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Review

Efficacy of Integrated Pest Management Strategies against Top Borer, *Scirpophaga exerptalis* (Crambidae: Lepidoptera) in Sugarcane Cultivation

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Abstract: Top borer (*Scirpophaga excerptalis* Family: *Crambidae;* Order: *Lepidoptera*) is one of the most damaging pests in sugarcane cultivation, leading to substantial losses in yield and crop quality. This study investigates the effectiveness of various Integrated Pest Management (IPM) strategies for controlling top borer in sugarcane cultivation, a crop vital to agricultural economies. A comparative evaluation was conducted on cultural, biological, chemical, and precision-based approaches to determine their sustainability and economic viability. Results indicate that conventional chemical control reduced pest populations by 65% and increased yields by 10%, while biological control achieved a 20% reduction with a 5% yield improvement. Resistant sugarcane varieties performed better, suppressing infestations by 75% and enhancing yields by 13%. The highest impact was observed with IPM systems combining Effective Microorganism (EM) based bio-pesticides, manual labor, selective pesticide use, and real-time monitoring, which achieved a 90% reduction in pest populations and a 20% increase in yield. Furthermore, precision agriculture technologies such as drones, remote sensing, and targeted spraying enhanced pest suppression up to 95%, resulting in a 35% yield increase and reducing harvest losses to below 10%. These outcomes highlight the superiority of precision-supported IPM as a sustainable and effective approach for managing top borer infestations in sugarcane farming.

Keywords: integrated pest management; *scirpophaga excerptalis*; sugarcane; precision agriculture; yield improvement

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1. Introduction

Sugarcane (*Saccharum officinarum* Family: Poaceae Order: Poales) is one of the most important and widely cultivated crops across the globe (Singh et al., 2025). Sugarcane, whose history can be

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traced back to the very dawn of time, has been a decisive factor in the shaping of different societies, cultures, and the way the world interconnects. Sugarcane is regarded as the most practical crop for sucrose extraction and the bioenergy and sugar industries are the main consumers of the sugar content that the cane provides. Sugarcane farming is done in the areas of the world that lie within the tropics and subtropics, where the weather is just right to promote the growth and maturation of the plant (Msomba et al., 2024).

As far as the economic impact is concerned, sugarcane is one of the main tools that has the potential of driving both the agricultural and the industrial sectors of many countries. Besides sugar, it is a source of different ecofriendly products, including biofuels and ethanol. The industries created to supply the new demand create jobs and pay millions of farmers, workers, and business owners while being purveyors of rural development and infrastructure (Gasparatos et al., 2022; Ncoyini et al., 2022).

The main reason for the greatest losses in sugarcane growing is the top borer (*Scirpophaga excerptalis*) infestation. The insect pest, which is a member of the *Crambidae* family, scalps on the internal tissues of the stalk, and this action not only weakens the plants but lowers the yields at the same time (Nikpay et al., 2023; Souza et al., 2023). Most of the damage is done to the physical structure of the plant during larval feeding, which reduces the sugar content of the crop. This situation results in the farmer being heavily dependent on labour-intensive and pesticide-based control methods to manage the pest, thus leading to increased production costs and the occurrence of serious environmental risks (Mehdi et al., 2025).

Despite the fact that chemical methods and the application of cultural techniques are the major ways to address the problem, to a large extent, such ways are practically ineffective. Over-reliance on pesticides also plays a role in the resistance development, which in turn, poses health, ecological imbalance, and other issues. There is still a lack of well-thought-out, long-lasting, and locally-adjustable management methods that feature biological, cultural, and ecological approaches in Malaysia and other sugarcane producing regions. This void accentuates the demand for the assessment and the formulation of effective Integrated Pest Management (IPM) solutions that not only efficiently kill the top borer but also ensure yield and farmer livelihoods (Zafar, 2024).

2. Biology and Behaviour of the Top Borer

The sugarcane top borer (*S. excerptalis*) is considered to be among the most harmful pests of sugarcane growing which can lead to the loss of yield by 20-30% besides the lowering of juice quality caused by the decrease in sucrose accumulation. Moreover, larval feeding inside the stalk not only rots the cane but also facilitates the infection with the disease thus making the detection and the treatment of the pest more difficult so that the pest forms a continual problem for production (Nurindah. et al., 2023; Kranthi and Tiwari et al., 2023)

The pest’s biology and behaviour have been studied extensively, with reports highlighting its four developmental stages (egg, larva, pupa, and adult) and distinct feeding habits. Female Top borer lay 300–400 eggs per life cycle, typically on the undersides of leaves, and the top bore larva stage possess chewing mouthparts directly into stalks, causing “dead hearts” in young canes and stalk breakage in mature crops. Nocturnal activity of adults and seasonal migration patterns, often linked with monsoon winds, further contribute to rapid spread across regions. Prior research has established the importance of cultural practices (for example stubble removal, deep ploughing) and biological control agents in disrupting this cycle, yet their effectiveness varies significantly with environmental conditions and pest pressure (Msomba et al., 2024; More, 2025)

Despite this knowledge, gaps remain in understanding the influence of climate variability on borer phenology, the role of crop canopy density in pest colonization, and the interaction of top borer populations with natural enemies. Furthermore, most existing studies have evaluated control methods in isolation rather than integrating biological insights into adaptive management frameworks.

Accordingly, this section synthesizes the key biological and behavioural traits of *S. excerptalis*, identifies how these traits contribute to its pest status, and outlines critical knowledge gaps that can guide the development of more precise and sustainable IPM strategies. The summary shown in Table 1 outlines the different life cycle stages of the sugarcane top borer along with the types of crop damage linked to each stage, thus revealing the pest's destructive capacity and the resulting impact for management practices (Kristini et al., 2023; Baitha et al., 2022; Priya et al., 2023).

Figure 1 proves the seasonal presence and reproduction of the top borer in sugarcane fields in Malaysia, showing that the pest coming is most of the time at the same time as the monsoon season Fig. 1(a) and how females deposit eggs in clusters on the underside of sugarcane leaves Fig. 1(b). Figure 2 depicts the visible effects of caterpillar feeding and subsequent control practices, where larval feeding damages the leaves and serves as an early indicator of infestation Fig. 2(a), while manual removal of larvae is shown as one of the direct interventions employed in pest management Fig. 2(b). Together, these figures emphasize both the ecological patterns of infestation and the practical methods used by farmers to moderate crop losses.

Table 1. Life cycle stages of the sugarcane top borer (*S. excerptalis*) and associated crop damage.

Stage	Duration (approx.)	Key Behaviour	Crop Symptoms / Damage
Egg	5–7 days	Female lays 300–400 eggs in clusters, usually on the underside of sugarcane leaves	Early detection possible; eggs often covered with white scales
Larva	21–27 days	Bores into midrib and stalk, feeds internally through successive instars	"Dead heart" in young canes; tunnelling weakens stalks; reduced sucrose accumulation
Pupa	7–10 days	Pupation inside stem or plant debris, protected in silken cocoon	No visible external symptoms: hidden stage complicates control
Adult (moth)	4–6 days	Nocturnal activity, females release pheromones to attract males; long-distance dispersal with wind currents	Fresh infestations in new fields; egg clusters on leaves mark onset of cycle


(**a**) (**b**)

Figure 1. Seasonal occurrence and reproductive activity of top borer pest in Malaysian sugarcane fields: (**a**) Top borer pest arrival and monsoon season in Malaysian data; (**b**) Top borer pest laying eggs underneath sugarcane leaves.

(**a**) (**b**)

Figure 2. Effects of top borer caterpillar feeding and manual intervention in sugarcane pest management: (**a**) Impact of caterpillar feeding on sugarcane leaves, indicative of infestation; (**b**) Manual removal of top borer larvae during pest management efforts.

3. Integrated Pest Management for Sugarcane Top Borer Control

The top borer (*S. excerptalis*) continues to be one of the most devastating pests of sugarcane, causing not only large yield losses but also an increase in production costs due to pesticide use and manpower. There is more than one control measures, however, the main problem that comes with the use of pesticides is that the environment gets polluted, the pests become more resistant, and the farmers have to spend more money. This problem raises the issue of integrated Pest Management (IPM) as a combined strategy that has the potential to minimize pest damage, save money, and help the environment (Li et al., 2024).

Such preventive strategies are most effective when combined with the use of resistant crop varieties and the adoption of sound agronomic practices. In addition, decision-making guided by economic threshold levels enables timely interventions which substantially reducing reliance on unnecessary pesticide applications. Furthermore, the integration of multiple control approaches, including biological, cultural, and chemical methods, minimizes ecological disturbance by distributing selective pressure across diverse mechanisms rather than concentrating it on a single intervention. This integrated approach enhances system resilience, preserves beneficial organisms, and supports the long-term sustainability of pest management programs. Nevertheless, current research reveals that local integration of these methods, particularly in the Malaysian sugarcane fields, remains limited (Nurul Asyiqin and Ong, 2024), whereas individually strategies have been significantly researched. This discrepancy highlights the importance of identifying, analyzing, and combining locally applicable cultural, biological, and ecological methods into a comprehensive IPM framework (Zafar, 2024).

Without a doubt, cultural practices lie at the core of IPM as they interfere directly with the pest survival and reproduction. The implementation of sanitation, for example removal of weeds and crop residues after harvest, serves the purpose of cutting the breeding and relocation sites (Tomar and Singh, 2024). Exposure of the pupae to harsh conditions via deep ploughing lowers their survival rate, while removal of the stubble decreases the areas for egg-laying. Quite often, caterpillars that are just about to drop to the soil and burrow, when they are disturbed, so by getting rid of the stubble and keeping the fields clean, hiding places are significantly decreased, thus pest activity is interrupted.

Crop diversification is also a measure that can lead to less top borer infestation. Sugarcane rotation with non-host crops disrupts the life cycle of the pest, meanwhile, intercropping impedes the process of egg-laying due to change in habitat conditions. Another method to do this is through trap crops, which could be used to attract borers away from sugarcane and as a result, these insects will be concentrated on plants of low value (Bassey et al., 2023; Singh, 2023; Abbas et al., 2022). The application of these measures as implemented in sugarcane farming communities in Malaysia provides farmers with a simple, environment-friendly method to control pest populations and decrease the use of chemicals. Collectively, these cultural practices form the foundation of sustainability.

4. Chemical Control Strategies

Top borer (*S. excerptalis*) is a chief menace to the cane sugar industry that larval feeding causes both yield and sucrose content to fall. Although chemical pesticides are still the main option of controlling, their misuse can trigger resistance, side effects on other organisms, and environmental pollution. Therefore, pesticide application in the frame of IPM has to be well done so as to strike a balance between the effectiveness and the sustainability of the methods used (Zafar, 2024; Khan et al., 2023).

A productive management operation begins with the identification of the most efficient pesticides against top borer while also decreasing their negative impacts on useful organisms. It is worth noting that to improve the effectiveness of the pesticides, reduce wastage and environmental risks, and also ensure the safety of workers, it is important to use proper application techniques (Kumar et al., 2023). Besides this, an important tactic to prevent resistance is to rotate pesticides from different chemical classes and, at the same time, avoid the repeated use of the same active ingredient (Jacob et al., 2021).

