y, Fouad WM, Gallo M et al (2012a) Rapid production of transgenic sugarcane with the introduction of simple loci following biolistic transfer of a minimal expression cassette and direct embryogenesis. Vitr Cell Dev Biol–plant 48:15–22. https://doi.org/10.1007/s11627-011-9389-9

Taparia Y, Gallo M, Altpeter F (2012b) Comparison of direct and indirect embryogenesis protocols, biolistic gene transfer and selection parameters for efficient genetic transformation of sugarcane. Plant Cell Tissue Organ Cult 111:131–141. https://doi.org/10.1007/s11240-012-0177-y

Technol SC (2001a) Feeding potential of predatory spiders on sugarcane pests International Society of Sugar Cane Technologists. Proceedings of the XXIV Congress, Brisbane, Australia, 17–21 September 2001. Volume 2. 2001pp.408–409

Technol SC (2001b) A new approach for control of *Diatraea saccharalis* (lepidoptera : crambidae) through the expression of an insecticidal cryia (b) protein in transgenic sugarcane international society of sugar cane technologists.proceedings of the xxiv congress, brisbane, Australia, 17–21 September 2001. Volume 2 2001pp.331–336

Temerak SA, Negm AA (2009) Impact and differential effect of certain biomortality factors on the eggs and newly-hatched larvae of the pink borer, *Sesamia cretica* Led. (Lep., Noctuidae) on two sugarcane varieties. J Appl Entomol 88:313–318. https://doi.org/10.1111/j.1439-0418.1979.tb02507.x

Theo R, Gustav B (2013) Toxicity to *Eldana saccharina* of a recombinant *Gluconacetobacter diazotrophicus* strain carrying a truncated *Bacillus thuringiensis cry1Ac* gene. African J Microbiol Res 7:1207–1214. https://doi.org/10.5897/AJMR12.867

Thomson JM, Lafayette PR, Schmidt MA et al (2002) Artificial geneclusters engineered into plants using a vector system based on intron-and intein-encoded endonucleases. Vitr Cell Dev Biol Plant 38:537–542. https://doi.org/10.1079/IVP2002329

Tomaz AC, Coutinho AE, Soares BO et al (2017) Assessing resistance of sugarcane varieties to sugarcane borer *Diatraea saccharalis* Fab. (Lepidoptera: Crambidae). Bull Entomol Res 108:547–555. https://doi.org/10.1017/S0007485317001183

Trials F (1980) Components of the sex pheromone of the female sugar cane borer, *Chilo sacchariphagus*. J Chem Ecol 6:385–394. https://doi.org/10.1007/BF01402916

Triana MF, França PHB, Queiroz AFO et al (2020) Morphological, chemical and electrophysiological investigations of *Telchin licus* (Lepidoptera: Castniidae). PLoS ONE 15:e0231689. https://doi.org/10.1371/journal.pone.0231689

Tzafrir I, Torbert KA, Lockhart BEL et al (1998) The sugarcane bacilliform badnavirus promoter is active in both monocots and dicots. Plant Mol Biol 38:347–356. https://doi.org/10.1023/a:1006075415686

Unnithan GC et al (2015) Cross-resistance to toxins used in pyramided Bt crops and resistance to Bt sprays in *Helicoverpa zea*. J Invertebr Pathol 132:149–156. https://doi.org/10.1016/j.jip.2015.10.003

Usha BH et al (2011) Effect of handling and processing on pesticide residues in food-a review. J Food Sci Technol 51:201–220. https://doi.org/10.1007/s13197-011-0499-5

Van Rensburg JBJ, Walters MC, Giliomee JH (1985) Geographical variation in the seasonal moth flight activity of the maize stalk borer, *Busseola fusca* (Fuller), in South Africa. South Afr J Plant Soil 2:123–126. https://doi.org/10.1080/02571862.1985.10634151

