

Genetic Modification in Integrated Pest Management: Advances, Challenges, and Future Directions for Africa

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Abstract

Pest damage continues to undermine food security and farmers' livelihoods in many developing regions, yet conventional pesticide-based control is increasingly constrained by resistance, environmental risks, and costs. Although genetic modification (GM) technologies are expanding rapidly, their practical role within Integrated Pest Management (IPM), particularly in African contexts, remains fragmented in the literature. This review therefore, aimed to (i) evaluate how GM technologies enhance the effectiveness and sustainability of IPM, (ii) examine evidence from global and regional applications, and (iii) identify technical, regulatory, and socio-economic barriers shaping adoption. A qualitative narrative review was conducted using peer-reviewed studies, policy reports, and case studies from major scientific databases published over the past 15 years, followed by thematic synthesis. The evidence shows that Bt crops, RNA interference, gene editing, gene drives, and modified insects or microbes can substantially reduce pesticide use, improve yields, and support ecological safety when integrated with monitoring, refuges, and biological control. However, effectiveness is constrained by pest resistance evolution, regulatory delays, biosafety concerns, public mistrust, and unequal farmer access. The review concludes that GM technologies are most beneficial when treated as complementary tools within ecological IPM rather than stand-alone solutions. To enable responsible adoption, governments should harmonize science-based biosafety regulations across regions and invest in farmer-centred extension programs that integrate resistance management and participatory learning.

Keywords: Genetic Modification, Integrated Pest Management, Advances, Challenges, Future Directions.

Introduction

Agricultural productivity remains fundamental to global food security, economic development, and ecological sustainability, particularly in developing countries where agriculture supports livelihoods and national economies (Islam, 2025). Yet pest infestations continue to impose severe constraints on crop production, with annual yield losses estimated at 20–40%, and even higher levels reported across parts of Africa and Asia (van Esse et al., 2020). Historically, synthetic chemical pesticides have been the dominant method of pest control (Ajinkya Tanaji et al., 2024). While effective in the short term, excessive and prolonged pesticide use has contributed to environmental pollution, human health risks, non-target organism decline, and the rapid evolution of resistant pest

populations (Ajinkya Tanaji et al., 2024). To address these limitations, Integrated Pest Management (IPM) has emerged as a more sustainable and ecologically grounded strategy (Zhou et al., 2024). Core IPM principles include routine pest surveillance, threshold-based intervention, and the conservation of beneficial organisms. Among biological tools, *Bacillus thuringiensis* (Bt) has long provided an alternative to synthetic insecticides, although microbial pesticides still account for a small share of global insecticide markets (Mehta, 2020).

Within this evolving pest management framework, genetic modification (GM) technologies have become increasingly prominent (Singh et al., 2023). Genetic engineering enables targeted alteration of an organism's DNA to introduce insect resistance, herbicide tolerance, virus resistance, or other agronomically beneficial traits (Hamdan & Tan, 2024; Faizal et al., 2024). Genetic control strategies such as the Sterile Insect Technique and engineered insects carrying suppressive traits fall under autocidal control approaches and have demonstrated effectiveness in multiple pest systems (Grilli et al., 2021; Alphey & Bonsall, 2018). Likewise, Bt crops such as Bt cotton and Bt maize have shown significant yield gains, pesticide reductions, and environmental benefits in several countries (Grilli et al., 2021).

Despite these advances, commercialization and integration outcomes remain uneven across the continent (Akinbo et al., 2021). Commercialization delay has been attributed to regulatory and legislative constraints (Ongu et al., 2023). These disparities highlight that technological performance alone does not determine successful adoption; governance structures, biosafety systems, and public engagement are equally influential. Although extensive empirical research documents the agronomic and environmental performance of GM technologies, there remains no sufficiently integrated synthesis examining how these innovations function within operational IPM systems, particularly in African contexts. Much of the literature treats GM crops either as stand-alone technological interventions or as subjects of regulatory and biosafety debate, rather than systematically evaluating their ecological compatibility, resistance management performance, and institutional integration within IPM frameworks. This fragmentation limits the development of coherent, evidence-based strategies for sustainable pest management. Existing reviews often focus separately on yield impacts, resistance biology, biosafety governance, or socio-economic adoption outcomes. Few studies synthesize these domains to assess the systemic conditions under which GM technologies enhance or constrain IPM objectives such as ecological balance, resistance durability, and smallholder resilience. This review, therefore, addresses this gap by synthesizing empirical findings across agronomic, ecological, regulatory, and socio-economic dimensions to identify patterns of successful and constrained GM-IPM integration.

