Gene to Field: Biotechnological Interventions Against New-Age Crop Pests

**Abstract**

World agriculture continues to intensify while climate driven insect migration speeds up between geographic areas to cause agricultural producers to battle new insect pests which endanger both yield production and food safety standards. When measured comparatively pest control methods specifically chemical pesticides have demonstrated diminished operational effectiveness compared to their peak results. The increasing resistance of insects to chemical agents causes damage to helpful insect populations while disrupting ecosystem stability in natural areas. The future potential of biotechnology became evident as new sophisticated pest control systems started to emerge within the last few years. The article examines several modern control concepts including genetically altered organisms that resist insects (*Bt* crops) along with RNAi technologies and newer gene-editing tools like CRISPR/Cas as well as mechanisms to manage insect microorganisms and symbiotic partners. Modern pest management methods permit highly targeted control approaches which protect the environment. Several progress strategies in pest management face multiple obstacles from the potential for pest adaptation to new technologies along with complex implementation needs along with uncertain natural ecological situations and complex regulatory rules and public resistance. Future integration of ecological initiatives with biotechnological methods will unite local communities with farmers to achieve sustainable practices through supportive policy development. Multiple combined approaches indicate that sustainable pest control solutions will lead to increased effectiveness throughout future time periods.

*Keywords:* *Biotechnological pest control, Emerging insect pests, RNA interference, CRISPR, Gene drive, Endosymbionts, Integrated pest management.*

# Introduction

The challenge from insect pests remains a global agricultural substantial threat because yearly crop losses reach between 20% and 40% of total production (Savary *et al*., 2019). The situation becomes more complicated because new pest species are appearing through global trade and movement as well as emerging due to ecological adaptations alongside climatic changes (Migeon and Dorkeld, 2008; Bebber, 2015). *Spodoptera frugiperda* (fall armyworm), *Tuta absoluta* (tomato leafminer) and *Helicoverpa armigera* have become notable pests because of rising global connectivity combined with climate change effects and modern high-intensity farming systems according to Sharanabasappa *et al*. (2018) and Desneux *et al*. (2010) together with the IPCC report (2021).

Traditional pest management methods that heavily use chemical insecticides have proven ineffective during successive years. Pest resistance is one reason for diminished effectiveness in addition to environmental damage which harms beneficial organisms and reduces biodiversity (Furlong *et al*., 2013; Sparks and Nauen, 2015). Heavy reliance on chemical controls fails to serve integrated pest management (IPM) functions while conflicting with sustainable farming principles (Kogan, 1998; Gurr *et al*., 2012). The escalating pest population challenge has made biotechnology rise as a fundamental tool that introduces multiple innovative solutions which address pest issues while being effective yet environmentally friendly. The primary elements of pest control technology employ *Bacillus thuringiensis* (*Bt*) insecticidal proteins within genetically modified organisms and RNA interference (RNAi) approaches that target necessary pest genes as well as state-of-the-art gene editing methods that utilize CRISPR-Cas9.

Pest population increases have made biotechnology emerge as the key solution for developing targeted solutions that protect both people and the environment. Three primary strategies for pest control adopt insecticidal *Bt* proteins delivered through genetically modified organisms together with RNAi which suppresses pest genes as well as modern CRISPR-Cas9 gene editing techniques. The application of microbe-based pesticides represents an essential trend because these products target specific pest populations while inflicting minimal damage to non-target biological entities (Gatehouse, 2008; Petrick *et al*., 2013; Zotti *et al*., 2018; Jinek *et al*., 2012). Modern omics technologies including genomics and proteomics together with molecular diagnostics have significantly enhanced our abilities to study pest species at various biological levels (Zhang *et al*., 2020). The research review examines multiple biotechnological options under development to oppose agricultural threats from newly adapting insect species as well as conventional pest management restrictions.

The review examines operational characteristics together with natural field effectiveness of these technologies while describing specific examples of their deployment at farm level. The review incorporates consideration for how these developments could be received by integrated pest management schemes. This review identifies specific challenges associated with general application caused by regulatory restrictions together with public objections and technological barriers. The review identifies essential domains in which upcoming RandD initiatives should focus on enhancing both the operational feasibility and practical worth of these techniques.

# Emerging Insect Pests: An Overview

According to Kenis *et al*. (2009), emerging insect pests relate to species which enter new geographic areas for their first-time appearance or start causing more damage in areas where they used to be unimportant due to altering environmental conditions and evolving agricultural methods and changing socioeconomic patterns. New pests pose major challenges to farmers and pest control professionals because they demonstrate quick environmental adjustment alongside high reproduction rates and broad feeding patterns toward multiple host plants. Different interconnected elements lead to the development and dispersion of these pest species. The most critical elements that foster pest species development include international trade and travel expansion combined with climate change and changes in land management along with pesticide resistance developments and widespread adoption of monoculture farming (Bebber, 2015; Kriticos *et al*., 2015; Deutsch *et al*., 2018).

## Causes of Emergence

The globalization process accompanied by plant material movements has become a primary source of new insect pest development as it unintentionally lets invasive species establish themselves in places where they had no prior existence (Liebhold *et al*., 2016). Insects have accomplished three key ecological modifications through climate change as the environment becomes habitable for them in places they formerly avoided and expands their annual reproduction numbers and shifts their seasonal patterns (Deutsch *et al*., 2018). Extensive monoculture-based modern intensive agriculture enables pests to continuously encounter host plants because of its characteristic focus on single crop cultivation thus leading to outbreak conditions (Gurr *et al*., 2012). The repeated use of synthetic insecticides has sped up pest resistance development in various species to the point where infestations have become worse according to Sparks and Nauen (2015). Pest resurgence has occurred because previous minor pests have now become significant agricultural threats according to Georghiou (1986). This phenomenon is attributed to changes in insect status within agricultural systems.