Van RJ, Jansens S, Hfte H et al (1990) Receptors on the brush border membrane of the insect midgut as determinants of the specificity of *Bacillus thuringiensis* delta-endotoxins. Febs J 56:1378. https://doi.org/10.1128/aem.56.5.1378-1385.1990

van der Christell C et al (2013) In vitro selection of transgenic sugarcane callus utilizing a plant gene encoding a mutant form of acetolactate synthase. Vitr Cell Dev Biol Plant 49:198–206. https://doi.org/10.1007/s11627-013-9493-0

Vanweelden MT, Wilson BE, Beuzelin JM et al (2015) Yield response to mexican rice borer (Lepidoptera: Crambidae) injury in bioenergy and conventional sugarcane and sorghum. J Econ Entomol 108:2296–2304. https://doi.org/10.1093/jee/tov190

Vargas G, Lastra LA, Solís MA (2013) First record of *Diatraea tabernella* (Lepidoptera: Crambidae) in the caucariver valley of Colombia. Florida Entomol 96:1198–1201. https://doi.org/10.1653/024.096.0367

Vargas G, Gomez LA, Michaud JP (2015) Sugarcane stem borers of the colombian cauca river valley: current pest status, biology, and control. Florida Entomol 98:728–735. https://doi.org/10.1653/024.098.0249

Varma A, Tandan BK (1996) Pathogenicity of Three entomogenous fungi against insect pests of sugarcane. J Biol Control 10:87–91. https://doi.org/10.18641/JBC/10/1

Vejar-Cota G, Rodríguez-del-Bosque LA, Sahagún D (2008) Economic and ecological impacts of hand removing dead hearts caused by *Diatraea considerate* (Lepidoptera: Crambidae) on Sugarcane in Mexico. Southwest Entomol 33:157–159. https://doi.org/10.3958/0147-1724-33.2.157

Venugopal PD, Dively GP (2017) Climate change, transgenic corn adoption and field-evolved resistance in corn earworm. R Soc Open Sci 4:170210. https://doi.org/10.1098/rsos.170210

Vickers JE, Grof CPL, Bonnett GD et al (2005a) Effects of tissue culture, biolistic transformation, and introduction of *PPO* and *SPS* gene constructs on performance of sugarcane clones in the field. Aust J Agric Res 56:449–456. https://doi.org/10.1071/AR04159

Vickers JE, Grof CPL, Bonnett GD et al (2005b) Overexpression of polyphenol oxidase in transgenic sugarcane results in darker juice and raw sugar. Crop Sci 45:354–362. https://doi.org/10.2135/cropsci2005.0354

Vinogradov AE (2003) DNA helix: the importance of being GC-rich. Nucleic Acids Res 3:1838–1844. https://doi.org/10.1093/nar/gkg296

Wang WZ, Yang BP, Feng XY et al (2017) Development and characterization of transgenic sugarcane with insect resistance and

herbicide tolerance. Front Plant Sci 8:1–10. https://doi.org/10.3389/fpls.2017.01535

Wartha CA, de Aguiar PN, Tomaz AC et al (2022) Classification of sugarcane genotypes susceptible and resistant to the initial attack of sugarcane borer *Diatraea saccharalis* using epicuticular wax composition. Phytochemistry 199:113175. https://doi.org/10.1016/j.phytochem.2022.113175

Waterhouse DE (2007) The major arthropod pests and weeds of agriculture in Southeast Asia: distribution, importance and origin. Energy Policy 35:5953–5957

Way M, Goebel F-R, Conlong D (2004) Trapping *Chilo sacchariphagus* (Lepidotera: Crambidae) in sugarcane using synthetic pheromones. Proc Annu Congr South African Sugar Technol Assoc 78:291–295

Wei H, Wang ML, Moore PH, Albert HH (2003) Comparative expression analysis of two sugarcane polyubiquitin promoters and flanking sequences in transgenic plants. J Plant Physiol 160:1241–1251. https://doi.org/10.1078/0176-1617-01086