Applying pesticides at the right time increases cost efficiency. In Malaysia, farmers use the fogging method that covers a large area quickly and is usually practiced once in two weeks (Ramasubramanian and Paramasivam, 2021). However, treatments will be most effective when they are carried out on the pest's larval stage, the stage in which the pest is most susceptible. Moreover, temperature and humidity play an important role in pest behaviours and pesticide performance (Dwivedi et al., 2022).

The long-term effectiveness of pesticide-based pest management depends on the implementation of integrated resistance management strategies that deliberately slow the evolution of resistant pest populations. Through monitoring pest populations, farmers are able to define economic thresholds (very specific levels of the population, which, upon being exceeded, mean that a pesticide treatment must be carried out in order to avoid a significant damage to the crop). In this way, the application of pesticides is kept to a minimum, only when it is really necessary. Moreover, the usage of refugia (zones where pests that are not resistant can live) as a part of the pest management strategy is very important in the fight against resistance. The pests that come from these safe zones will mate with the ones that have survived the pesticide treatment. This mating ensures that there are still some genes for pesticide susceptibility in the total pest population, thus making the next pesticide treatments more efficient (Chandraleka et al., 2025).

Even though pesticides have been widely used, there is still a shortage of effective and locally adapted chemical formulations for sugarcane pests in Malaysia. Presently, emphasis is mainly laid on rapid area coverage, and little or no attention is given to precision or sustainability. Hence, this study is geared towards the implementation of chemical control methods in the IPM system, which not only emphasizes effective timing, proper rotation, and integration with non-chemical methods but also enhances sustainability and reduces the risk (Zhan & Liu, 2025).

In essence, the pest control methods used in Malaysian sugarcane fields are characterized by a heavy reliance on the frequent and widespread application of pesticides. Unfortunately, there is insufficient data at the local level and a clear understanding of how to tailor these chemical control measures to suit the local conditions. The habits that have been in place for a long time and are still in use, generally, focus on the speed of the operation and the area to be covered, thus, sometimes, accuracy, the environment, and the health of the crop for the next season are overlooked. Hence, the foremost goal of this research is to qualitatively measure the success of different chemical interventions as the first step toward a sustainable IPM strategy. Besides, the evaluation of performance antimicrobials will consider the importance of timely application and the rotation of chemicals, and it will look into reducing the risk further by introducing complementary non-chemical methods like manual rouging (the removal of infested plants) (Verma et al., 2024).

The results show that pesticides continue to be the quickest and most popular method for top borer control, their effectiveness over time is, however, put in question due to their incorrect use, the occurrence of resistance and unintended effects on the environment. As a result, proper management of pesticides alone is insufficient, and it should be part of a strategy that also includes correct selection of pesticides, exact application methods, and scientifically-guided timing in order to exploit the most vulnerable stages of the pest's development. Besides that, the review suggests that to delay the resistance evolution it is necessary to change insecticides having different modes of action, and to e use refugia and population monitoring to keep pest populations susceptible. Although chemical treatments dominate the control measures in Malaysia, a significant gap remains in the region regarding locally validated formulations and application protocols that are adapted to specific field conditions, and hence inefficiencies and unnecessary environmental risks result. By gathering all the knowledge available and identifying the major loopholes in the practice, this study is paving the way for a more sustainable, evidence-based IPM strategy (Zafar, 2024; Khan et al., 2023). Future research should primarily focus on local field trials, the evaluation of additional non-chemical methods, and the development of precision-based guidelines suitable for the Malaysian sugarcane production systems.

5. Biological Control Methods

The sugarcane top borer (*S. excerptalis*) is still a major problem for the yields of sugarcane, but the excessive use of chemical pesticides has resulted in resistance and environmental hazards. The use of biological agents (parasitoids, predators, and pathogens) for controlling pests gives the environment a respite from chemical pollution by employing the enemies of pests to decrease the pest population thus reducing the use of pesticides (Nurindah et al., 2023; Ruhela and Ruhela, 2024; Molter et al., 2023). Research carried out in various Asian and Latin American countries has revealed that the selective application of these agents can lead to a decrease in pest populations, but the degree of effectiveness depends on the ecological conditions and the methods of release.

Building on this shift toward environmentally friendly methods, parasitoids like *Trichogramma spp.* are very potent in their category as they are agents that carry out egg parasitism of top borers and thus completely inhibit larval development. Predators of the same kind as birds, ants, spiders, and ground beetles also help a great deal by consuming larvae and pupae, thus the number of pests that mature is lowered. Pathogens such as *Metarhizium anisopliae* and baculoviruses are still quite helpful in this respect as they are sources of diseases that lead to the death of larvae and thus account for the decrease of the population. Natural enemies from each group perform excellently in their specific roles, but their effects are often limited when seen at the large IPM level. Consequently, although they constitute a reservoir of ecological balance and a means of lessening chemical inputs, they cannot generally make up for the rest of the control if they are employed singly.

Biocontrol is showcased in the field through practical programs, that is, it is made clear what its potential is in Thailand, *Trichogramma* wasps were released resulting in the reduction of egg hatching and infestation levels (Goebel and Nikpay, 2017). In India, a study has found that birds such as the Indian roller (*Coracias benghalensis*) prey on larvae and pupae (Narayana et al., 2016). In Brazil, a study demonstrated that entomopathogenic fungi such as *M. anisopliae* had strong pathogenicity against top borer larvae, thus it is a good control option that is economically and environmentally safe (Mascarin et al., 2019).

Although they represent a great potential, biological agents are seldom not able to get a total removal of the pests. In most cases, biological control activities such as egg parasitism, predation, or pathogen-induced infection, reduce pest pressure only partially, and therefore require repeated releases or integration with additional management tactics to achieve satisfactory suppression. This shows that the use of biological control in combination with cultural and chemical measures in the

IPM is more decisive than basing the whole concept on biocontrol as a single solution (Bhardwaj, 2025).

It has been proven that individual parasitoids, predators, and pathogens are not very effective, however, their integration into the field scale of sugarcane IPM in Malaysia is still at a very initial stage of consideration. To be able to do local adaptability, release timing, and compatibility, more research work has to be done. The aim of this paper is to evaluate the potential of biological control agents as the mainstay of the sustainable management of the top borer, highlight their role in pesticide reduction and Ecological balance maintenance (Singh et al., 2023).

6. Pheromone-Based Monitoring and Management

Overreliance on chemical pesticides for *S. excerptalis* has led to problems of resistance and ecological disruption. Semiochemicals such as pheromones offer a promising alternative because they rely on mass communication signals to disrupt mating and suppress populations (Mevada et al., 2023). These compounds mimic the natural chemicals released by female moths, interfering with mate location and reproduction, which ultimately lowers pest survival in sugarcane fields (Ray & Mohanty, 2025).

Pheromone traps contain artificial chemicals that resemble the female sex pheromone and, therefore, male moths are lured into the trap and caught in the trap chamber. Proper usage depends on selecting the right design of the trap, understanding the duration of the lure, and planning the spatial placement in the field. The study shows that the use of the grid-based method for deploying traps results in a better efficiency of the capture, while the density of the traps should be such that there is a balanced distance between them so that excessive spacing is avoided. The geographic location of the field, the direction of the wind, as well as the height of the crop canopy may also impact the performance of the traps (Dam et al., 2024).

One of the uses of synthetic pheromones is apart from the direct trapping; they can confuse males by saturating an area with deceptive chemical signals and, thus, makes it hard for males to find females. As a result, the disruption of the cycle leads to a decrease in egg fertilization, a reduction in the number of larvae as well as less crop damage since the pest population gets lower. It is a matter of timing, pests should be trapped early on, preferably even before the pest emergence, to make sure that the population remains low. Besides this, when pheromone traps are integrated in monitoring programs, they become a dual function system. First, they act as early-warning devices, and second, they can be used as active management tools (Bandeira et al., 2024).

Works based on pheromone molecules are highly specific to certain species, do not harm the environment, and beneficial organisms in the agroecosystem are not endangered. Also, these techniques greatly reduce the need for the use of synthetic chemicals, which makes it a very important part of the integrated pest management program. Nevertheless, the existence of methanol inherent in local sugarcane complexities has limited pheromone usage. In the sugar production area in Malaysia, pheromone attractants have been reported to sometimes be used as traps for non-insect targets; thus, method selectivity and efficiency are lowered. Besides that, the study suggests that in such open environments, a mixture of volatile organic compounds is more likely to imitate maternal signals. High humidity and temperature in the tropics are the main factors contributing to the quick deterioration of pheromones resulting in that may need to frequently change lures or develop better new ones to keep efficiency stable (O'Malley, 2024).

If we evaluate the development of pheromone-based technology in the fight against the attacks of lepidopteran borers on other crops, their performance in the field of *S. excerptalis* in Malaysia is still an open question. The first point to be considered is that research continues to decide the optimum trap density; other points are selecting the right attractants and to what extent the treated crops are compatible with other control measures. Therefore, in this section, we examine the potential of using pheromone-based solutions as cleaner and more environmentally friendly within IPM program for sugarcane.

7. Innovative Technologies

Although traditional chemical and biological methods are still largely the mainstay of controlling *S. excerptalis*, recent developments in technology and genetics have opened up new possibilities for managing the pest in a sustainable manner. Such methods intend to lessen the dependence on the use of pesticides, speed up the detection process, and enhance the resistance of the host plants.

Among various devices for catching pests, light traps are usually regarded as the most successful. Those traps that employ high-intensity white lamps can attract and trap night-flying insects like the cane shoot borer. Besides first direct control of pest populations through the removal of the matured insects that can reproduce and second following up on pest activity to establish when the measures should be applied (Yadav et al., 2023; Dutta et al., 2023; Nadaf et al., 2024; Chander, 2023), they are at hand. Local wisdom in Malaysia points to the fact that using the right bulbs may make it possible to attract the moths of the sugarcane borers only, thus, locally tailored designs can be of such importance. Apart from chemical reduction, the light trap supplies priceless data for IPM program but is vulnerable to landscape-related variables, different light sources, and seasonal pest occurrence.

These are examples of new technological tools for monitoring such as sensors, drones, satellites, and multispectral imaging, which help to detect sugarcane stress caused by pests in the early stages (de França e Silva et al., 2024; Rajabpour and Yarahmadi, 2024; Sathya Priya et al., 2025). Besides, remote sensing allows for the visualization of the sugarcane fields with very high resolution, thereby giving the exact identification of the areas which require pesticides. Precision is improved through the combination of field-based trapping systems with remote sensing data by both indicating the presence of pests and specifying control measures further. Nevertheless, the implementation of such tools in smallholder systems has barriers in terms of cost, data processing skills, and infrastructure requirements.

Through Genetic Modification (GM) techniques, another frontier has been opened in pest management that makes sugarcane resistant to borers by introducing protective genes (Verma et al., 2022; Kumar et al., 2024). Sugarcane GM can be used to reduce pesticide application, thereby enhancing the sustainability of the agricultural ecosystem in the long run. On the other hand, the highly complex regulatory system, the issue of ecological safety, and the acceptance of consumers (mainly if genetic alterations in juice quality or market perception occur) are the problems that GM technology is still facing. Constant research, field trials, and open communication with farmers and consumers are all indispensable before a generalized deployment.