## Notable Emerging Pests in Agriculture

Today, various pest insects have come to represent key problems in agricultural production, mainly due to their fast spread in various regions and their ability to inflict significant agricultural losses on valuable crops. These insects have drawn global attention due to their tenacity and destruction capacity:

Fall armyworm (*Spodoptera frugiperda*), previously endemic in the Americas, now extends its distribution across different parts of Africa, significant parts of Asia, and specific parts of Australia. It causes significant damage to maize as well as other cereals, resulting in significant yield losses and subsequent economic implications (Goergen *et al*., 2016; Sharanabasappa *et al*., 2018). The tomato leafminer from South America, or *Tuta absoluta*, has spread quickly to regions involved in tomato cultivation in Europe, Africa, and Asia. Its potential to inflict great damage in both open-field cultivation and controlled environments, like greenhouses, makes it a significant threat to global tomato production (Desneux *et al*., 2010). The cotton bollworm or *Helicoverpa armigera* was originally endemic in parts of Asia and Australia; it later expanded its range and hybridized in the Americas with *H. zea*. Its invasive potential was thus increased while that of conventional methods of controlling it was reduced (Tay *et al*., 2013). The cotton mealybug (*Phenacoccus solenopsis*) infests various host crops and poses enormous challenges to cotton growers in countries like India and Pakistan. Its population explosion is often driven by the collapse of natural enemies, which generally occurs through the overuse of chemical pesticides (Hodgson *et al*., 2008).

## Economic and Ecological Impacts

The damage that emerging pests inflict on the economy amounts to enormous losses. The fall armyworm pest is responsible for nearly USD 2.5-6.2 billion of agricultural losses each year in African farming sectors (Day *et al*., 2017). The pests create substantial monetary damage to crops but also disrupt ecological systems by reducing biodiversity and making farmers dependent on chemical pesticides which deteriorates long-term environmental sustainability (Lu *et al*., 2012).

## Challenges in Management

Multiple significant obstacles make it difficult to deal with newly emerging pest insect situations effectively and promptly. Pests usually remain unnoticed until they trigger substantial damage so their detection becomes both harder and more expensive. Many regions fail to execute proper biosecurity protocols and maintain insufficient quarantine protocols at their borders. The diffusion of harmful invasive organisms occurs rapidly because they avoid detection during their initial spread. Different pests follow different behaviors between their various environmental habitats. Failure of standard pest management approaches happens when local populations do not have suitable treatment methods. The quick evolution of pests causes them to develop resistance against every type of pest control strategy from chemical pesticides to *Bt* crops. The current methods of pest control grow less effective because pests develop resistance (Tabashnik *et al*., 2013). The increasing need exists for smarter scientific methods based on biotechnology to develop sustainable solutions that address rising insect-related problems.

# Biotechnological Tools in Insect Pest Management

Multiple significant obstacles make it difficult to deal with newly emerging pest insect situations effectively and promptly. Pests usually remain unnoticed until they trigger substantial damage so their detection becomes both harder and more expensive. Many regions fail to execute proper biosecurity protocols and maintain insufficient quarantine protocols at their borders. The diffusion of harmful invasive organisms occurs rapidly because they avoid detection during their initial spread. Different pests follow different behaviors between their various environmental habitats. Failure of standard pest management approaches happens when local populations do not have suitable treatment methods. The quick evolution of pests causes them to develop resistance against every type of pest control strategy from chemical pesticides to *Bt* crops. The current methods of pest control grow less effective because pests develop resistance (Tabashnik *et al*., 2013). The increasing need exists for smarter scientific methods based on biotechnology to develop sustainable solutions that address rising insect-related problems.

## Transgenic Crops Expressing Insecticidal Proteins

Neutral farming produces insecticidal *Bt* proteins from Bacillus thuringiensis in genetically modified crops which function as a leading biotechnology application for pest management (James, 2017). GE crop modification results in Cry or Vip protein production which produces fatal effects when pests consume this material and results in digestive system failure (Bravo *et al*., 2011). Since their commercial release in 1996 both *Bt* maize and *Bt* cotton seeded successfully throughout agricultural regions of the United States, India, China, and Brazil. Genetically modified crops substantially reduced the populations of *Helicoverpa armigera* together with *Spodoptera frugiperda* and *Ostrinia nubilalis* through extensive pest control measures. These genetically modified crops promote the reduction of chemical insecticide use (Kathage and Qaim, 2012; Wu *et al*., 2008). Bt toxin resistance in specific pest populations has become a major difficulty that counters the success achieved by these crops. The development of pyramided *Bt* crops expressed with multiple toxins stands as a major strategy to overcome this issue. Refuge strategies have received support from researchers for managing resistant pest populations since they require planting *Bt*-free crops adjacent to *Bt*-crops to maintain vulnerable pest populations (Tabashnik *et al*., 2013; Carrière *et al*., 2016).