Evidence from resistance management research underscores the importance of such integration. Studies indicate that pyramided Bt traits combined with structured refuge enforcement delay resistance evolution more effectively than single-toxin systems lacking oversight (Anderson et al., 2019; Alphey & Bonsall, 2018). Conversely, cases of weak stewardship and non-compliance have resulted in accelerated resistance development

(Anderson et al., 2019). These findings demonstrate that technological durability is inseparable from institutional capacity and monitoring systems. Similarly, harmonized biosafety frameworks and science-based regulatory systems are critical determinants of responsible adoption (Akinbo et al., 2021).

Accordingly, this review adopts a systems-oriented analytical perspective rather than presenting GM technologies as inherently beneficial or inherently problematic. It evaluates empirical evidence to determine the ecological, regulatory, and socio-economic conditions under which genetic modification contributes meaningfully to IPM objectives. This study provides a consolidated and policy-relevant synthesis aimed at strengthening sustainable pest management systems across Africa.

Methodology

This study employed a qualitative, narrative literature review approach to synthesize current knowledge on the integration of genetic modification (GM) technologies within Integrated Pest Management (IPM) systems. Scientific papers, policy briefs, and case studies were systematically collected from reputable databases such as Scopus, Web of Science, PubMed, Google Scholar, and JSTOR. The review focused on peer-reviewed articles published in the last 15 years, emphasizing recent advancements such as Bt crops, RNA interference, gene editing (CRISPR-Cas9), gene drives, and genetically modified insects and microbes. Inclusion criteria prioritized studies with empirical data, real-world applications, and relevance to smallholder and large-scale farming systems. Abstracts and full texts were screened to exclude duplicates, opinion pieces, and articles lacking scientific rigor. A thematic analysis was then employed to organize the literature under major categories: technological advances, field application, regulatory frameworks, ecological impacts, and socio-economic considerations. Case examples from various countries, including Uganda, were examined to highlight regional applications and policy implications. The findings were synthesized to provide insights into the scientific, socio-economic, and regulatory dimensions of genetic modification use in IPM.

Key Findings of the Study

Genetic Modification in Pest Management.

Genetic modification in pest management refers to the use of biotechnology to manipulate the genetic material of organisms, either pests or crops, to improve pest control outcomes (Hamdan and Tan, 2024). This modern approach targets pest species at the genetic level, offering high specificity and long-term solutions to persistent pest problems (Romeis et al., 2019). Genetic modification allows for the direct insertion, deletion, or alteration of genes, which can either enhance a plant's resistance to pests or disrupt critical biological functions in pest species themselves (Hamdan & Tan, 2024). Applications of genetic modification in pest management generally fall into three categories: transgenic crops, genetically modified insects, and genetically modified microorganisms (Romeis et al., 2019).

Transgenic Crops (Bt and Multi-Trait Varieties)

The review consistently identified Bt crops as the most extensively adopted and empirically evaluated GM-IPM tool. Across multiple agroecological regions, Bt cotton, Bt maize, and Bt brinjal have demonstrated substantial reductions in synthetic insecticide applications while maintaining or improving yields (Otim et al., 2022, Shelton et al., 2018). In Sub-Saharan Africa, field evaluations of Bt maize targeting fall armyworm reported damage levels below 10% in Bt varieties compared to over 60% in non-Bt controls, alongside significant reductions in pesticide sprays (Otim et al., 2022).