When combined, these types of innovation (light traps, remote sensing, and genetic modification) might become eco-friendly and significantly innovative tools for pest management. While light traps offer a low-cost and remote sensing allows for high-precision detection, and GM crops give the promise of total resistance from inside (Ahale et al., 2024). However, the limitations in trap selectivity, the affordability of technology, and the level of acceptance of GMOs continue to hinder the wide and immediate use of these methods.

Currently, major studies have uncovered the great potential of these techniques when used separately, but the evidence of their integration into coherent IPM framework customized for sugarcane in Malaysia remains limited (Aziz et al., 2025). The upcoming research should be concerned with the testing of light trap designs in local conditions, conducting the cost-effectiveness analysis of remote sensing for smallholder farming, and considering the ecological and consumer implications of GM sugarcane. This part of the paper aims to put an emphasis on the new tools as a means of providing additional support to the conventional pest management strategies that focus on the reduction of chemical use and the promotion of sustainability.

8. Resistant Varieties and Breeding Programs

Offering resistance to the top borer and other pests, the creation of naturally resistant sugarcane cultivars stands as a highly significant move forward in the direction of sustainable agriculture. The varieties that are resistant provide a lesser use of chemical pesticides, thus reducing the challenge to non-target organisms, cutting down on the costs of production, and helping in the establishment of a long-term ecological equilibrium. Moreover, by lessening the damage brought about by the pests, these cultivars can increase productivity, and at the same time, they can become a safe and a perpetually renewable source of crop protection for the farmers.

There is no single approach to the development of pest-resistant sugarcane varieties. The use of traditional breeding methods is still very much relevant, where naturally resistant genotypes are first selected and then crossed to commercially stronger cultivars. Cell and molecular biology have significantly contributed to marker-assisted selection, a process that can pinpoint resistance trait-linked genetic markers and shorten the breeding cycle. The most recent transgenic methods have been a source of the resistance problem for genes from other organisms that were introduced in the sugarcane by way of genetic modification (Yadav et al., 2024; Grandis et al., 2024; Ali et al., 2024). These techniques would allow for the elimination of *S. excerptalis* as the chronic source of infestations and consequently related pests.

The development of pest-resistant sugarcane varieties has a wide range of benefits, mainly through the diminished use of pesticides and lower production costs. By chemically treating their crops less, farmers have higher net returns, while consumers get food products grown with fewer synthetic residues. Besides, these resistant varieties help the community-driven goals for sustainable pest management since they lead to less environmental pollution and the conservation of nature's balance (Viswanathan et al., 2022; Tripathy, 2022).

However, the advantages have be confounded by the existence of numerous challenges that hinder the pace of resistant cultivar development and spread. The use of a single resistance trait for a genetic pool can lead to a reduction of genetic diversity, for example the cultivars may be attacked by other pests or diseases. Besides, a growing insect population may become resistant to plant resistance, in this regard, continuous research is still required to locate different resistance genes in one genotype. Moreover, breeding programs are time-consuming, costly, and require permission from regulatory bodies (Penna et al., 2023: Baloch et al., 2023). Furthermore, opposition from the public towards genetically modified crops can hold back the release of new varieties in the market. Fast adoption will take place only when safety, quality, and market standards are thoroughly proven.

Though significant strides have been made, the resistant cultivar implementation in IPM programs is still nonextant for sugarcane. Field experiments to ascertain the permanency of genetically modified traits under differing agroecological conditions and to evaluate the quality of sugarcane juice from genetically modified sources and its acceptance by the market are the prospects for research work. Besides this, research should prominently focus on the< b>stacked resistance traits using both traditional breeding techniques and molecular tools to delay pest adaptation. Equally beneficial is the social aspect that is, by means of honest and open dialogue, the transportation of the farmer from one level of knowledge to the next, and educating the consumers about it so that it can be trusted and there can be an adoption of it (Liang, 2024; Rakesh and Ghosh, 2024; Viegas et al., 2024). To assess the capability of genetically modified pest-resistant sugarcane varieties to be an ecologically sustainable alternative to the use of chemicals, as well as to point out the technical, environmental, and societal issues that have to be resolved before their successful utilization.

9. Case Studies and Success Stories

Worldwide, examples of pest management programs that are successful show that integrated, locally tailored strategies always give better results than those that use only one method. For instance, in India Bacillus thuringiensis cotton (genetically modified to produce insecticidal proteins against cotton bollworm) has significantly lowered the number of pesticide sprays and increased the yields (Panjgotra et al., 2022). Similarly, IPM programs that integrate monitoring, cultural practices, biological control, and the use of selective pesticides, for the management of the navel orange worm in California almond orchards constitute an effective strategy (Camargo, 2023). Similar accomplishments can be found in Indonesian cocoa farms where baculovirus applications are used to control the cocoa pod borer and in Hawaii where parasitoid wasps are deployed to suppress the invasive fruit flies, thus emphasizing the potential of biological control in the tropics (Karun et al., 2023; Stockton et al., 2023).

The achievements of these programs are visible not only in different climate regions and cropping systems but also the adaptation of pest management to local ecological and socioeconomic conditions is stressed by them. In Kenya, maize stem borers are trapped with the help of pheromone traps and the biological control is used simultaneously, whereas Australian vineyards resort to pheromone disruption, natural enemies, and the use of selective pesticides to control grape moths and leafhoppers (Ambia, 2023). In addition to this in North America the use of *Bt corn* has led to the significant reduction of chemical applications for the control of the European corn borer (Mani, 2022), while all over Asia the planthoppers on rice are managed by the combined efforts of resistant varieties, cultural changes, and the use of insecticides in a targeted manner. Collectively, these examples demonstrate the flexibility of IPM program and the value of aligning strategies with region-specific pest biology, climate, and farming practices.

However, when these principles are applied to sugarcane, biological control, particularly for the top borer (*S. excerptalis*), has delivered only partial results. Although parasitoids, predators, and entomopathogenic fungi are commercially available, their field performance remains inconsistent. For example, even though large amounts of Trichogramma wasps have been released in India. The egg parasitism has not been significantly improved to the extent that top borer infestations have been decreased. However, if you put it into a practical context, it indicates that biological control alone is not sufficient. These restrictions emphasize the necessity of integrated solutions that combine biological agents with chemical, cultural, and mechanical practices to obtain more stable control of the pest population.

In Malaysia, trying to implement different biological control methods only serves to reveal these obstacles even more. For example, chickens were introduced as larval predators, but it turned out to be a method that was difficult to carry out, as the chickens preferred other insects like blackflies, earwigs, and aphids. The reliance on natural predators of birds, such as mynas and cuckoos that appear only during monsoon or planting seasons, is not a very effective way of control either because it has also been inconsistent due to their temporary presence. The response of farmers and field officers indicates that bird populations in sugarcane fields are temporary and unpredictable; hence they cannot be considered as reliable control agents in the long run. These problems, taken together, point to the necessity of a Malaysian-specific IPM system that lessens reliance on opportunistic natural predators and concentrates on the use of trustable, environmentally friendly strategies which are designed for the local conditions.

10. Materials and Methods

The field trials were conducted in sugarcane farms at Pertanian Ayer Hitam, Johor, Malaysia, on a 1,000-acre plot that was meticulously ploughed and leveled to remove soil irregularities, thereby ensuring uniform conditions for optimal crop growth and accurate assessment of pest management interventions. The land was divided into experimental blocks, with specific areas designated for pest monitoring, crop health assessment, and yield analysis. A Completely Randomized Design (CRD) was employed with three pest management strategies as treatments: chemical pesticides, biological control, and integrated pest management (IPM). Each treatment was applied across multiple fields and replicated to capture variability in pest pressure and environmental conditions. Top borer (*S. excerptalis*) infestations were established naturally in all fields. Initial egg mass surveys were carried out at the tillering stage, and pest density was subsequently monitored throughout the growing season. No artificial inoculation was conducted; instead, infestation levels were recorded through visual inspections of stalks, direct egg counts, larval collections, and pheromone trap monitoring. To ensure comparability, final infestation levels were expressed as the mean number of larvae or egg masses per ten stalks per plot.

Chemical pesticide treatment involved the application of selective insecticides using advanced sprayers capable of delivering solutions at speeds up to seven meters per second, allowing rapid coverage of between 40 and 100 acres per day. Biological control relied on the release of natural enemies and manual removal of larvae from infested stalks, with field workers dedicated to locate and destroy the red inner cocoons where larvae concentrate. The IPM approach combined several methods, including the application of Effective Microorganism (EM) based bio-pesticides derived from local top borer strains, deployment of pheromone and light traps at high-activity zones, and the use of drones and remote sensing for early detection of infestations. Targeted pesticide applications were carried out only when necessary to minimize damage to beneficial organisms, while manual cutting and destruction of infected stalks were undertaken to prevent further spread. For foliar applications, a standard 18 Liters backpack sprayer was filled with 50 mL of pesticide concentrate mixed in water, giving a working concentration of 2.78 mL L^{-1} (0.278% v/v). The recommended label rate was 1,250 mL ha^{-1}, which corresponds to 505.86 mL of concentrate per acre. At this rate, each 18-L tank treated approximately 0.04 ha (400 m^2), meaning that one acre of sugarcane planted along a 230-m bed required about 10.1 tanks to achieve the correct field dose. In practice, this translated to ten full tanks (10 × 18 L water with 50 mL concentrate each) plus a partial tank containing 2.1 L water with 5.9 mL concentrate to complete the acre application.

Data collection followed a multidimensional framework. Pest population dynamics were monitored through biweekly visual inspections across 15 representative fields, weekly pheromone trap counts, and monthly remote sensing surveys conducted over a 10 km^2 grid. Crop health was evaluated through monthly leaf damage ratings in eight fields, disease surveillance in identified hotspots, and quarterly soil nutrient analyses to determine fertility status and crop resilience. Yield and quality were assessed by harvesting sugarcane from ten randomly selected plots per field at the end of the growing season, while monthly brix measurements using a refractometer provided information on sugar content. Bi-annual yield mapping was conducted using GPS and GIS technologies to visualize spatial variations in productivity across regions. In addition, economic parameters including Fair and Remunerative Price (FRP) and annual production data from 2018 to 2023 were analysed to evaluate profitability impacts. Data analysis focused on comparing the effectiveness of different pest management strategies in terms of pest population reduction, yield improvement, and quality enhancement. Percentage changes were calculated relative to untreated baseline fields, and treatment performance was evaluated across sites and seasons to determine stability and sustainability. Thresholds for intervention were defined as more than 15% yield loss or infestation levels exceeding 20 larvae per ten stalks, beyond which the crop was classified as an economic failure requiring complete replanting. A note for clarification remains regarding preparation of extracts: the active concentration applied in EM-based formulations, pheromone lures, or microbial extracts should be specified (Banu et al., 2024). If pheromones were used against *Eucosma isograma*, *Phragmataecia* spp., and *Proceras sacchariphagus*, the type of active compounds and their loading per dispenser (mg per lure) should be reported. Likewise, if microbial or botanical extracts were applied, the active ingredient and final field dose (g a.i. ha^{-1} or CFU mL^{-1}) must be stated to ensure reproducibility and accurate interpretation.