Wei JL, Huang CH, Pan XH et al (2012) Developmental threshold temperature and effective accumulated temperature of *Tryporyza intacta* pupa in sugarcane. China Plant Prot 32:38–40

Wei JL, Huang CH, Shang XK et al (2014) Biological studies on pupae, adults and eggs of *Tryporyza intacta* in sugarcane. Sugar Crop China 3:23–24

Wei Y, Wu S, Yang Y, Wu Y (2017) Baseline susceptibility of field populations of *Helicoverpa armigera* to *Bacillus thuringiensis* Vip3Aa toxin and lack of cross-resistance between *Vip3Aa* and *Cry* toxins. Toxins (basel) 9:127. https://doi.org/10.3390/toxins9040127

Wei Z, Yanhui L, Wopke VDW et al (2018) Multidecadal, county-level analysis of the effects of land use, Bt cotton, and weather on cotton pests in China. Proc Natl Acad Sci 115:201721436. https://doi.org/10.1073/pnas.1721436115

Weng LX, Deng H, Xu JL et al (2006) Regeneration of sugarcane elite breeding lines and engineering of stem borer resistance. Pest Manag Sci 62:178–187. https://doi.org/10.1002/ps.1144

Weng LX, Deng HH, Xu JL et al (2011) Transgenic sugarcane plants expressing high levels of modified *cry1Ac* provide effective control against stem borers in field trials. Transgenic Res 20:759–772. https://doi.org/10.1007/s11248-010-9456-8

White WH, Miller JD, Milligan SB et al (2001) Inheritance of sugarcane borer resistance in sugarcane derived from two measures of insect damage. Crop Sci 41:1706–1710. https://doi.org/10.2135/cropsci2001.1706

White WH, Viator RP, Dufrene EO et al (2008) Re-evaluation of sugarcane borer (Lepidoptera: Crambidae) bioeconomics in Louisiana. Crop Prot 27:1256–1261. https://doi.org/10.1016/j.cropro.2008.03.011

Wilson BE, Hardy TN, Beuzelin JM et al (2015a) Expansion of the mexican rice borer (Lepidoptera: Crambidae) into rice and sugarcane in Louisiana. Environ Entomol 44:757–766. https://doi.org/10.1093/ee/nvv016

Wilson BE, Vanweelden MT, Beuzelin JM et al (2015b) A relative resistance ratio for evaluation of stem borer susceptibility among sugarcane cultivars. J Econ Entomol 108:1363–1370. https://doi.org/10.1093/jee/tov076

Wilson BE, Vanweelden MT, Beuzelin JM et al (2017) Efficacy of insect growth regulators and diamide insecticides for control of stem borers (Lepidoptera: Crambidae) in sugarcane. J Econ Entomol 110:453–463. https://doi.org/10.1093/jee/tow305

Wilson BE, Salgado LD, Villegas JM (2022) Optimizing chemical control for *Diatraea saccharalis* (Lepidoptera: Crambidae) in sugarcane. Crop Prot 152:105843. https://doi.org/10.1016/j.cropro.2021.105843

Wu KM, Lu YH, Feng HQ et al (2008) Suppression of cotton bollworm in multiple crops in China in areas with Bt toxin-containing cotton. Science 321:1676–1678. https://doi.org/10.1126/science.1160550

Wu X, Huang F, Leonard BR, Ghimire M (2010) Growth and development of *Bacillus thuringiensis Cry1Ab*-susceptible and *Cry1Ab*-resistant sugarcane borer on diet and conventional maize plants. Entomol Exp Appl 133:199–207. https://doi.org/10.1111/j.1570-7458.2009.00919.x

Xiao Y, Wu K (2019) Recent progress on the interaction between insects and *Bacillus thuringiensis* crops. Philos Trans R Soc B Biol Sci 374:20180316. https://doi.org/10.1098/rstb.2018.0316

Xie JJ, Yang JX, Luo QW et al (2020) Survey of sugarcane pests in Xianggui sugarcane area and countermeasures of pest control. Plant Dis Pests 11:13–16