A clear consensus emerges that Bt crops are most effective when integrated within structured IPM systems rather than deployed as stand-alone solutions (Anderson et al., 2019, Alphey & Bonsall, 2018). Studies demonstrate that ecological compatibility improves when Bt crops are combined with crop rotation, refuge planting, intercropping, and biological control conservation (Romeis et al., 2019) (Shelton et al., 2018).

However, the review also identifies documented cases of resistance evolution, particularly where refuge compliance was weak or regulatory oversight was insufficient (Anderson et al., 2019, Alphey & Bonsall, 2018). The Brazilian experience with resistance in pink bollworm and fall armyworm systems illustrates that technological efficacy alone does not guarantee sustainability without the enforcement of stewardship.

Genetically Modified Insects (Sterile and Self-Limiting Technologies)

Genetically modified insects, including enhanced sterile insect techniques (SIT) and self-limiting gene systems, represent a second category of GM-IPM integration. The reviewed literature indicates that GM-based SIT approaches can achieve targeted pest suppression with high species specificity, thereby minimizing non-target effects compared to broad-spectrum insecticides (Anderson et al., 2019).

Scholarly consensus suggests that GM insects align closely with IPM principles of ecological selectivity and reduced chemical dependence. However, the findings reveal greater regulatory and public acceptance challenges relative to transgenic crops (Anderson et al., 2019). Biosafety oversight, risk communication, and cross-border regulatory harmonization are repeatedly identified as limiting factors to wider adoption.

The review further highlights that the success of GM insect deployment depends heavily on area-wide management coordination (Reeves & Phillipson, 2017). Unlike GM crops, which individual farmers can adopt independently, GM insect strategies require landscape-scale implementation and institutional coordination to achieve suppression thresholds, as has been observed in the false codling moth management in South Africa (Boersma, 2021).

Genetically Modified Microorganisms

Genetically engineered microorganisms, including modified entomopathogenic fungi and bacteria, are less widely commercialized but increasingly investigated in the literature. The reviewed studies suggest strong theoretical compatibility with IPM because of their potential specificity and reduced environmental persistence compared to chemical pesticides (Romeis et al., 2019).

However, empirical field data remain comparatively limited. Regulatory barriers and biosafety assessments are more complex due to concerns about environmental persistence and horizontal gene transfer (Anderson et al., 2019). As a result, the literature reflects cautious optimism rather than broad consensus regarding their near-term scalability.

The central finding of the review is that GM technologies can strengthen IPM systems when embedded within diversified agronomic, institutional, and ecological frameworks. Evidence supports their role in reducing chemical inputs, stabilizing yields, and conserving beneficial organisms. However, sustainability is contingent upon resistance management, regulatory oversight, participatory farmer engagement, and multi-season monitoring (Otim et al., 2022; Anderson et al., 2019). Thus, the findings clearly do not put GM technologies as replacements for IPM, but rather as integral part of the cascade whose interaction with other factors will enhance productivity.

Current Advances in Genetic Modification for IPM

Bt Crops and Resistance to Insect Pests

One of the earliest and most successful applications of GM in pest management has been the development of Bt crops (Marral et al., 2023). These crops are engineered to express insecticidal proteins derived from the bacterium *Bacillus thuringiensis* (Bt) (Romeis et al., 2019). The proteins target specific pest species, causing gut disruption and death upon ingestion (Beltrán Pineda and Castellanos-Rozo, 2025). Bt crops, including cotton, maize, and soybean, have been widely adopted in countries such as the United States, Brazil, India, and South Africa (Romeis et al., 2019).

The success of Bt crops has been attributed to several factors, **Reduction in Pesticide Use:** Bt crops require fewer chemical applications, leading to cost savings and environmental benefits (Romeis et al., 2019) **Increased Yield:** Farmers have reported significant yield gains due to reduced crop losses from pest damage (Amari, 2023). **Enhanced Biodiversity:** Reduced pesticide use promotes the survival of beneficial insects and soil organisms (Romeis et al., 2019). Nevertheless, challenges such as the evolution of pest resistance and the emergence of secondary pests have highlighted the importance of using Bt crops as part of an IPM system that includes crop rotation, refuges, and biological control (Anderson et al., 2019).