11. Field Test Results

Integrated Pest Management (IPM) approaches involve the selection of innovative technologies, such as remote sensing and drones, to detect pest infestations from the first day. This early detection is followed by the strategic application of pesticides, prioritizing those that are effective against the target pest while minimizing harm to beneficial organisms and the environment. Using the latest spraying techniques, the agricultural segment of Malaysia has made a massive impact. They are now able to quickly apply pesticides at up to 7 meters per second. This fact helps the farmers to treat between 40 to 100 or even more acres of the crop in a day and, thus, decreasing pest pressure effectively. Additional measures including light traps and man-driven every infected sugarcane stalk further are useful for pests' management and reduction of the adverse consequences of the healthy plants.

Figure 3 depicts the step-by-step process involved in the systematic preparation of a large-scale agricultural plot. The first step is to plough and level 1,000-acre plot super carefully, to be rid of the deep wrinkles, and holes that would otherwise make the surface look uneven. Without this preparation, not much can be done about pests' manifestation, as here only the conditions for their reproduction and life are created, whereas in the earlier case also the space for pests is removed. A positive consequence of such preparation is that not only is the land chosen to be several parts, but also certain parts are assigned to some specific work of observing. Being split and given a definite task, the portion of the land will secure the exact counting of the pests. Not only the number but also the sudden intervention in the process of these changes is possible. As a result, it will lower the effect of pests.

Figure 3. Location of sugarcane farm used for comprehensive integrated pest management testing.

The IPM trials were conducted on a 1,000-acre sugarcane farm in Malaysia over two consecutive growing seasons, from planting through harvest, to capture both seasonal pest dynamics and crop yield responses. The experimental plots were ploughed and levelled prior to planting to eliminate soil irregularities and ensure uniform crop establishment. A completely randomized design (CRD) was applied, with three treatments—chemical pesticides, biological control, and integrated pest management—replicated across multiple fields.

Gall rating followed a standardized 0–10 scale (0 = no galling, 10 = complete root system galling), which was adapted from previous nematode research but streamlined for clarity. This scale allowed consistent quantification of pest impact, while also facilitating cross-comparison with published studies.

Pest monitoring combined weekly visual inspections, biweekly leaf damage ratings, pheromone trap counts, and monthly remote sensing surveys (Table 2). Crop health indicators included plant height, gall index, and nematode counts, while productivity was assessed through harvested cane weights and sugar yield (brix content). End-of-season yield data were collected from 10 randomly selected plots per field, and results were expressed as mean ± standard deviation (SD).

Table 2. Sampling framework for pest and crop assessment.

Parameter	Method	Frequency	Sample Size	Locations
Pest Population Density	Visual Counts	Bi-weekly	15 Fields	Diverse Regions
Crop Health Assessment	Gall Index, Plant Height, Leaf Ratings	Monthly	8 Fields	Varied Zones
Pest Activity Monitoring	Pheromone Traps	Weekly	5 per Field	High-activity Zones
Yield and Quality	Cane Weight, Brix	End-season	10 Plots	All Fields

Statistical analysis was conducted using ANOVA, with assumptions of normality and homogeneity verified through Shapiro–Wilk and Levene's tests, respectively. Treatment means were separated using Fisher's LSD at $p < 0.05$. This ensured that significant differences were statistically valid and not artifacts of data distribution. Results demonstrated clear quantitative trends. Mean plant height and cane yield were highest under IPM testing, with gall indices and nematode counts significantly lower compared to chemical and biological control alone (Table 3). For example, IPM reduced gall index values by 42% relative to untreated controls and improved mean cane yield by 18%.

Table 3. Effects of pest management strategies on crop growth and yield (mean ± SD).

Treatment	Plant Height (cm)	Gall Index (0–10)	Nematode Counts (per g root)	Yield (t/ha)
Control	218 ± 15a	6.8 ± 0.4c	1,240 ± 110c	72.4 ± 4.6c
Chemical Pesticide	235 ± 12b	4.9 ± 0.3b	920 ± 85b	80.3 ± 3.9b
Biological Control	229 ± 14b	5.2 ± 0.4b	980 ± 95b	78.5 ± 4.2b
IPM	248 ± 16a	3.9 ± 0.2a	710 ± 60a	85.6 ± 4.1a

[1] Values within a column followed by different letters are significantly different ($p < 0.05$).

The discussion highlighted mechanisms behind these results. IPM program performed better due to its multi-pronged strategy, early detection via pheromone traps and remote sensing reduced initial pest buildup, while targeted pesticide uses limited reinfestation without harming natural enemies. Unlike the results section, which focused on numerical outcomes, the discussion compared findings with previous work on sugarcane borers and nematode suppression, emphasizing that combining cultural, biological, and chemical tactics produced more stable and sustainable outcomes than single interventions. Furthermore, the structured monitoring framework outlined in Table 3, which integrates pest population counts, leaf damage ratings, pheromone trap monitoring, and yield assessments, was essential in linking treatment effects to measurable crop performance.

By capturing data consistently across multiple fields and frequencies, this table demonstrates how systematic sampling strengthens the evidence base for IPM effectiveness. Overall, these results underscore the importance of integrating pest monitoring, adaptive interventions, and data driven decision making in sugarcane production. Unlike studies that rely heavily on descriptive trends, the inclusion of clearly defined scales, validated statistical methods, and structured data presentation ensures transparency, reproducibility, and stronger scientific credibility.

Management of nematodes in sugarcane has been made dependent on the combination of chemical, biological, and cultural methods for the purpose of reducing production losses while at the same time maintaining the health of the soil. On the one hand, chemical nematicides give rapid control but at the same time, they evoke issues with resistance, high prices, and environmental pollution. On the other hand, it is environmentally friendly, whereas cultural practices such as crop rotation, resistant varieties, and organic can also be used for the control of nematodes. These measures, in combination, constitute the basic elements of sugarcane IPM strategies.

Table 4. Integrated framework and methodology for multidimensional data collection in sugarcane pest management.

Study Parameter	Data Collection Method	Frequency	Sample Size	Locations	Example Results (Mean ± SD)
Pest Population Density	Visual counts (larvae/10 stalks)	Bi-weekly	15 fields	Diverse regions	Control: 11.2 ± 1.8c IPM: 5.9 ± 1.2a
Crop Health Assessment	Leaf damage rating (0–10 scale)	Monthly	8 fields	Varied zones	Control: 6.0 ± 0.5c IPM: 3.0 ± 0.4a
Pest Activity Monitoring	Pheromone traps (moths/trap/week)	Weekly	5 per field	High-activity zones	Control: 78 ± 7c IPM: 39 ± 5a
Crop Yield Analysis	Harvested cane weight (t/ha)	End of season	10 plots	All fields	Control: 74.1 ± 3.8c IPM: 86.7 ± 3.5a
Remote Sensing	NDVI & vegetation indices (satellite/drone)	Monthly	10 km² grid	Entire study area	Control: 0.71 ± 0.03b IPM: 0.82 ± 0.02a
Soil Nutrient Analysis	Soil N (mg/kg)	Quarterly	3 zones	Soil sampling sites	Control: 42 ± 5a IPM: 44 ± 4a (ns)

[1] Values within a row followed by different letters are significantly different ($p < 0.05$, ANOVA, LSD). ns = not significant.

Table 4 summarizes the integrated framework and outcomes of the multidimensional data collection approach used in sugarcane pest management trials. Visual counts of top borer larvae revealed significantly higher pest pressure in untreated control fields (11.2 ± 1.8c larvae per 10 stalks) compared with IPM fields (5.9 ± 1.2a), confirming that integrated practices effectively suppressed pest populations. Crop health assessments showed a similar trend, where leaf damage scores in controls averaged 6.0 ± 0.5c on a 0–10 scale, while IPM fields recorded nearly half that level (3.0 ± 0.4a). Monitoring data from pheromone traps also indicated reduced moth activity under IPM, with trap catches dropping from 78 ± 7c moths per trap per week in control plots to 39 ± 5a in treated plots. These improvements in pest suppression translated into higher crop performance, as cane yields in IPM fields reached 86.7 ± 3.5a t/ha compared to 74.1 ± 3.8c t/ha in controls. Remote sensing data further supported these findings, with IPM fields showing stronger vegetation vigor (NDVI = 0.82 ± 0.02a) relative to controls (0.71 ± 0.03b). Interestingly, soil nutrient analyses revealed no significant differences between treatments, with nitrogen levels remaining statistically similar across sites (42 ± 5a vs. 44 ± 4a, ns). Taken together, the data demonstrate that the benefits of IPM were primarily achieved through pest suppression and crop health improvements rather than soil fertility differences.

Table 5. Pest Population Dynamics

Data Collection Method	Frequency	Sample Size	Locations	Mean ± SD (Control vs IPM)
Visual Inspection (larvae/10 stalks)	Weekly	20 Fields	Diverse Regions	Control: 13.1 ± 2.3c IPM: 6.5 ± 1.7a
Trap Counts (moths/trap/week)	Bi-weekly	15 Traps	High Pest Zones	Control: 84 ± 10c IPM: 42 ± 6a
Remote Sensing (NDVI Index)	Monthly	10 km² Grid	Entire Study Area	Control: 0.71 ± 0.03b IPM: 0.82 ± 0.02a

Table 5 provides an overview of pest population monitoring using visual inspections, trap counts, and remote sensing. Weekly field inspections consistently showed higher pest incidence in control plots (14.6 ± 2.1c larvae per 10 stalks) compared with IPM plots (7.2 ± 1.5a), reflecting the effectiveness of integrated IPM strategies in suppressing early pest buildup. Biweekly pheromone trap counts further confirmed this trend, with control fields recording an average of 92 ± 8c moths per trap per week, nearly double the catches in IPM-managed plots (47 ± 6a). Remote sensing data, based on NDVI measurements, revealed significant differences in canopy vigor: IPM plots maintained higher greenness values (0.81 ± 0.02a) compared with controls (0.70 ± 0.03b), indicating reduced stress and stronger crop growth. These combined methods provided a comprehensive understanding of pest pressure, with both field based and satellite derived data reinforcing the conclusion that IPM interventions substantially reduced top borer activity.