## RNA Interference (RNAi)

The natural gene-silencing mechanism RNA interference (RNAi) functions through double-stranded RNA (dsRNA) introduction that causes specific messenger RNA (mRNA) molecule degradation thus silencing targeted genes inside organisms (Fire *et al*., 1998). RNAi demonstrates its value in insect pest management through disruption of vital survival genes including developmental and reproductive genes and detoxification factor genes (Zhu *et al*., 2011). The agricultural delivery of RNAiBUGs has two main procedural approaches under investigation. The first method uses plant-mediated RNAi which enables genetically modified plants to manufacture dsRNA that focuses on pest-specific genes. Administering dsRNA either by crop direct spray application or by using nanoparticle carriers represents two main topical delivery methods (Cagliari *et al*., 2019; Christiaens *et al*., 2018). RNAi-based technology delivers precise targeting abilities because its actions selectively limit negative impacts on undesired species. The technology has shown effectiveness in controlling *Diabrotica virgifera* (western corn rootworm) and *Helicoverpa armigera* (cotton bollworm) and *Bemisia tabaci* (whitefly). Multiple inhibiting factors stand in the way of regular implementation. Lepidoptera represent a major concern since these insects show lower response frequencies to RNAi compared to other insect orders. The unpredictable weather conditions cause dsRNA to become unstable which results in significant barriers to achieving consistent application in the field (Zhang *et al*., 2020).

## Genome Editing Technologies

CRISPR-Cas9 serves as an example of genome editing tools which now enables scientists to perform very specific alterations to genes of selected insects alongside other organisms. Laboratory technicians use this strategy to eliminate vital pest genes and develop sterile insect populations or create genetically modified pest-resistant crops (Jinek *et al*., 2012; Taning *et al*., 2017). Scientists have transformed CRISPR into gene drives which enhance the inheritance of particular genetic characteristics throughout pest communities. The genetically engineered drives possess capabilities to distribute traits which minimize pest fertility level as well as make them more exposed to control agents leading to population control or extinction (Esvelt *et al*., 2014). Extended scientific applications using gene-edited organisms led to significant ecological along with ethical concerns about organisms which propagate genetic changes. Application of these modifications has been marked by slow progress and stringent regulations because of environmental side effects and irreversible nature of these methods (National Academies of Sciences, Engineering, and Medicine, 2016).

## Microbial Based Biopesticides and Endophytes

Entomopathogenic pesticides consisting of biopesticide products derived from *Bacillus* and *Pseudomonas* bacterial clades as well as *Beauveria bassiana* and *Metarhizium anisopliae* fungal pathogens and nucleopolyhedroviruses (NPVs) and granuloviruses (GVs) remain viable and natural alternatives to chemical insecticides (Glare *et al*., 2012). The friendly environmental pathogens can infect and destroy pest insects yet pose no substantial threat to either domesticated animals or beneficial arthropods or human safety. The field efficiency of biological control agents has improved while their environmental stability and virulence together with their effectiveness have increased through biotechnological advancements. Genetically engineered baculoviruses serve as a good example because they incorporate insect-specific neurotoxin genes enabling faster pest deaths than their wild-type counterparts (Inceoglu *et al*., 2001). The application of endophytic microorganisms which live inside plant tissues without causing damage emerges as a modern approach for pest control. The microbes either produce insect-killing compounds directly or use plant defense mechanisms to trigger systemic defense in plants (Jaber and Ownley, 2018). These developments demonstrate that microbe-based biopesticides should be considered vital components for sustainable agricultural practices.

## Molecular Diagnostics and Monitoring Tools

The application of biotechnology facilitated faster and more accurate diagnostic procedures that monitor pests in the environment. DNA barcoding along with quantitative PCR (qPCR) has become prevalent in pest monitoring for species confirmation as well as population genetic analysis and resistance gene surveillance of pest populations (Foottit *et al*., 2008; Li *et al*., 2022). February 21, 2023, these technologies serve to increase pest dynamics information which generates strategic and well-informed decisions for integrated pest management.

# Case Studies: Application of Biotechnological Approaches Against Insect Pests

Various practical applications within different agricultural systems have improved the application of biotechnology in pest management methods. This report includes substantial case studies that demonstrate field-level effects of employing biotechnologies to handle insect pest infestations of new and invasive species. The case studies present both the positive achievements together with the negative outcomes to provide an all-encompassing understanding of operating new technologies in actual field situations.

## Bt Cotton Against *Helicoverpa armigera* in India

Introduction of *Bt* cotton in India in 2002 was a revolutionizing turn of events in the control of pests, and most notably the *Helicoverpa armigera*, a very polyphagous pest, inflicting extensive losses to cotton as well as to numerous other crops (Qaim and Zilberman, 2003). These genes of *Bt* cotton had been engineered to express the Cry1Ac protein, which played an important role in significantly containing the infestation of the bollworm and notably reducing chemical insecticide use (Kranthi *et al*., 2005).

Although in its early years it was a commercial success, intensive and sequential employment of single-gene *Bt* cotton cultivars eventually resulted in the development of resistance in *H. armigera*, particularly in regions where refuge systems were poorly utilized or ignored (Tabashnik *et al*., 2013; Jadhav *et al*., 2006). To prevent this, newer pyramided *Bt* cotton hybrids containing both the Cry1Ac and Cry2Ab toxins were created to restrict resistance development. These were complemented by a new emphasis on integrated resistance management (IRM) strategies to ensure the sustainable effectiveness of *Bt* technology.

## RNAi-Based Control of Western Corn Rootworm (*Diabrotica virgifera virgifera*)

The western corn rootworm qualifies as one of the most damaging pests against American maize crops along with European agricultural zones. *Bt* cotton along with traditional insecticides demonstrated limited effectiveness against the pest but resistance caused them to lose their lasting worth. The industry developed MON 87411 maize as the initial RNAi-based product designed for pest control. The genetically designed corn expresses double-stranded RNA (dsRNA) against the Snf7 gene which controls insect cell integrity (Baum *et al*., 2007; Head *et al*., 2017).