Ye J, Yang YY, Xu LP et al (2016) Economic impact of stem borer-resistant genetically modified sugarcane in Guangxi and Yunnan provinces of China. Sugar Tech 18:1–9. https://doi.org/10.1007/s12355-015-0414-x

Yoseph A, Desmond C (2009) Phytophagous insect pests of sugarcane in Ethipian estates. Proc South Afr Sugarcane Technol Assoc 82:144–154

Young GR, Kuniata LS (1992) Life history and biology of *Sesamia grisescens* walker (Lepidoptera: Noctuidae), a sugarcane borer in Papua New Guinea. Aust J Entomol 31:199–203. https://doi.org/10.1111/j.1440-6055.1992.tb00483.x

Yu X, Li X, Zhao X et al (2011) Tissue culture-induced genomic alteration in maize (*Zea mays*) inbred lines and F1 hybrids. Ann Appl Biol 158:237–247. https://doi.org/10.1111/j.1744-7348.2011.00458.x

Zale J, Jung JH, Kim JY et al (2016) Metabolic engineering of sugarcane to accumulate energy-dense triacylglycerols in vegetative biomass. Plant Biotechnol J 14:661–669. https://doi.org/10.1111/pbi.12411

Zeevi V, Liang Z, Arieli U, Tzfira T (2012) Zinc finger nuclease and homing endonuclease-mediated assembly of multigene plant transformation vectors. Plant Physiol 158:132–144. https://doi.org/10.1104/pp.111.184374

Zeng T (2004) Control of insect pests in sugarcane: IPM approaches in China. Sugar Tech 6:273–279. https://doi.org/10.1007/BF02942508

Zhang LH, Xu JL, Birch RG (1999) Engineered detoxification confers resistance against a pathogenic bacterium. Nat Biotechnol 17:1021–1024. https://doi.org/10.1038/13721

Zhang XQ, Liang YJ, Qin ZQ et al (2019b) Application of multi-rotor unmanned aerial vehicle application in management of stem borer (lepidoptera) in sugarcane. Sugar Tech 21:1–6. https://doi.org/10.1007/s12355-018-0695-y

Zhang RY, Li WF, Yin J et al (2019a) Control effects of a new sex pheromone trap and biological agents on *Sesamia inferens* Walker and *Argyroploce schistaceana* (Snellen). Agric Biotechnol 5. https://doi.org/10.5555/20023165649

Zhangsun D, Luo S, Chen R, Tang K (2007) Improved agrobacterium-mediated genetic transformation of GNA transgenic sugarcane. Biologia 62:386–393. https://doi.org/10.2478/s11756-007-0096-2

Zhao JZ, Cao J, Li Y et al (2003) Transgenic plants expressing two *Bacillus thuringiensis* toxins delay insect resistance evolution. Nat Biotechnol 21:1493. https://doi.org/10.1038/nbt907

Zhi WW, Yang BP, Feng XY et al (2017) Development and characterization of transgenic sugarcane with insect resistance and herbicide tolerance. Front Plant Sci 8:1535. https://doi.org/10.3389/fpls.2017.01535

Zhou D, Xu L, Gao S et al (2016) *Cry1Ac* transgenic sugarcane does not affect the diversity of microbial communities and has no significant effect on enzyme activities in rhizosphere soil within one crop season. Front Plant Sci 7:1–16. https://doi.org/10.3389/fpls.2016.00265

Zhou D, Liu X, Gao S et al (2018) Foreign *cry1Ac* gene integration and endogenous borer stress-related genes synergistically improve insect resistance in sugarcane. BMC Plant Biol 18:1–14. https://doi.org/10.1186/s12870-018-1536-6

Zhu YJ, Mccafferty H, Osterman G et al (2011) Genetic transformation with untranslatable coat protein gene of sugarcane yellow leaf virus reduces virus titers in sugarcane. Transgenic Res 20:503. https://doi.org/10.1007/s11248-010-9432-3