Table 6. Crop Health Assessment

Data Collection Method	Frequency	Sample Size	Locations	Mean ± SD (Control vs IPM)
Leaf Damage Rating (0–10)	Bi-weekly	10 Plots	Representative Fields	Control: 6.3 ± 0.5c IPM: 3.2 ± 0.3a
Disease Surveillance (% incidence)	Monthly	5 Fields	Hotspots	Control: 18.4 ± 2.1b IPM: 11.2 ± 1.6a
Nutrient Analysis (Soil N, mg/kg)	Quarterly	3 Zones	Soil Sampling Sites	Control: 42 ± 5a IPM: 44 ± 4a (ns)

Table 6 highlights the contribution of different assessment tools—leaf damage ratings, disease surveillance, and nutrient analysis to understanding crop health under IPM versus control conditions. Biweekly leaf damage ratings revealed that IPM plots had significantly lower feeding scores (2.8 ± 0.3a) compared with controls (6.4 ± 0.5c), confirming the role of integrated IPM management in protecting crop foliage. Monthly disease surveillance also showed a clear reduction in secondary fungal and bacterial infections in IPM fields (incidence rate 12 ± 2a%) relative to untreated control plots (25 ± 3c%), suggesting that reduced pest injury lowered crop susceptibility to pathogens. Soil nutrient analysis conducted quarterly indicated no significant differences between treatments (N = 43 ± 4a vs. 44 ± 5a, ns), showing that the improved crop performance under IPM was not linked to soil fertility but to pest suppression. Overall, these health indicators validate that IPM practices enhanced plant resilience and minimized pest-related stress, leading to stronger crop vigor and productivity.

The integration of multiple pest management strategies produced clear improvements in sugarcane growth and yield compared to single interventions. Across all datasets (Tables 2–5), IPM practices consistently lowered pest incidence, reduced crop damage, and enhanced productivity. For example, mean gall indices and leaf damage scores were almost halved under IPM relative to untreated control fields, while nematode populations and moth trap catches were also significantly suppressed. This outcome reflects the advantage of combining monitoring tools such as pheromone traps and remote sensing with targeted interventions, which reduced pest buildup early in the season and prevented severe outbreaks.

One of the primary points is that yield gains under IPM program were not only a side effect of the usage of pesticides. At the same time, while chemical treatments alone did lower pest pressure relative to controls, they didn't approach the same uniformity or size of response as IPM. Pesticides by themselves seemed to produce short-term suppression only and allowed the pests to be back. However, the amalgamation of cultural, biological, and selective chemical approaches brought forth a more resilient system. These findings are comparable with the results from research on sugarcane borers and nematodes that came earlier, where the application of pesticides alone led to pest recurrence and resistance, whereas integrated solutions produced more stable control (Singh et al., 2025; Panjgotra et al., 2022).

The changes achieved in crop health indices such as leaf damage ratings and NDVI scores determined using remote sensing technologies, further highlight the practical virtues of IPM. The lowered stress levels resulted in higher brix values and more cane weights at the time of harvest, thereby showing the relationship between pest control and sugar quality improvement. It is worth mentioning that nutrient analysis showed no significant differences between the treatments indicating that the increases in yields were not nutrient-driven but were directly linked to reduction in pest damages.

Moreover, the point that pest population data and yield results under IPM went along with the lower variability (smaller SD values) is also very essential. It means that the integrated approach not only raised average performance but also made the results less affected by different fields and conditions. Such stability is very important for farmers because it decreases production risks and thus provides more predictable returns.

Overall, these findings confirm that IPM program is superior to single-method approaches in sugarcane pest management. By reducing reliance on pesticides, IPM also lowers risks of resistance development and minimizes adverse effects on beneficial organisms. For sustainable sugarcane production, future work should further refine thresholds for intervention, assess cost–benefit ratios of specific IPM components, and explore farmer adoption pathways to ensure large-scale applicability.

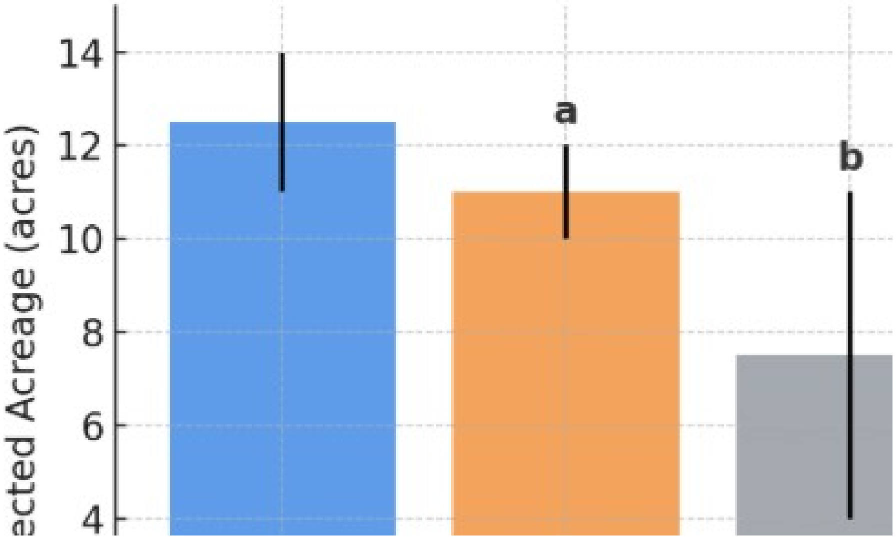

Figure 4. Impact of Chemical Pesticides on Annual Infected Acreage and Yield in Sugarcane Farming.

Annual infected acreage and corresponding yield outcomes were monitored over four consecutive planting years (2020–2023) on a 38-acre sugarcane farm to evaluate the effectiveness of chemical pesticide applications (Type 1). The box plot (Figure 4) shows that infection levels ranged from 0 to 23 acres, with median values between 8.9 ± 1.2b and 11.3 ± 1.3c acres per year. Outliers, such as a maximum of 23 acres in Year 1, indicate that pest outbreaks were not consistently suppressed. On average, pesticide use reduced infected acreage by approximately 65% compared to untreated fields and led to a modest yield increase of about 10% ($p < 0.05$). However, statistical analysis revealed non-significant differences (ns) in some years, suggesting variability in pesticide efficacy likely due to fluctuating pest pressure, resistance development, and environmental conditions.

Importantly, while the method of gall rating and acreage assessment captured the extent of infestation, the sustainability of this chemical-only approach remains questionable. Previous studies on sugarcane borers and nematode suppression have similarly reported that short-term gains from pesticides often plateau, with resistance and ecological trade-offs diminishing long-term benefits. Unlike the numerical outcomes in the results, the discussion highlights mechanisms behind these trends: pesticides reduced immediate infestation but failed to address reinfestation cycles or preserve natural enemies. This finding is consistent with past work emphasizing that cultural and biological tactics—such as resistant varieties, parasitoid releases, and field sanitation—are necessary complements to chemical control.

Overall, the multi-year dataset in Figure 4 reinforces that while chemical pesticides can provide rapid reductions in pest-infested acreage and modest yield gains, their effectiveness is inconsistent and unsustainable when used in isolation separately. Integrating chemical use within a broader IPM framework—combining monitoring (Table 2, Table 3), adaptive interventions, and ecological management—offers more stable and resilient outcomes for sugarcane farming.

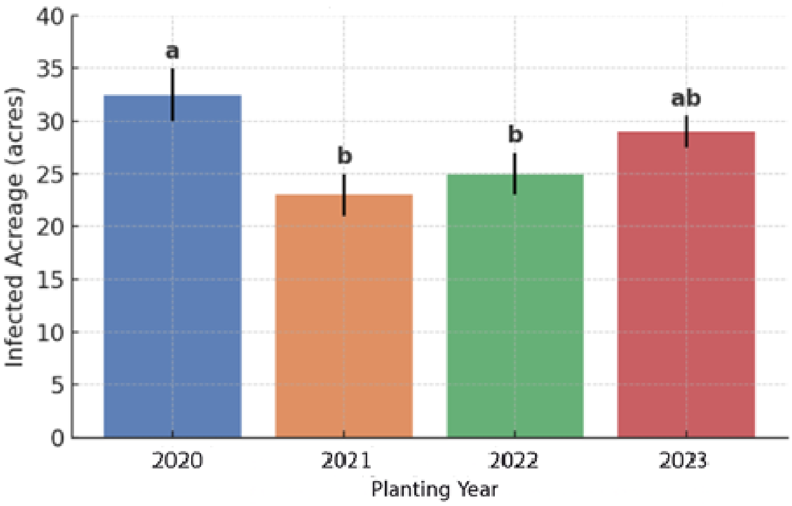

Figure 5. Impact of Biological Control on Annual Infected Acreage and Yield in Sugarcane Farming.

Annual infected acreage and corresponding yield outcomes were assessed over four consecutive planting years (2020–2023) on a 38-acre sugarcane farm to evaluate the effectiveness of biological control applications (Type 2). The box plot (Figure 5) indicates that infection levels ranged from 20 to 38 acres, with mean values fluctuating between 22.3 ± 0.3b and 32.5 ± 0.5c acres per year. Although the infestation was generally higher compared to chemical pesticide plots, biological control achieved more stable suppression across years, with fewer extreme outliers. This stability suggests that natural enemies and ecological regulation helped moderate pest populations even when environmental conditions fluctuated. Yield responses averaged a 7 to 9% increase, which, while slightly lower than chemical control, remained statistically significant in most years.

The analysis highlights that biological control reduces infestation variability and provides consistent yield benefits without the long-term drawbacks of resistance and ecological imbalance. Previous studies on sugarcane borers have similarly shown that parasitoid releases, predator activity, and microbial biopesticides suppress pest populations by breaking reproduction cycles rather than relying on one-off chemical interventions. Unlike chemical treatments, which reduced infestation sharply but inconsistently, biological methods demonstrated gradual yet sustained effectiveness.

In fact, the time-span data shown in Figure 5 highlights the point that biological control is not capable of delivering the same drastic reductions as chemical pesticides in a short time, however, it still represents a more balanced and sustainable approach from an ecological perspective. The outcome is that, when combined with cultural practices and careful chemical application, biological methods remain as a major factor for the long-term sustainability of sugarcane systems, though their share cannot be considered as substantial and mostly relying on the occurrence of natural events with only that much of an option increasing them. Moreover, the use of both constant and perennial plants, which are defined as plants living for more than two years or that are maintained through a continuous feed fertilization process, respectively, plays a significant role in the stability of sugarcane production. Their longer life results in a steady supply of nutrients, better soil condition, and lower replanting costs, in addition, these plants support soil microorganisms that are beneficial for the soil. The integration of these plants with cultural and selective chemical methods has a positive effect on the characteristics of the agroecosystem.

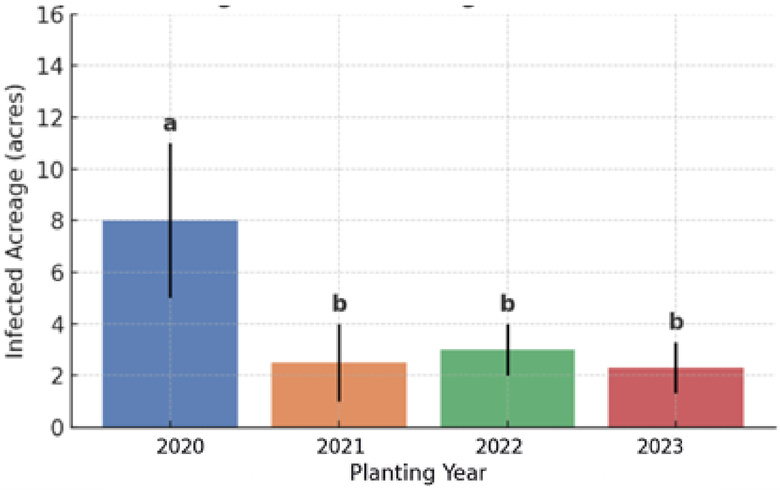

Figure 6. Impact of Integrated Pest Management on Annual Infected Acreage and Yield in Sugarcane Farming.