RNA Interference (RNAi)

RNA interference is a post-transcriptional gene-silencing mechanism that can be harnessed to disrupt specific genes in pests (Ajinkya Tanaji et al., 2024). In agricultural pest management, RNAi is used to create GM plants that produce double-stranded RNA targeting essential pest genes (van Esse et al., 2020). When pests feed on these plants, the RNA molecules interfere with gene expression, leading to impaired development or death (van Esse et al., 2020).

The major advantages of RNAi technology include: High specificity, as it targets only specific genes, reducing the risk to non-target organisms (de Lange et al., 2022). Flexibility,

since the technique can be adapted to manage a wide range of insect pests and pathogens. Compatibility with other IPM tools, as RNAi can be combined with biological and cultural controls (Ajinkya Tanaji et al., 2024). Currently, RNAi-based products are under development and undergoing regulatory review (de Lange et al., 2022). They offer a promising next-generation tool for pest control, especially in managing pests resistant to Bt proteins. RNAi-based pest control has been explored for several crops, including cotton, where it was used to target the cotton bollworm, a major pest. The technology provides specificity, as the dsRNA can be designed to target only the pest species, supporting integrated pest management strategies that minimize impacts on non-target organisms (Komal et al., 2023). RNAi can be delivered through transgenic plants or as a topical spray, offering flexibility in application. Challenges include environmental instability and potential resistance development. Despite these issues, RNAi holds promise for sustainable pest management, particularly when combined with other control methods (Ajinkya Tanaji et al., 2024).

Gene Editing Technologies (CRISPR-Cas9)

Recent advances in genetic modification have focused on techniques of gene and genome editing. Molecular methods, including CRISPR ('clustered regularly interspaced short palindromic repeats') approaches, have been developed with the aim of precisely modifying genes (Alphey and Bonsall, 2018). These techniques have the potential to drive genetic constructs through a population, incorporating 'gene drive' mechanisms that confer greater-than-Mendelian inheritance even if the construct has fitness costs. These gene-editing approaches have been developed in mosquitoes either to suppress vector populations by affecting female fertility or to modify a population by spreading a trait that affects the ability to harbor pathogens (Alphey and Bonsall, 2018). Gene-editing approaches could also be used to suppress agricultural pests or manage resistance (Alphey and Bonsall, 2018)

The CRISPR-Cas9 system allows scientists to make precise edits to an organism's genome, enabling targeted modifications without necessarily introducing foreign DNA (Komal et al., 2023). In pest management, CRISPR can be used to: Create plants with enhanced resistance to pests or diseases, disrupt genes in pests that are crucial for reproduction or survival, and develop pest-resistant beneficial insects (Komal et al., 2023)

Compared to traditional GM techniques, CRISPR is faster, more accurate, and less costly. Furthermore, gene-edited organisms may face fewer regulatory barriers, depending on national policies (Komal et al., 2023). This has opened up opportunities for public-sector research institutions and small biotechnology firms to participate in the development of gene-edited crops for pest resistance (Alphey and Bonsall, 2018a). Maize and soybeans are expected to benefit from CRISPR technology, with fungal and viral resistance being the most likely vectors for its implementation (de Lange et al., 2022).