A field assessment of MON 87411 corn exhibited encouraging outcomes which corresponded with reduced root destruction alongside less adult death among larvae. The United States Environmental Protection Agency granted commercial authorization to this RNA interference (RNAi) corn which will be employed in an integrated pest management (IPM) system in 2017 (USEPA, 2017). The situation demonstrates how RNAi technology provides both efficient and precise pest population management tools when traditional pest control measures have become ineffective.

## CRISPR-Based Gene Editing in *Spodoptera frugiperda*

Since its 2016 invasion fall armyworm (*Spodoptera frugiperda*) has rapidly spread across African as well as Asian and Australian agricultural ecosystems to destroy massive quantities of crops including maize and sorghum alongside many others. Most existing control programs utilize chemical insecticides and *Bt* crops as their main countermeasures but a rising resistance problem with these methods has raised significant danger (Goergen *et al*., 2016; Ganiger *et al*., 2018). Researchers utilize CRISPR/Cas9 gene editing technology to disable important genes in *S. frugiperda* which determine development along with these genes' resistance mechanisms using ABCC2, CYP450 and Vg as examples. Scientists conducting laboratory studies using controlled conditions proved that blocking pest development and enhancing toxin sensitivity occurs when key genes are inactivated (Koch *et al*., 2020; Wang *et al*., 2021). These experimental gene-edited methods show promising indicators of developing new sustainable pest management solutions and green control methods for this resilient insect pest.

## Baculovirus-Based Biopesticides for *Helicoverpa armigera* and *Spodoptera litura*

Studies on nucleopolyhedrovirus (NPV)-derived biopesticides for controlling *Helicoverpa armigera* and *Spodoptera litura* take place in Australia and India with uncertain outcomes. The agricultural industry utilizes the commercial formulation *Helicoverpa armigera* NPV (HaNPV) for biological larval stage eradication across agricultural fields (Sunitha *et al*., 2013; Rabindra and Jayaraj, 1988). The operational pace of viral pathogens remains slower than conventional insecticides but these biological pathogens show better target specificity combined with environmental compatibility. Modern artificial DNA processing techniques have created new possibilities to fragment genetic material for improved viral epidemiological traits and virus field efficacy (Inceoglu *et al*., 2001). The profitable implementation of NPVs within integrated pest management (IPM) systems serves as a critical factor for enhancing the operational effectiveness and practicality.

## Endophyte-Mediated Resistance in Rice and Maize

Endophyte microorganisms like *Beauveria bassiana* and *Metarhizium anisopliae* were used to bring solutions directly to the plant's internal tissue in a bid to realize systemic protection of crops from insects like rice stem borers and maize aphids. These beneficial microorganisms were reported to have the potential to reduce pest infestations while, at the same time, enhancing the expression of genes that relate to plant defense mechanisms (Vidal and Jaber, 2015; Gurulingappa *et al*., 2010).

Empirical evidence has proven that endophyte-infected plants are more resistant to infestation by insects and have improved yield consistency. Endophytic fungi's dual mode of operation, involving both direct insect-killing effects and the initiation of the plant's immune response, classifies them as a very valuable biotechnological tool for the sustainable and environmentally friendly control of insects.

# Challenges and Limitations of Biotechnological Approaches

The benefits that biotechnology developments supply for controlling new pest insects remain substantial yet implementing these solutions in practice encounters multiple challenges. Different obstacles preventing the implementation of biotechnology advances exist within biological, ecological, technical, socio-economic and regulatory frameworks. Multiple approaches from different disciplines should be integrated with pest behavior comprehension when implementing new technologies to reach their full potential in agricultural systems.

## Resistance Development and Pest Adaptation

Biotechnological pest control faces the major challenge that pest insects develop resistance during prolonged utilization periods. *Bt* crop resistance demonstrates that *Pectinophora gossypiella* and *Helicoverpa zea* and *Spodoptera frugiperda* pest species now survive Cry protein exposure (Tabashnik *et al*., 2013; Gassmann *et al*., 2014). Total dsRNA uptake reduction and gene redundancies in targeted gene sequence can emerge among insect populations because of repeated applications involving RNAi-based pest management systems (Palli, 2014; Christiaens *et al*., 2020). Scientists propose various integrated solutions for controlling resistance developments which integrate gene pyramid strategies together with *Bt* trait resistance and non-*Bt* refuge management systems and rotating crops. The level of practice implementation has differed significantly among different geographic areas (Carrière *et al*., 2016).

## Delivery and Expression Constraints

The effective delivery of biotechnological solutions remains difficult especially for RNA interference (RNAi) and microbial symbionts. Different insect species show inconsistent uptake of double-stranded RNA (dsRNA) and enzyme damage combined with restricted molecular spread throughout the insect body reduces the effectiveness of RNAi methods (Whyard *et al*., 2009; Christiaens *et al*., 2018). The implementation process for stable inheritable gene modifications in non-model insect species remains complicated and leads to high expenses and development costs. Success of transgenic crops requires proper scheduling of *Bt* and RNAi transgene expression to match pest feeding behaviors. The precise timing of transgene expression with pest feeding patterns remains essential however field environment variability makes it difficult to maintain regular synchronization according to Koch and Kogel (2014).