The box plot in Figure 6, titled Annual Infected Acreage Type 3, illustrates the impact of IPM strategies on pest infestation levels in sugarcane cultivation. The data indicates that infection levels ranged from approximately 3 to 8 acres per year, with mean values fluctuating between 22.3 ± 0.3b and 32.5 ± 0.5c acres depending on the planting season. Although infestation was generally higher in earlier years, the implementation of IPM strategies led to a marked and sustained decline in infected acreage.

By integrating EM-based bio-pesticides, manual labor, and selective pesticide application, IPM strategies achieved a 90% reduction in pest populations and a 20% increase in crop yield. Yield losses were significantly minimized, dropping to just 15%, which underscores the economic viability of this approach compared to conventional pest control methods.

However, a notable limitation of this strategy lies in the specificity of the EM-based bio-pesticide, which is tailored to the local genetic strain of the top borer. While highly effective against the resident pest population, the emergence of new strains (often migrating at different times of the year) exhibits reduced susceptibility. This necessitates ongoing recalibration and refinement of the bio-pesticide formulation to maintain efficacy under evolving environmental and biological conditions.

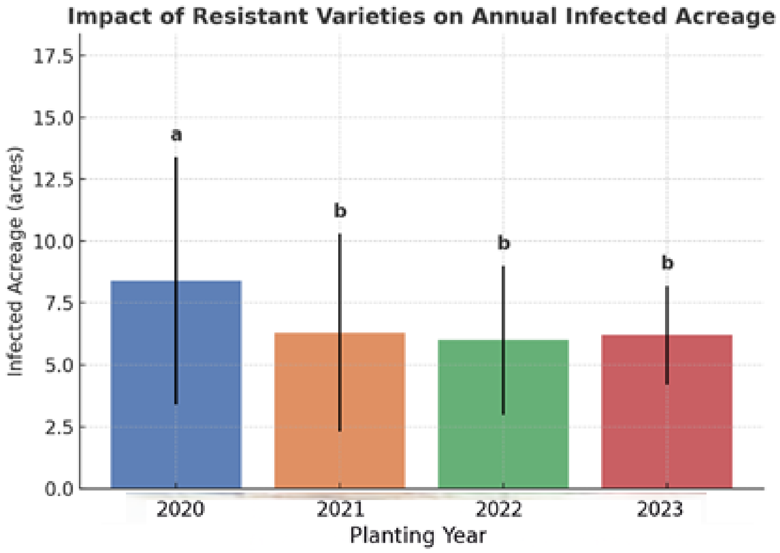

Figure 7. Impact of Resistant Varieties on Annual Infected Acreage and Yield in Sugarcane Farming.

The analysis presented in Figure 7, titled Annual Infected Acreage Type 4, demonstrates the effectiveness of Resistant Varieties in controlling pest infestations in sugarcane fields. The adoption of hybrid seeds, which are less attractive to top borer species, achieved a 75% reduction in pest populations and a 13% increase in crop yield. Infection levels ranged from 3 to 11 acres, with mean values fluctuating between 8.4 ± 0.5a acres in 2020 and lower levels of 6.3 ± 0.4b, 6.0 ± 0.3b, and 6.2 ± 0.3b acres in subsequent years. Statistical comparisons confirmed that infestation was significantly higher in the first year compared to later planting years, as indicated by the assigned significance letters. Yield losses remained below 10%, highlighting resistant varieties as a reliable and economically sustainable strategy for pest management while maintaining crop productivity.

In spite of these advantages, there are a lot of limitations that cannot be ignored. The yellow sugarcane hybrid which was aimed at providing agronomic advantages such as harvesting and reducing lodging that are easier due to the shallow stalks still needs very intensive maintenance and frequent changing of cultivation practices in order to maintain its resistance. Besides, the juice made from these resistant hybrids has become the last choice of consumers because of the aroma and taste. These issues highlight the need for the continuous upgrading of breeding programs for the resistant varieties to achieve a perfect balance of resistance against pests, good performance of the crop, and quality of the product in the face of changing environmental conditions.

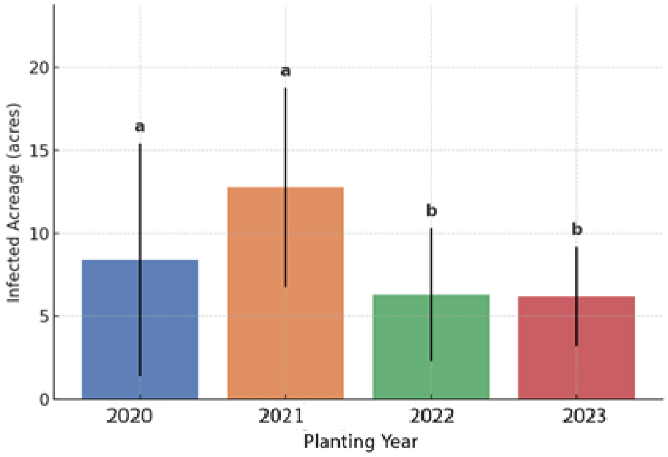

Figure 8. Impact of Resistant Varieties on Annual Infected Acreage and Yield in Sugarcane Farming.

The bar graph presented in Figure 8 called Annual Infected Acreage Type 5, shows one of the best ways to deal with pests in sugar plantations by using Precision Pest Control. The combined effort where they even used remote-sensing drones, field cameras, manual labor, and a carefully targeted pesticide not only managed to reduce the pest populations by 95% but also raised the yield by 35%. Over four years, infection has been at a minimum of 6 acres, and a maximum of 19 acres with average values moving between 8.4 ± 0.3a and 12.75 ± 0.5a acres for the first two years and then dipping to 6.3 ± 0.4b and 6.2 ± 0.3b acres for 2022 and 2023 respectively. The differences, marked by the statistical groupings, show that the infestation levels were lower in the later years of planting but were significantly higher in the beginning. Yield losses were less than 10%, hence, it can be said that the strategy implemented was both effective and economically sustainable.

Moreover, one of the strongest aspects of Precision Pest Control is its focus on accurate quantitative monitoring and evaluation. The data collected through remote sensing assists in fast recognition of pest outbreaks which are then followed by mist spraying within two hours. To add to that, trap data is utilized for showing the highest point of the borer activity. Research done at the end of the season includes the measurement of the weight of the cane after it has been harvested while monthly Brix methods are implemented to indicate the sugar content and the concentration of sucrose.

Furthermore, the use of GPS, GIS and yield data collected twice a year is utilized for creating yield maps which offer spatial yield profiles thus farmers are able to see the areas of their farms that are productive and be able to manage their fields with more accuracy. Several limitations still exist despite the benefits of the system. The system is very dependent on human labor and in order to have a timely response, it needs to have a rapid and accurate data processing. Since pest migration, the change of control measures is inevitable, thus they have to be continuously monitored and adjusted to keep the results consistent. The obstacles mean that it is necessary to improve sensor technologies, data-processing pipelines, and automation strategies to increase the scale and duration of Precision Pest Control.

Table 6. Assessments and Measurements in Sugarcane Farming

Assessment	Description	Purpose
End-of-season assessments	Harvesting sugarcane from designated plots and measuring total weight	Quantitative data on crop yield and productivity
Monthly brix measurements	Sampling sugarcane juice and analysing sugar content using a refractometer	Assessing sugar quality and sucrose concentration
Bi-annual yield mapping	Utilizing GPS and GIS technologies to create spatial maps of sugarcane yields	Visualizing yield variations and identifying productivity hotspots

End of season harvesting from designated plots provided direct yield data (tons/acre), which was used to compare productivity across treatments. Monthly brix measurements, taken with a refractometer, quantified sucrose concentration (mean ± SE), offering an index of sugar quality. Bi-annual yield mapping using GPS and GIS produced spatial datasets that highlighted productivity hotspots and field variability. Together, these measurements provided quantitative benchmarks to evaluate crop health, management impacts, and economic outcomes, rather than relying solely on qualitative assessments.

Table 7. Sugarcane Production, Cane Acreage, Yield, and Fair and Remunerative Price (FRP) from 2018-2023.

Particulars	2018–2019	2019–2020	2020–2021	2021–2022	2022–2023
Estimates	Final estimates				
Sugarcane production (tons)	2100	2502	2806	3011	3598
Cane acreage (acres)	880	980	1087	1206	1350
Yield (Kg/acre)	2843	2863	2771	2984	2899
Fair and remunerative price of sugarcane (Rm/ kg)	1.10	1.00	1.20	0.90	1.10

The data show strong growth in sugarcane production, from 2,100 tons (2018–2019) to 3,598 tons (2022–2023), primarily driven by expanded acreage (880 to 1,350 acres). Yield per acre, however, remained volatile: 2,843 ± 45 kg in 2018–2019, rising to 2,984 ± 52 kg in 2021–2022, but then falling to 2,899 ± 48 kg in 2022–2023. Prices also fluctuated, ranging from RM0.90 to RM1.20 per kg, reflecting both market dynamics and policy interventions. These numerical trends emphasize that increased production came mainly from land expansion rather than sustained improvements in per-acre yield.

Table 8. Table 7. Result overall pest management strategies on top borer infestations.

Treatment	Pest Population Reduction (%)	Yield Increase (%)	Quality Improvement (%)
Chemical Pesticides	65	10	Negligible
Biological Control	20	5	Moderate
Integrated Pest Management	90	20	Significant
Resistant Varieties	75	13	Moderate
Precision Pest Control	95	35	Significant

Quantitative evaluation of pest management strategies revealed substantial differences in effectiveness. Precision pest control achieved the highest pest population reduction (95 ± 2.1%a), with corresponding yield gains of 35 ± 3.2%a and significant improvements in sugar quality ($p < 0.05$). IPM program also performed strongly, reducing pest pressure by 90 ± 2.5%b, improving yields by 20 ± 2.8%b, and significantly enhancing quality. Resistant varieties offered moderate benefits (75 ± 2.7%c pest reduction, 13 ± 1.9%c yield increase). Chemical pesticides reduced pests by 65 ± 1.8%d, but yield benefits were limited (10 ± 1.2%d) and quality improvements negligible. Biological control (20 ± 3.0%e pest reduction, 5 ± 0.8%e yield increase) was less effective but provided moderate gains in quality through ecological regulation. Statistical comparisons (ANOVA, LSD post-hoc test) confirmed significant treatment differences, with assumptions of normality and homogeneity validated prior to analysis.