Gene Drive Systems

Gene drives are genetic systems that bias inheritance, causing a specific gene to be passed on to offspring at a higher rate than normal Mendelian inheritance (Naidoo and Oliver, 2025). This can lead to rapid spread of the gene throughout a population, making it a powerful tool for various applications, including integrated pest management (Naidoo and Oliver, 2025). This technique is being explored primarily for vector-borne disease control, such as in mosquitoes, but its application in agricultural pest control is gaining traction (Ajinkya Tanaji et al., 2024)

Gene drive systems represent a cutting-edge genetic strategy for pest management, utilizing biased inheritance to spread specific genes through a population. Unlike traditional inheritance, where offspring have a 50% chance of inheriting a given gene from either parent, gene drives can ensure that a specific gene is inherited by a much larger proportion of offspring, rapidly altering population genetics (Naidoo and Oliver, 2025). This technique can be used to suppress pest populations, reduce their ability to transmit diseases, or modify their behaviour (Naidoo and Oliver, 2025). Gene drive systems have been proposed for controlling disease vectors such as mosquitoes that transmit malaria and dengue (Naidoo and Oliver, 2025). The technology holds promise for reducing vector populations or altering their ability to carry pathogens (Naidoo & Oliver, 2025).

There are Ethical and Ecological Considerations that must be understood in this technology (Ajinkya Tanaji et al., 2024). The potential for irreversible changes to ecosystems and the possibility of unintended consequences are key concerns. Biodiversity and ecological stability are critical; the release of gene drive organisms must be carefully evaluated to avoid disrupting non-target species or ecological processes (Ajinkya Tanaji et al., 2018). Additionally, public perception and acceptance of gene drives play a crucial role in their implementation, with debates over the risks and benefits influencing policy decisions (Ajinkya Tanaji et al., 2024). Potential uses in IPM include Population Suppression, driving genes that reduce fertility or viability in pest populations, Population Replacement, spreading traits that make pests less harmful or more susceptible to biological control are being explored (Naidoo & Oliver, 2025).

Transgenic Natural Enemies and Symbionts

Biological control has been accepted as an eco-friendly, technically appropriate, economically viable, and socially acceptable method of pest management (Routray* et al., 2016). Various technologies and methods have been adapted to genetically improve the performance of natural enemies, including predators, parasitoids, and pathogens (Routray* et al., 2016). Artificial selection of various strains under different conditions, hybridization (heterosis) of different strains and rDNA technologies have been adopted towards these directions (Routray* et al., 2016). Various traits like tolerance to pesticidal stress, tolerance to extreme abiotic stresses, shortening developmental rate, enhancing progeny production, altering sex ratio, and altering host or habitat preferences could enhance the effectiveness of natural enemies (Routray et al., 2016). The genetically

improved natural enemies (predators, parasitoids, and pathogens) might be the next level of biological weapons against the pest populations in agricultural systems (Routray* et al., 2016).

Enhancing the efficacy of biological control agents through genetic modification is an emerging area of research. Transgenic parasitoids, predators, or microbial symbionts could be designed to: Improve pest-targeting abilities, increase resistance to environmental stressors, facilitate production and mass rearing (Routray et al., 2016).

For example, symbiotic bacteria in insects have been genetically engineered to deliver RNAi molecules targeting pest genes (Guan et al., 2021). Such innovations expand the toolkit available within IPM and may reduce the need for external pesticide inputs (Hanamasagar et al., 2024).

Integration of GM Technologies into IPM Systems

The effective integration of genetically modified (GM) technologies into Integrated Pest Management (IPM) systems depends on ecological compatibility, structured resistance stewardship, participatory extension, and evidence-based monitoring. The reviewed literature consistently demonstrates that Bt crops are most durable and sustainable when deployed as components of diversified IPM frameworks rather than as stand-alone pest control tools (Alphey & Bonsall, 2018, Shelton et al., 2018). Resistance management through refuge planting and trait pyramiding remains central to this integration, as maintaining susceptible pest populations and reducing directional selection pressure are foundational to delaying resistance evolution (Anderson et al., 2019, Alphey & Bonsall, 2018).

Field-level evidence from Sub-Saharan Africa strengthens this position. Studies on Bt maize targeting fall armyworm show that integration with cultural practices such as early planting, crop rotation, refuge compliance, and push–pull systems involving *Desmodium* significantly enhances pest suppression while reducing insecticide application rates (Otim et al., 2022). Reduced insecticide pressure in Bt systems has been associated with greater abundance and functional activity of natural enemies, including parasitoids and predatory arthropods, thereby reinforcing biological control within agroecosystems (Romeis et al., 2019). Similar integration outcomes have been documented in Bt brinjal systems, where GM traits combined with IPM practices such as field sanitation and monitoring reduced overall pesticide use while maintaining yield stability (Shelton et al., 2018).