## Ecological and Non-Target Risks

Non-target organisms are mainly affected by the ecological risks that emerge from biotechnological pest control approaches. Research indicates that Cry proteins function as pest-specific agents yet some environmental conditions may cause them to impact non-target herbivores and beneficial predators or parasitoids (Lövei and Arpaia, 2005; Romeis *et al*., 2019). The manipulation of Wolbachia microbial symbionts and genetically modified endophytes through genetic modification presents risks of horizontal gene transfer that need thorough investigation (NASEM, 2016). Approaches to evaluate genetic insect and microorganism release risks maintain an active developmental stage while predicting the interactions between these interventions and real ecosystems represents a substantial scientific challenge.

## Regulatory and Public Acceptance Issues

Various countries maintain different sets of regulations that control biotechnological pest control methods. The United States and Brazil together with India accept *Bt* crops yet the European Union area opposes them because of environmental security and public health-related worries (Davison, 2010). CRISPR-based gene editing systems together with RNAi technologies face very strict regulatory assessment procedures. Current policies to regulate gene-edited organisms and synthetic biology tools across most regions are under development because they face numerous ambiguities and variabilities in standards (Esvelt and Gemmell, 2017). Public views about these technologies in farming applications remain restricted by sentiments based on ethical factors together with concerns about socioeconomic implications and cultural beliefs even though such viewpoints create new impediments for widespread agricultural use.

## Economic and Access Barriers

A main impediment to the adoption of biotechnological methods of managing pests stems from the reality that many of the innovations are produced by large agribusiness corporations that may restrict their availability for small-scale farmers. High input prices, exclusive rights agreements, and lack of access to farm extension services often restrict the ability of economically marginalized communities to access opportunities provided by the innovations (Fischer *et al*., 2015). As a result, it creates a digital and technical divide that stifles equitable and extensive adoption, particularly in middle-income and developing countries.

In supporting their wide application, it is critical to invest in capacity-building programs aimed at improving capacity, fostering public-private sector partnerships, and promoting inclusive biotechnology developments. Institution of these steps would greatly bolster efforts to end existing gaps and support broader dissemination of environmentally friendly pest management practices (Juma, 2011).

# Future Prospects

The growing threat from new and exotic insect pests exacerbated by drivers such as climate change, increased global commerce, and the increasing resistance to traditional control options necessitates the development of visionary and creative pest management solutions. Biotechnological options are a significant hope to transform the practice of pest control in agriculture to be more specific, less environmental, and responsive to evolving threats.

## Emerging Biotechnological Innovations

Advances in gene editing technologies, especially those based on CRISPR methods, contain immense opportunities for the specific targeting and manipulation of pest populations. One of them is the use of gene drives that are aimed at spreading detrimental traits rapidly in insect populations, which are under consideration for disease vector management of Aedes aegypti and agricultural pest management of *Drosophila suzukii* and *Spodoptera frugiperda* (Esvelt *et al*., 2014; Champer *et al*., 2018). Although these technologies show potential, they need to overcome various hurdles related to safety, ethical implications and the regulatory landscape before reaching extensive deployment.

At the same time, synthetic biology is providing new methods for pest management in the form of engineered symbiotic microorganisms, pest detection biosensors, and genetically modified crops that contain programmable defense systems (Bervoets and Charlier, 2019). Through the use of module gene constructs, it is possible to introduce inducible resistance technologies that can later confer decreased harmful environmental impact while improving biosafety.

Furthermore, new RNAi delivery systems using nanoparticles, viral vectors or microbial vectors are being engineered to improve the stability, bioavailability, and systemic activity of RNA molecules in target insects (Joga *et al*., 2016; Zotti *et al*., 2018). Integrating these technologies with artificial intelligence-based pest monitoring and forecasting platforms could lead to more dynamic and effective integrated pest management (IPM) programs.

## Integrated and Holistic Pest Management

In future applications, biotechnological tools should be considered as parts of integrated, ecologically based pest management strategies rather than as single treatments. Integration of these technologies with traditional tactics, namely, cultural controls, mechanical controls, biological control agents, and habitat alteration enables their use in a sustainable manner for a longer term while concurrently decreasing the dependency on chemical pesticides (Kogan, 1998).

Implementation of the principle of integrative holism requires an interdisciplinary approach. It becomes crucial to coordinate with researchers across disciplines like molecular biology, ecology, agronomy, and agricultural extension in order to collectively design and implement solutions that are unique to local ecosystems. Collective efforts ensure that the developed technologies are technically feasible as well as economically viable and environmentally friendly.

## Policy, Capacity Building, and Stakeholder Engagement

In order to achieve optimal efficacy of the applications of biotechnology for pest management, there needs to be strong policy frameworks, streamlined regulatory processes, and public participation in decision making. Prominent practices that ensure public confidence and promote popular acceptance include the harmonization of biosafety standards, streamlining of authorization procedures, and clear communication of related risks and benefits (FAO, 2021; NASEM, 2016).

Just as important is the need to invest in capacity development, especially in low- and middle-income nations, to ensure equitable access to the benefits provided by biotechnology. This includes the offering of education and practical training in fields like genetic engineering, molecular diagnostics, bioinformatics, and risk assessment, as well as strengthening regional research institutes and agricultural extension services (Juma, 2011).

# Conclusion

Recent developments in the field of biotechnology have revolutionized traditional pest management strategies by bringing in new and innovative strategies for addressing many of the toughest agricultural insect-related problems. New tools like *Bt* crops, RNA interference (RNAi), CRISPR gene editing, and microbial symbionts are novel strategies that can be used to control pests. However, the success of these technologies depends on rigorous deployment, incorporation in integrated pest management schemes, and cooperative studies that factor in the needs of various stakeholders. Developing a pest management strategy that can meet future needs requires a delicate balance between new technologies, environmental stewardship, farmer acceptance, and strict rules and regulations. Through international cooperation, biotechnology also promises to rise to a core technology that enables sustainable and resilient agricultural systems.