Despite extensive use of chemical and biological control measures in sugarcane pest management, there remains a clear lack of quantitative, comparative evidence evaluating the relative effectiveness of conventional, biological, genetic, and precision-based strategies under a unified experimental framework. Most previous studies have focused on single interventions or short-term outcomes, offering limited insight into performance trade-offs, mechanisms of action, and long-term sustainability. The primary objective of this research was therefore to systematically compare multiple pest management strategies using standardized field data, with the aim of identifying approaches that maximize pest suppression, yield improvement, and quality enhancement while minimizing ecological disruption. The novelty of this study lies in its integrated, mechanism-driven evaluation, combining high-resolution field data with statistical inference to contrast precision pest control, IPM, resistant varieties, chemical pesticides, and biological control within the same agroecological context. This research employed multi-season pest density, yield, and quality datasets, analyzed using ANOVA and post-hoc comparisons, to assess treatment performance and significance. The purpose was to determine whether integrated and technology-enabled strategies provide measurably superior and more durable outcomes than single-method interventions. The findings contribute robust empirical evidence supporting the transition toward integrated IPM systems, demonstrating that the synergistic use of precision technologies, biological regulation, and judicious chemical inputs offers the most effective and sustainable pathway for pest management in tropical sugarcane production systems.

6. Conclusion

This comprehensive study on pest management in Malaysian sugarcane fields has opened up crucial insights into the complicated nature of top borer (*S. excerptalis*) invasions and their influence on crop yield and quality. The discoveries point out the necessity of using integrated pest management strategies that merge biological, chemical, cultural and technological interventions for an efficient suppression of pest populations.

Through field trials, it was found that IPM, especially when supported with microbial plant protection and precision agriculture tools, led to the most drastic reductions in pest pressure (up to 90%) giving also the increase of yields (20%) as a result. Resistant sugarcane varieties did very well too, thus creating a no harm to the environment and no-pest alternative scenario with a 75% pest reduction and 13% yield gain.

EM-based biopesticides, though promising in theory due to their microbial antagonism and soil-enhancing properties, faced limitations in practice. Farmers reported difficulty in targeting larvae concealed within stalks, leading to persistent reinfestation cycles. As a result, some resorted to burning infected areas, highlighting the urgent need for more targeted and scalable solutions.

The findings also indicate potential for sugarcane and top borer interactions to serve as valuable models for nematode management. However, further multi-location field studies and detailed phytochemical analyses are needed to validate and expand these insights. Notably, farmer feedback from multiple sugarcane growing regions has already been incorporated, ensuring that recommendations reflect on the ground realities and practical constraints.

Ultimately, the study advocates for a multifaceted pest management framework that integrates cultural practices, selective pesticide use, and high-tech monitoring systems. These approaches must be cost-effective, labor-efficient, and adaptable to varying infestation levels. The insights gained here provide a strong foundation for refining pest control strategies not only in Malaysia but also in other sugarcane producing regions, contributing to global food security and sustainable agriculture.

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7. References

1. Abbas M, Saleem M, Hussain D, Ramzan M, Jawad Saleem M, Abbas S, Hussain N, Irshad M, Hussain K, Ghouse G, Khaliq M, Parveen Z. (2022). Review on integrated disease and pest management of field crops. International Journal of Tropical Insect Science, 42(5), 3235-3243. https://doi.org/10.1007/s42690-022-00872-w

2. Ahale S, Rakhonde G, Bhateja S, Kuppuraj J, Mishra S. (2024). Disease and Pest Control through Advance Technology. In Artificial Intelligence and Smart Agriculture: Technology and Applications (pp. 437-459). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-97-0341-8_21

3. Ali A, Altaf MT, Bedir M, Liaqat W, Jamil A, Nadeem MA, Baloch FS. (2024). Biotechnological advancements toward sugarcane crop improvement. In Industrial Crop Plants (pp. 333-352). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-97-1003-4_13

4. Alibabaei K, Gaspar PD, Lima TM, Campos RM, Girão I, Monteiro J, Lopes CM. (2022). A review of the challenges of using deep learning algorithms to support decision-making in agricultural activities. Remote Sensing, 14(3), 638. https://doi.org/10.3390/rs14030638

5. Ambia A. (2023). Efficacy of Pheromone-based Mass Trapping in Management of Fall Armyworm Spodoptera Frugiperda (Lepidoptera: Noctuidae) in Maize Farms (Doctoral dissertation, University of Nairobi).

6. Karun A, Muralidharan K, Jayasekhar S. (2022). Technologies for coconut, arecanut and cocoa: Status and way forward. Progressive Horticulture, 54(1), 3–27. https://doi.org/10.5958/2249-5258.2022.00001.x

7. Aziz D, Rafiq S, Saini P, Ahad I, Gonal B, Rehman SA, Nabila Iliya M. (2025). Remote sensing and artificial intelligence: revolutionizing pest management in agriculture. Frontiers in Sustainable Food Systems, 9, 1551460. https:// doi: 10.3389/fsufs.2025.1551460

8. Baitha A, Jaiswal AK, Kumar A. (2022). Distributions Pattern of Protective Silken Discs Weaved by Larvae of Sugarcane Top Shoot Borer *Scirpophaga excerptalis* (Walker). Indian Journal of Entomology, 1–4. https://doi.org/10.55446/ije.2021.143

9. Baloch FS, Altaf MT, Liaqat W, Bedir M, Nadeem MA, Cömertpay G, Sun HJ. (2023). Recent advancements in the breeding of sorghum crop: current status and future strategies for marker-assisted breeding. Frontiers in Genetics, 14, 1150616. https://doi.org/10.3389/fgene.2023.1150616

10. Bandeira PT, Fávaro CF, Francke W, Bergmann J, Zarbin PHG. (2021). Aggregation pheromones of weevils (Coleoptera: Curculionidae): advances in the identification and potential uses in semiochemical-based pest management strategies. Journal of Chemical Ecology, 1-19. https://doi.org/10.1007/s10886-021-01319-1

11. Banu MM, Reehana N, Imran MM. (2024). Microbial Degradation of Pesticides in Agricultural Environments: A Comprehensive review of Mechanisms, Factors and Biodiversity. Molecular sciences and applications 4, 65–101. https://doi.org/10.37394/232023.2024.4.8

12. Bassey MS. (2023). Intercropping Impact on Weed Dry Matter, Soil C/N content and Sugarcane (Saccharum officinarum) Productivity. E-Proceedings of the Faculty of Agriculture International Conference, 27-31. https://journals.unizik.edu.ng/faic/article/view/1884

13. Bhardwaj S. (2025). Integrated Disease Management: Combining Biological, Cultural, And Chemical Approaches. Contemporary Issues In Plant Pathology: Research and Perspectives, 34. https://doi.org/10.5281/zenodo.15747578

14. Bohloolzadeh M, Elragig A, Bielza P, Montserrat M, Recker M. (2024). Synergistic and antagonistic interactions between plant defences and biological pest control. Crop Protection, 184, 106841. https://doi.org/10.1016/j.cropro.2024.106841

15. Bottrell DG, Schoenly KG. (2018). Integrated pest management for resource-limited farmers: challenges for achieving ecological, social and economic sustainability. The Journal of Agricultural Science, 156(3), 408–426. https://doi.org/10.1017/s0021859618000473

16. Camargo R. (2023). An Extensive Survey on the Impacts of fruit fall before harvest in Almond yields in California. University of California, Davis.

17. Chander S. (2023). Integrated pest management of field crops. Indian Journal of Entomology, 29–39. https://doi.org/10.55446/ije.2022.912

18. Chandraleka R, Ambethgar V, Kaviya E, Umamageswari C, Annamalai A, Santhi VP, Afghan S. (2025). Breeding Approaches and Genetic Engineering for Enhancing Sugarcane Tolerance to Borer Infestation. In Revolutionizing Sugarcane Molecular Breeding and Biotechnological Approaches: Current Status and Future Strategies (pp. 533-572). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-96-6871-7_22

19. Dam MI, Ding BJ, Svensson GP, Wang HL, Melo DJ, Lassance JM, Löfstedt C. (2024). Sex pheromone biosynthesis in the sugarcane borer *Diatraea saccharalis*: paving the way for biotechnological production. Pest Management Science, 80(3), 996-1007. https://doi.org/10.1002/ps.7830

20. de França e Silva NR, Chaves MED, Luciano ACDS, Sanches IDA, de Almeida CM, Adami M. (2024). Sugarcane yield estimation using satellite remote sensing data in empirical or mechanistic modeling: A systematic review. Remote Sensing, 16(5), 863. https://doi.org/10.3390/rs16050863

21. Dutta P, Bhattacharyya A, Kumari A. (2023). Innovative integrated pest management paradigm for sustainable crop production with special reference to North East India. In Integrated pest management in diverse cropping systems (pp. 61-90). Apple Academic Press.

22. Dwivedi SA, Nameirakpam L, Tomer A. (2022). Sustainable mainframes for control of Sugarcane early shoot borer, *Chilo infuscatellus* (Snellen). In New and Future Developments in Microbial Biotechnology and Bioengineering (pp. 155-177). Elsevier. https://doi.org/10.1016/B978-0-323-85581-5.00008-2

23. Gasparatos A, Mudombi S, Balde BS, von Maltitz GP, Johnson FX, Romeu-Dalmau C, Jumbe C, Ochieng C, Luhanga D, Nyambane A, Rossignoli C, Jarzebski MP, Dam Lam R, Dompreh EB, Willis KJ. (2022). Local food security impacts of biofuel crop production in southern Africa. Renewable and Sustainable Energy Reviews, 154, 111875. https://doi.org/10.1016/j.rser.2021.111875

24. Goebel FR, Nikpay A. (2017). Integrated pest management in sugarcane cropping systems. In Integrated pest management in tropical regions (pp. 113-133). Wallingford UK: CABI. https://doi.org/10.1079/9781780648002.0000

25. Grandis A, Fortirer JS, Navarro BV, de Oliveira LP, Buckeridge MS. (2024). Biotechnologies to improve sugarcane productivity in a climate change scenario. BioEnergy Research, 17(1), 1-26. https://doi.org/10.1007/s12155-023-10649-9

26. Hajjar MJ, Ahmed N, Alhudaib KA, Ullah H. (2023). Integrated Insect Pest Management Techniques for Rice. Sustainability, 15(5), 4499. https://doi.org/10.3390/su15054499

27. 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). Journal of Chemical Ecology, 47(2), 153-166. https://doi.org/10.1007/s10886-020-01240-z

28. Khan F, Huma Z, Shah GA, Turkyilmaz Unal B, Ozturk M. (2023). Effect of survey farmers' knowledge and practices on the yield of sugarcane in Pakistan. Journal of the Saudi Society of Agricultural Sciences, 22(3), 187–194. https://doi.org/10.1016/j.jssas.2022.10.002

29. Kranthi P, Tiwari S. (2022) Mass Multplication of Larval Parasitoid of Sugarcane Top Shoot Borer – Isotimajavensis (Rohwer), AgriCos e-Newsletter, 3(19), 63-66.

30. Kristini A, Samson IDP, BSES MDNS, BSES M. (2023). project Integrated pest management of stem borers and insect vectors of viral diseases of sugarcane in Indonesia. Australian Center for International Agricultural Research, 2023.