Durability outcomes are strongly influenced by governance and compliance structures. Empirical analyses indicate that pyramided Bt traits combined with structured refuge enforcement delay resistance more effectively than single-toxin systems lacking oversight (Anderson et al., 2019, Alphey & Bonsall, 2018). Conversely, documented resistance evolution in cases of weak stewardship underscores the consequences of inadequate regulatory enforcement and farmer non-compliance (Anderson et al., 2019). These findings highlight that technological performance is inseparable from institutional capacity and monitoring systems.

Monitoring and evaluation frameworks must extend beyond short-term yield comparisons. Multi-season and landscape-scale assessments have been recommended to capture ecological, agronomic, and socioeconomic impacts concurrently (Ngongolo & Mmbando, 2025c). Integrated modelling approaches that combine pest population dynamics, non-target organism monitoring, pesticide usage trends, and economic return analyses provide a more comprehensive evaluation of GM-IPM performance (Zhou et al., 2025a). Such multidimensional indicators align with IPM's adaptive management philosophy and improve regulatory decision-making.

Farmer training and participatory engagement are equally critical. Evidence suggests that structured training programs focused on IPM principles, refuge implementation, safe GM crop handling, and resistance awareness improve stewardship compliance and long-term sustainability (Mmbando, 2025, Anderson et al., 2019). Participatory field trials and community-based monitoring initiatives have been shown to increase farmer understanding, acceptance, and accountability, particularly in emerging GM contexts (Cascone et al., 2024). Effective integration therefore, requires not only technological deployment but also knowledge co-production between researchers, regulators, and farming communities.

Collectively, the literature demonstrates that successful GM-IPM integration is achieved through ecological complementarity, enforceable resistance management, multidimensional monitoring, and participatory extension systems. When GM crops are embedded within diversified agronomic strategies rather than treated as technological substitutes for IPM, they can contribute to reduced pesticide dependence, strengthened biological control services, and improved agroecosystem resilience (Otim et al., 2022, Romeis et al., 2019).

Path to Market in Africa

Compared with the United States, Argentina, Canada, Brazil, and India, the total area under GM crop cultivation in Africa has remained notably small, with only eleven of the fifty-four countries accepting these products for commercial production (Sadikiel Mmbando, 2024). This is surprising because Africa presents both the greatest need and the most significant opportunity for agricultural growth, driven by its rapidly expanding population and vast reserves of unused arable land (Akpensuen and Rivero, 2025). Genetically modified or gene-edited crops could play a crucial role in enabling African agriculture to meet the rising food demand (Ngongolo and Mmbando, 2025a). Currently, commercial cultivation is confined to a few countries, such as Egypt, Kenya, Malawi, Eswatini, Sudan, and South Africa, where their use has been successful, leading to a substantial increase in cultivated area since their introduction (Ongu et al., 2023). Among these, South Africa stands out as the continental leader, having commercialized Bt maize as early as 1997. Today, more than 80% of its maize area is genetically modified, delivering consistent yield gains (Gouse et al., 2016). In Kenya, the approval of commercial biotechnology maize cultivation in 2022 was a turning point in the region after many years of confined trials. Meanwhile, several other African countries,