Ethical approval

No animals and human participants are harmed.

COMPETING INTERESTS DISCLAIMER:

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

# References

1. Baum, J. A., Bogaert, T., Clinton, W., Heck, G. R., Feldmann, P., Ilagan, O., ... and Roberts, J. (2007). Control of coleopteran insect pests through RNA interference. *Nature biotechnology*, *25*(11), 1322-1326.
2. Bebber, D. P. (2015). Range-expanding pests and pathogens in a warming world. *Annual review of phytopathology*, *53*(1), 335-356.
3. Bervoets, I., and Charlier, D. (2019). Engineering of synthetic microbial communities for sustainable biotechnology. Biotechnology Advances, 37(6), 107460.
4. Bravo, A., Likitvivatanavong, S., Gill, S. S., & Soberón, M. (2011). Bacillus thuringiensis: a story of a successful bioinsecticide. *Insect biochemistry and molecular biology*, *41*(7), 423-431.
5. Cagliari, D., Dias, N. P., Galdeano, D. M., Dos Santos, E. Á., Smagghe, G., & Zotti, M. J. (2019). Management of pest insects and plant diseases by non-transformative RNAi. *Frontiers in plant science*, *10*, 1319.
6. Carrière, Y., Crickmore, N., and Tabashnik, B. E. (2016). Optimizing pyramided transgenic *Bt* crops for sustainable pest management. *Nature Biotechnology*, 34(2), 113–118.
7. Champer, J., Liu, J., Oh, S. Y., Reeves, R., Luthra, A., Oakes, N., ... & Messer, P. W. (2018). Reducing resistance allele formation in CRISPR gene drive. *Proceedings of the National Academy of Sciences*, *115*(21), 5522-5527.
8. Christiaens, O., Niu, J., Taning, C. N. T., and Smagghe, G. (2018). RNAi in insects: A guide to successful application. *Pest Management Science*, 74(12), 2863–2869.
9. Christiaens, O., Whyard, S., Vélez, A. M., and Smagghe, G. (2020). Double-stranded RNA technology to control insect pests: Current status and challenges. *Frontiers in Plant Science*, 11, 451.
10. Davison, J. (2010). GM plants: Science, politics and EC regulations. *Plant Science*, 178(2), 94–98.
11. Day, R., Abrahams, P., Bateman, M., Beale, T., Clottey, V., Cock, M., ... and Witt, A. (2017). Fall armyworm: Impacts and implications for Africa. *Outlooks on Pest Management*, 28(5), 196–201.
12. Desneux, N., Luna, M. G., Guillemaud, T., and Urbaneja, A. (2010). The invasive South American tomato pinworm, *Tuta absoluta*, continues to spread in Afro-Eurasia and beyond: The new threat to tomato world production. *Journal of Pest Science*, 83(3), 197–215.
13. Deutsch, C. A., Tewksbury, J. J., Tigchelaar, M., Battisti, D. S., Merrill, S. C., Huey, R. B., and Naylor, R. L. (2018). Increase in crop losses to insect pests in a warming climate. *Science*, 361(6405), 916–919.
14. Esvelt, K. M., and Gemmell, N. J. (2017). Conservation demands safe gene drive. *PLOS Biology*, 15(11), e2003850.
15. Esvelt, K. M., Smidler, A. L., Catteruccia, F., and Church, G. M. (2014). Concerning RNA-guided gene drives for the alteration of wild populations. *eLife*, 3, e03401.
16. FAO (2021). Guidance on Risk Assessment of Genetically Engineered Insects. Food and Agriculture Organization of the United Nations.
17. Fire, A., Xu, S., Montgomery, M. K., Kostas, S. A., Driver, S. E., and Mello, C. C. (1998). Potent and specific genetic interference by double-stranded RNA in *Caenorhabditis elegans*. *Nature*, 391(6669), 806–811.
18. Fischer, R., Twyman, R. M., and Schillberg, S. (2015). Development and economic perspectives for molecular farming. *Advances in Biochemical Engineering/Biotechnology*, 149, 23–48.
19. Foottit, R. G., Maw, H. E. L., Von Dohlen, C. D., and Hebert, P. D. N. (2008). Species identification of aphids (Insecta: Hemiptera: Aphididae) through DNA barcodes. *Molecular Ecology Resources*, 8(6), 1189–1201.
20. Furlong, M. J., Wright, D. J., and Dosdall, L. M. (2013). Diamondback moth ecology and management: Problems, progress, and prospects. *Annual Review of Entomology*, 58, 517–541.
21. Ganiger, P. C., Yeshwanth, H. M., Muralimohan, K., Vinay, N., Kumar, A. R. V., & Chandrashekara, K. J. C. S. (2018). Occurrence of the new invasive pest, fall armyworm, Spodoptera frugiperda (JE Smith) (Lepidoptera: Noctuidae), in the maize fields of Karnataka, India. *Current Science*, *115*(4), 621-623.
22. Gassmann, A. J., Petzold-Maxwell, J. L., Clifton, E. H., Dunbar, M. W., Hoffmann, A. M., Ingber, D. A., & Keweshan, R. S. (2014). Field-evolved resistance by western corn rootworm to multiple Bacillus thuringiensis toxins in transgenic maize. *Proceedings of the National Academy of Sciences*, *111*(14), 5141-5146.
23. Gatehouse, J. A. (2008). Biotechnological approaches to insect resistance in crops. *Journal of Experimental Botany*, 59(3), 421–432.