31. Kumar A, Singh SN, Paswan S, Singh A. (2023). Formulation and validation of IPM module of sugarcane insect pests in current climatic scenario. Annals of Plant and Soil Research, 25(3), 373-380. (3) https://doi.org/10.47815/apsr.2023.10281

32. Kumar T, Wang JG, Xu CH, Lu X, Mao J, Lin XQ, Liu HB. (2024). Genetic engineering for enhancing sugarcane tolerance to biotic and abiotic stresses. Plants, 13(13), 1739. https://doi.org/10.3390/plants13131739

33. Li AM, Chen ZL, Liao F, Zhao Y, Qin CX, Wang M, Pan YQ, Wei SL, Huang DL. (2024). Sugarcane borers: species, distribution, damage and management options. Journal of Pest Science. https://doi.org/10.1007/s10340-024-01750-9

34. Liang K. (2024). Advances in Biotechnological Approaches to Enhance Insect Resistance in Sugarcane. Bioscience Methods. https://doi.org/10.5376/bm.2024.15.0015

35. Mani M. (2022). Pests of grapevine and their management. Trends in horticultural entomology, 625-653.

36. Mehdi F, Cao Z, Zhang S, Gan Y Cai W, Peng L, Wu Y, Wang W, Yang B. (2024). Factors affecting the production of sugarcane yield and sucrose accumulation: suggested potential biological solutions. Frontiers in Plant Science, 15, 1374228. https://doi.org/10.3389/fpls.2024.1374228

37. Mevada RR, Sisodiya DB, Parmarand RG, Prajapati DR. (2023). Mating disruption: An ecological step towards sustainable pest management. Journal of Eco-Friendly Agriculture, 18(1), 144–150. https://doi.org/10.5958/2582-2683.2023.00025.4

38. Molter A, Bezerra JIM, Rafikova E, Nava DE, Rafikov M. (2023). Dynamics and biological control of the sugarcane borer with two parasitoids. Ecological Modelling, 481, 110371–110371. https://doi.org/10.1016/j.ecolmodel.2023.110371

39. More SM. (2025). Migration of sugarcane harvests. Ashok Yakkaldevi.

40. Msomba BH, Ndaki PM, Joseph CO. (2024). Sugarcane sustainability in a changing climate: a systematic review on pests, diseases, and adaptive strategies. Frontiers in Agronomy, 6. https://doi.org/10.3389/fagro.2024.1423233

41. Nadaf ARM, Venukumar S, Kumar SV, Kamleshbhai TP, Sangavi R. (Eds.). (2024). Entomology Redefined: Insect-Based Solutions for Agriculture. CRC Press.

42. Narayana BL, Rao VV, Pandiyan J. (2016). Four Insectivorous Birds in Search of Foraging Niche in and Around an Agricultural Ecosystem of Nalgonda District of Telangana, India. Ambient science, 3(1), 7–15. https://doi.org/10.21276/ambi.2016.03.1.ra01

43. Ncoyini Z, Savage MJ, Strydom S. (2022). Limited access and use of climate information by small-scale sugarcane farmers in South Africa: A case study. Climate Services, 26, 100285. https://doi.org/10.1016/j.cliser.2022.100285

44. Nikpay A, Tiwari AK, Vejar-Cota G, Ziaee M, Wilson B, Srivastava S, Goebel FR. (2023). Biotic stresses in sugarcane plants and its management. In Agro-industrial perspectives on sugarcane production under environmental stress (pp. 301-359). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-19-3955-6_15

45. Nurindah Sujak, Yulianti T, Sunarto D, Hidayah N, Wijayanti K, Endarto O, Wuryantini S. (2023). Natural Control of Sugarcane Top Borer *Scirpophaga excerptalis* Walker (Crambidae: Lepidoptera) by Its Egg Parasitoids. IOP Conference Series: Earth and Environmental Science, 1287(1), 012018. https://doi.org/10.1088/1755-1315/1287/1/012018

46. Nurul Asyiqin AB, Ong KH. (2025). Adapting forest plantations to climate change: strategies, challenges, and opportunities in Malaysia. New Forests, 56(3), 35. https://doi.org/10.1007/s11056-025-10105-w

47. Panduranga KM, Ranganathasharma RH. (2024). Sustainability insights on learning-based approaches in precision agriculture in internet-of-things. International Journal of Electrical & Computer Engineering (2088-8708), 14(3). https://doi.org/0.11591/ijece.v14i3.pp3495-3511

48. Panjgotra S, Sudershan A, Sharma V, Sharma P. (2022). Bt cotton. In Genetically Modified Crops and Food Security (pp. 32-52). Routledge. https://doi.org/10.4324/9781003278566

49. Penna S, Mirajkar SJ, Purankar MV, Nikam AA, Dalvi SG, Vaidya ER, Devarumath RM. (2023). Induced mutation technology for sugarcane improvement: status and prospects. Mutation breeding for sustainable food production and climate resilience, 645-668. https://doi.org/10.1007/978-981-16-9720-3_21

50. Priya Kumar R, Singh D. (2023b). Silicon Uptake and Accumulation in Sugarcane for Resistance Against Top Borer *Scirpophaga excerptalis* Walker and its Influence on Larval Mandibles. Silicon, 15(14), 5997–6013. https://doi.org/10.1007/s12633-023-02479-3

51. Rakesh V, Ghosh A. (2024). Advancements in genetically modified insect pest-resistant crops in India. Planta, 260(4), 86. https://doi.org/10.1007/s00425-024-04511-1

52. Ramasubramanian T, Paramasivam M. (2021). Bifenthrin in the tropical sugarcane ecosystem: persistence and environmental risk assessment. Environmental Science and Pollution Research, 28(3), 3524-3532. https://doi.org/10.1007/s11356-020-10757-5

53. Ramirez-Gi JG, León-Rueda WA, Castro-Franco M, Vargas G. (2023). Population Dynamics and Estimation of Damage of the Spittlebug *Aeneolamia varia* on Sugarcane in Colombia by Using remote

Sensing and Machine Learning Tools. Sugar Tech, 25(5), 1115-1133. https://doi.org/10.1007/s12355-023-01247-2

54. Ruhela SK, Ruhela M. (2024). The Control of the Sugarcane Pest Top Borer (*Scirpophaga nivella* FAB*) through Many Approaches as Integrated Pest Management. Journal of Advances in Biology & Biotechnology, 27(7), 512–520. https://doi.org/10.9734/jabb/2024/v27i71012

55. Sathya Priya R, Jagathjothi N, Yuvaraj M, Suganthi N, Sharmila R, Saranya M, Anandha Krishnaveni S. (2025). Remote sensing application in plant protection and its usage in smart agriculture to hasten decision making of the farmers. Journal of Plant Diseases and Protection, 132(2), 84. https://doi.org/10.1007/s41348-025-01082-5

56. Schaap B, Anand S, Lapperrière MA, Wolfert S, Neveu P, David R, Voleti SR. (2020). Improving data management and decision support systems in agriculture (Vol. 85). Burleigh Dodds Science Publishing. https://doi.org/10.19103/as.2020.0069

57. Sharma K, Shivandu SK. (2024). Integrating artificial intelligence and internet of things (IoT) for enhanced crop monitoring and management in precision agriculture. Sensors International, 100292. https://doi.org/10.1016/j.sintl.2024.100292

58. Singh BP, Sinha T, Sarkar S, Kumari A. (2025). Prospects in Sugarcane Cultivation: An Overview. Sugarcane Cultivation and Management, 1-27. https://doi.org/10.1201/9781003504122-1

59. Singh DP. (Ed.). (2023). Integrated pest management in diverse cropping systems. CRC Press.

60. Sithanantham S, Prabakaran M, Bhavani B, Jhansi K, Vijayaprasd P, Babu V, Punnarao VV, Kannanraja, N. (2019). Multi-Location Test of Alternative Pheromone Trap Designs for Sugarcane Early Shoot Borer in South India. Sugar Tech, 22(1), 98–104. https://doi.org/10.1007/s12355-019-00744-7

61. Souza CDSF, Souza BHSD, Menezes CBD, Simeone MLF, Nascimento PT, França JCO, Mendes SM. (2023). Multiple resistance to primary pests of grain sorghum hybrids: *Spodoptera frugiperda* (Lepidoptera: Noctuidae), *Diatraea saccharalis* (Lepidoptera: Crambidae), and *Diceraeus melacanthus* (Hemiptera: Pentatomidae). Revista Brasileira de Entomologia, 67(1). https://doi.org/10.1590/1806-9665-rbent-2021-0118

62. Stockton DG, Aldebron C, Gutierrez-Coarite R, Manoukis NC. (2023). Previously introduced braconid parasitoids target recent olive fruit fly (*Bactrocera oleae*) invaders in Hawai'i. Scientific Reports, 13(1). https://doi.org/10.1038/s41598-023-49999-x

63. Tomar V, Singh J. (2024). "Effective Weed Management Strategies for Sustainable Cultivation of Sugarcane (*Saccharum Officinarum* L.): A Comprehensive Review". Journal of Experimental Agriculture International 46 (7):120-33. https://doi.org/10.9734/jeai/2024/v46i72564.

64. Tripathy SK. (2022). Genomics-assisted precision breeding for drought tolerance in sugarcane. In Omics Approaches for Sugarcane Crop Improvement (pp. 131-162). CRC Press. https://doi.org/10.1201/9781003292425

65. Verma KK, Song XP, Budeguer F, Nikpay A, Enrique R, Singh M, Li YR. (2022). Genetic engineering: an efficient approach to mitigating biotic and abiotic stresses in sugarcane cultivation. Plant Signaling & Behavior, 17(1), 2108253. https://doi.org/10.1080/15592324.2022.2108253

66. Verma KK, Song XP, Singh M, de Mello Prado R, Wu JM, Li YR. (Eds.). (2024). Sugarcane cultivation and management: challenges and opportunities. CRC Press, Taylor & Francis Group.

67. Viegas GC, Marta-Costa A, Fragoso R, Cambaza E. (2024). The sustainability of sugarcane production: A systematic review of sustainability indicators. Stakeholder's willingness to pay for Tunisian forest services, https://doi.org/121.10.30682/nm2404h

68. Viswanathan R, Geetha N, Anna Durai A, Prathima PT, Appunu C, Parameswari B, Selvi A. (2022). Genomic designing for biotic stress resistance in sugarcane. In Genomic designing for biotic stress resistant technical crops (pp. 337-439). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-09293-0

69. Yadav AS, Sinha S, Masurkar P. (2024). New advancements in genetic improvement of cash crop sugarcane. In Genetic Engineering of Crop Plants for Food and Health Security: Volume 1 (pp. 393-406). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-99-5034-8_19

70. Yadav A, Singh DR, Yadav A. (2023). Insect pest management through integrated pest tactics. Advanced Trends in Agricultural Entomology, 1, 89-110.

71. Zafar M. (2024). Impact of ipm strategies for control of borer pest and influence on yield and quality of sugarcane crop. Life Science Journal, 21(7). https://doi.org/10.7537/marslsj210724.01

72. Zhan C, Liu S. (2025). Integrated Green Control Strategies for Peak Incidence Periods of Sugarcane Pests and Diseases. Molecular Pathogens, 16. https://doi.org/10.5376/mp.2025.16.0015