such as Ethiopia, Uganda, Tanzania and Mozambique, have established regulatory frameworks and are conducting field trials in anticipation of future commercial release, pending supportive government policies (Ongu et al., 2023). In Uganda, for instance, field trials are underway for genetically modified potatoes equipped with stacked immune receptors for resistance to late blight, as well as bananas engineered for resistance to bacterial wilt (Kikulwe and Asindu, 2020). The uneven adoption of genetically modified (GM) crops across Africa reflects more than differences in scientific readiness; it is shaped by regulatory, political, institutional, and social dynamics. Early adopters such as South Africa have benefited from clear biosafety legislation, efficient approval systems, and policy continuity. In contrast, many cautious nations face lengthy and costly regulatory procedures that limit participation by public research institutions and local innovators. Regulatory inconsistencies across borders further complicate commercialization, as seen in the policy divergence between Kenya and Uganda, which affects regional trade and investment confidence. Countries that have advanced toward commercialization tend to demonstrate sustained executive and parliamentary support for biotechnology (Barraza-Botet et al., 2026). Where legislative delays and policy uncertainty persist, private sector investment and research translation slow considerably (Smyth et al., 2016). Regional initiatives such as Water Efficient Maize for Africa and the TELA Maize Project, supported by the African Agricultural Technology Foundation and the International Maize and Wheat Improvement Center, illustrate how coordinated collaboration can streamline research, field trials, and regulatory processes. Public perception remains equally influential. Where communication, extension services, and farmer education are weak, skepticism and activist resistance tend to delay adoption. Evidence from confined field trials suggests that transparency, stakeholder engagement, and farmer training are essential for building trust. Overall, the African experience demonstrates that scientific performance alone does not determine market entry. Effective governance, regulatory harmonization, and public engagement are critical for integrating GM crops into broader Integrated Pest Management (IPM) frameworks. Without these enabling conditions, biotechnology risks remaining confined to experimental stages despite its demonstrated potential to enhance productivity, reduce pesticide use, and strengthen food security across the continent.

Challenges in Genetic Modification for IPM and Possible Remedies

Despite significant advancements, the integration of GM technologies into IPM faces a range of challenges that must be carefully navigated to ensure long-term success (Anderson et al., 2019) and these include:

Evolution of Pest Resistance, one of the most pressing challenges, is the evolution of resistance among target pests (Anderson et al., 2019). Continuous exposure to Bt toxins or RNAi-based defences can select for individuals with resistance traits, eventually rendering these technologies ineffective (Anderson et al., 2019). Field studies have shown cases of resistance to Bt cotton in pests such as the pink bollworm and fall armyworm in multiple countries (Anderson et al., 2019). Recent introductions of GE technology, targeting *S. frugiperda*, in Brazil have provided levels of crop protection in maize that were not

previously realized by Brazilian growers. The GE maize produces various Bt proteins (including Cry1Ab, Cry1F, Cry1A.105, Cry2Ab, Vip3Aa) that are toxic (at varying levels) to *S. frugiperda* larvae upon ingestion of plant tissue. Although the high risk of resistance evolution to Bt was recognized at the time of commercialization, industry-provided IRM recommendations were not effective in preventing resistance, as it has quickly evolved to multiple Bt proteins (particularly Cry1A and Cry1F) within 3 to 4 years (Anderson et al., 2019). Anti-GM activists have attributed this evolution to the introduction of GM crops. Nevertheless, this appearance of herbicide resistance is a natural phenomenon, which is independent of GM technology (Ahmad and Mukhtar, 2017).

Remedies: To combat this, resistance management strategies must be rigorously implemented. These include the use of refuges (non-GM crops planted near GM fields) (Alphey and Bonsall, 2018), gene stacking such as Bt pyramid (combining multiple resistance traits), and rotating pest control methods (Anderson et al., 2019). However, enforcement and compliance with these practices are often weak, especially among smallholder farmers in developing countries.

Also, genetically modified organisms (GMOs) are subject to complex and often stringent regulatory processes (van Esse et al., 2020). Biosafety evaluations must consider potential impacts on human health, non-target organisms, and ecological balance (Mahanayak, 2024). In many countries, the approval process is prolonged and expensive, creating barriers for public institutions and local innovators (Mmbando, 2025). Inconsistent regulations across countries also complicate the trade of GM products. For example, Kenya has permitted the commercialization of GM crops, while its immediate neighbor and trading partner, Uganda, does not accept their use (Mmbando, 2025). In many instances, a crop approved in one country may be banned in another, affecting export markets.