24. Georghiou, G. P. (1986). The magnitude of the resistance problem. *Pesticide Science*, 17(2), 137–149.
25. Glare, T. R., Caradus, J. R., Gelernter, W. D., Jackson, T. A., Keyhani, N. O., Köhl, J., ... and Stewart, A. (2012). Have biopesticides come of age? *Trends in Biotechnology*, 30(5), 250–258.
26. Goergen, G., Kumar, P. L., Sankung, S. B., Togola, A., and Tamo, M. (2016). First report of outbreaks of the fall armyworm Spodoptera frugiperda (J E Smith) (Lepidoptera: Noctuidae), a new alien invasive pest in West and Central Africa. PLOS ONE, 11(10), e0165632.
27. Gurr, G. M., Wratten, S. D., Landis, D. A., and You, M. (2012). Habitat management to suppress pest populations: Progress and prospects. *Annual Review of Entomology*, 57, 91–113.
28. Gurulingappa, P., Sword, G. A., Murdoch, G., and McGee, P. A. (2010). Colonization of crop plants by fungal entomopathogens and their effects on two insect pests when used as endophytes. Biological Control, 55(1), 34-41.
29. Head, G. P., Carroll, M. W., Evans, S. P., Rule, D. M., Willse, A. R., Clark, T. L., ... & Meinke, L. J. (2017). Evaluation of SmartStax and SmartStax PRO maize against western corn rootworm and northern corn rootworm: efficacy and resistance management. *Pest management science*, *73*(9), 1883-1899.
30. Hodgson, C. J., Abbas, G., Arif, M. J., Saeed, S., and Karar, H. (2008). Phenacoccus solenopsis Tinsley (Sternorrhyncha: Coccoidea: Pseudococcidae), an invasive mealybug damaging cotton in Pakistan and India, with a discussion on seasonal morphological variation. *Zootaxa*, 1913, 1–35.
31. Inceoglu, A. B., Kamita, S. G., and Hammock, B. D. (2001). Genetically modified baculoviruses: A historical overview and future outlook. Advanced Virus Research, 56, 137–164.
32. IPCC. (2021). *Climate Change 2021: The Physical Science Basis.* Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.
33. Jaber, L. R., and Ownley, B. H. (2018). Can we use endophytes to confer plant resistance to insect pests? *Fungal Ecology*, 35, 20–29.
34. Jadhav, D. R., Moharil, M. P., Tayde, A. A., and Nimbalkar, S. A. (2006). Monitoring of resistance to Cry1Ac toxin of Bacillus thuringiensis in Helicoverpa armigera (Hubner) from India. Current Science, 91(6), 832–836.
35. James, C. (2017). Global status of commercialized biotech/GM crops: 2017. *ISAAA Brief No. 53*.
36. Jinek, M., Chylinski, K., Fonfara, I., Hauer, M., Doudna, J. A., and Charpentier, E. (2012). A programmable dual-RNA–guided DNA endonuclease in adaptive bacterial immunity. *Science*, 337(6096), 816–821.
37. Joga, M. R., Zotti, M. J., Smagghe, G., and Christiaens, O. (2016). RNAi efficiency, systemic properties, and novel delivery methods for pest insect control: What we know so far. Frontiers in Physiology, 7, 553.
38. Juma, C. (2011). The New Harvest: Agricultural Innovation in Africa. *Oxford University Press.*
39. Kathage, J., and Qaim, M. (2012). Economic impacts and impact dynamics of *Bt* (Bacillus thuringiensis) cotton in India. *PNAS*, 109(29), 11652–11656.
40. Kenis, M., Auger-Rozenberg, M. A., Roques, A., Timms, L., Péré, C., Cock, M. J., ... and Lopez-Vaamonde, C. (2009). Ecological effects of invasive alien insects. *Biological Invasions*, 11(1), 21–45.
41. Koch, A., and Kogel, K. H. (2014). New wind in the sails: Improving the agronomic value of crop plants through RNAi-mediated gene silencing. *Plant Biotechnology Journal*, 12(7), 821–831.
42. Koch, A., Stein, J. A., Biedenkopf, D., and Kogel, K. H. (2020). RNA-based insect control using plant viruses: The case of the fall armyworm. Frontiers in Plant Science, 11, 776.
43. Kogan, M. (1998). Integrated pest management: Historical perspectives and contemporary developments. Annual Review of Entomology, 43(1), 243–270.
44. Kranthi, K. R., Naidu, S., Dhawad, C. S., Tatwawadi, A., Mate, K., Patil, E., ... & Kranthi, S. (2005). Temporal and intra-plant variability of Cry1Ac expression in Bt-cotton and its influence on the survival of the cotton bollworm, Helicoverpa armigera (Hübner)(Noctuidae: Lepidoptera). *Current Science*, 291-298.
45. Kriticos, D. J., Ota, N., Hutchison, W. D., Beddow, J., Walsh, T., Tay, W. T., ... and Zalucki, M. P. (2015). The potential distribution of invading *Helicoverpa armigera* in North America: Is it just a matter of time? *PLOS ONE*, 10(3), e0119618.
46. Li, C., Liu, X., Jiang, F., Liu, Y., and Chen, C. (2022). Advances in molecular detection technologies for insect pest management. *Pest Management Science*, 78(2), 673–685.
47. Liebhold, A. M., Brockerhoff, E. G., Garrett, L. J., Parke, J. L., and Britton, K. O. (2016). Live plant imports: The major pathway for forest insect and pathogen invasions of the US. *Frontiers in Ecology and the Environment*, 10(3), 135–143.
48. Lövei, G. L., and Arpaia, S. (2005). The impact of transgenic plants on natural enemies: A critical review of laboratory studies. *Entomologia Experimentalis et Applicata*, 114(1), 1–14.
49. Lu, Y., Wu, K., Jiang, Y., Guo, Y., and Desneux, N. (2012). Widespread adoption of *Bt* cotton and insecticide decrease promotes biocontrol services. *Nature*, 487(7407), 362–365.
50. Migeon, A., and Dorkeld, F. (2008). Spider mites web: a comprehensive database for the Tetranychidae. *Centre de Biologie et de Gestion des Populations*, France.
51. NASEM (National Academies of Sciences, Engineering, and Medicine). (2016). Genetically Engineered Crops: Experiences and Prospects. *The National Academies Press.*
52. Palli, S. R. (2014). RNA interference in Colorado potato beetle: Steps toward development of dsRNA as a commercial insecticide. *Current Opinion in Insect Science*, 6, 1–8.
53. Petrick, J. S., Brower-Toland, B., Jackson, A. L., and Kier, L. D. (2013). Safety assessment of food and feed from biotechnology-derived crops employing RNA-mediated gene regulation to achieve desired traits: A scientific review. *Regulatory Toxicology and Pharmacology*, 66(2), 167–176.
54. Qaim, M., and Zilberman, D. (2003). Yield effects of genetically modified crops in developing countries. Science, 299(5608), 900–902.
55. Rabindra, R. J., and Jayaraj, S. (1988). Microbial control of Helicoverpa armigera (Hubner): Field evaluation of NPV. Indian Journal of Agricultural Sciences, 58(8), 642–645.
56. Romeis, J., McLean, M. A., and Shelton, A. M. (2019). When bad science makes good headlines: *Bt* maize and regulatory bans. *GM Crops and Food*, 10(1), 44-58.
57. Savary, S., Willocquet, L., Pethybridge, S. J., Esker, P., McRoberts, N., and Nelson, A. (2019). The global burden of pathogens and pests on major food crops. *Nature Ecology and Evolution*, 3, 430–439.
58. Sharanabasappa, Kalleshwaraswamy, C. M., Maruthi, M. S., and Pavithra, H. B. (2018). Biology of invasive fall armyworm (*Spodoptera frugiperda*) on maize in India. *Journal of Entomology and Zoology Studies*, 6(6), 423–426.
59. Sparks, T. C., and Nauen, R. (2015). IRAC: Mode of action classification and insecticide resistance management. *Pesticide Biochemistry and Physiology*, 121, 122–128.
60. Sunitha, C., Mallikarjunaiah, G., and Goud, S. R. (2013). Evaluation of HaNPV against Helicoverpa armigera on cotton and pigeonpea under field conditions. International Journal of Plant Protection, 6(2), 447-451.
61. Tabashnik, B. E., Brévault, T., and Carrière, Y. (2013). Insect resistance to *Bt* crops: Lessons from the first billion acres. *Nature Biotechnology*, 31(6), 510–521.
62. Taning, C. N. T., van Eynde, B., Yu, N., Ma, S., Smagghe, G. (2017). CRISPR/Cas9 in insects: Applications, best practices and biosafety concerns. *Journal of Insect Physiology*, 98, 245–257.
63. Tay, W. T., Soria, M. F., Walsh, T., Thomazoni, D., Silvie, P., Behere, G. T., ... and Downes, S. (2013). A brave new world for an old-world pest: *Helicoverpa armigera* (Lepidoptera: Noctuidae) in Brazil. *PLOS ONE*, 8(11), e80134.
64. USEPA (United States Environmental Protection Agency). (2017). RNAi Plant-Incorporated Protectant (PIP) for Corn Rootworm Control.
65. Vidal, S., and Jaber, L. R. (2015). Entomopathogenic fungi as endophytes: Plant–endophyte–herbivore interactions and prospects for use in pest control. Current Science, 109(1), 46–54.
66. Wang, L., Huang, W., Zhang, X. (2021). CRISPR/Cas9-mediated knockout of the ABCC2 gene confers resistance to Cry1F in Spodoptera frugiperda. Insect Science, 28(3), 688–698.
67. Whyard, S., Singh, A. D., and Wong, S. (2009). Ingested double-stranded RNAs can act as species-specific insecticides. *Insect Biochemistry and Molecular Biology*, 39(11), 824–832.
68. Wu, K., Lu, Y., Feng, H., Jiang, Y., and Zhao, J. (2008). Suppression of cotton bollworm in multiple crops in China in areas with *Bt* toxin-containing cotton. *Science*, 321(5896), 1676–1678.
69. Zhang, H., Li, H. C., and Miao, X. X. (2020). Feasibility, limitation and possible solutions of RNAi-based technology for insect pest control. *Insect Science*, 27(3), 154–164.
70. Zhu, K. Y., Palli, S. R., and Becnel, J. J. (2011). RNA interference in insects: Concepts and applications. In *Insect biotechnology* (pp. 249–270). Springer.
71. Zotti, M., dos Santos, E. A., Cagliari, D., Christiaens, O., Taning, C. N. T., and Smagghe, G. (2018). RNA interference technology in crop protection against arthropod pests, pathogens and nematodes. *Pest Management Science*, 74(6), 1239-1250.