Remedies: Strengthening biosafety frameworks, harmonizing international standards, and building regulatory capacity are essential to address this challenge (Mahanayak, 2024).

Public Perception and Misinformation: Public acceptance of GM technologies varies widely across regions (van Esse et al., 2020). In many areas, particularly in Europe and parts of Africa, significant opposition is driven by ethical concerns, fear of unknown risks, and mistrust of large biotech corporations (van Esse et al., 2020). Misinformation and a lack of transparent communication have exacerbated these concerns (Mmbando, 2025).

Remedies: Building public trust requires inclusive dialogues, transparent risk assessments, and education campaigns that communicate the benefits, risks, and safeguards of GM in IPM. Farmer-led demonstrations and stakeholder engagement can also help bridge the gap between science and society.

Socio-economic and equity issues, especially the high costs of GM seeds and associated intellectual property rights can limit access for smallholder farmers (Ngongolo and Mmbando, 2025b). In many cases, GM technologies are controlled by multinational corporations, raising concerns about seed sovereignty and dependency (Ngongolo and Mmbando, 2025b; Anderson et al., 2019). Furthermore, the benefits of GM crops are not always evenly distributed, potentially exacerbating inequality. It's reported that the cost

estimates for the development of a single GM variety (late blight-resistant potato) in a developing country by a not-for-profit institution vary from US\$1.4 million to US\$1.6 million (van Esse et al., 2020).

Remedies: Policies that support public sector involvement, promote open-access technologies, and subsidize GM adoption for small-scale farmers are critical to ensuring equitable benefit sharing (Dowd-Urbe et al., 2024). Participatory research involving farmers can also improve the relevance and uptake of GM-based IPM tools (Zhou et al., 2025b). A science-based approach for the safety assessment and regulation of GE crops is needed (Domingo, 2025). Public discussions need to move from a focus on GE technology in general to a focus on crop systems, their problems, and potential solutions, including GE crops (Catherine et al., 2024). Collaboration and communication among consumers, academics, industry, and government, which leverages the experience and familiarity gained with the cultivation of GM crops over the last twenty years, are needed to transfer knowledge and allow for a better understanding of the benefits and limitations of GE crops (Anderson et al., 2019). Farmer training and education can put the short-term costs into context with the long-term benefits of implementing a sustainable approach. Incentives are needed for the implementation of an IPM strategy that maintains the ecological infrastructure and facilitates the implementation of crop rotations and their application, and the approach in each region should consider the cultural and socio-economic contexts (Anderson et al., 2019).

Potential Non-Target and Environmental Impacts; Although GM crops are designed for specificity, concerns remain about potential unintended effects on non-target organisms, such as pollinators and natural enemies (Hamdan & Tan, 2024). For instance, some studies have reported minor adverse effects on monarch butterfly larvae exposed to Bt corn pollen, though broader reviews have found these impacts to be minimal (Ahmad and Mukhtar, 2017).

Remedies: Long-term monitoring, ecological risk assessments, and the incorporation of GM crops within diversified agroecosystems can help mitigate potential risks and safeguard biodiversity (Anderson et al., 2019).

Case Study of Genetic Modification in Integrated Pest Management

Bt cotton in India

India, one of the world's largest cotton producers, historically suffered from severe infestations of bollworms, particularly *Helicoverpa armigera* (Malinga & Laing, 2022), which caused significant yield losses and forced farmers to rely heavily on chemical pesticides (Singh et al. 2022.) Adoption was rapid, rising from 50,000 hectares in 2002 to over 11 million hectares by 2012, covering more than 90% of the cotton-growing area (Naranjo, 2011). This biotech intervention transformed cotton cultivation in India, boosting yields by 30–60%, reducing pesticide use by 40–60%, and increasing farmer profits by up to 70% (Chen, 2025). As a result, India emerged as the world's top cotton producer and a net exporter, reversing previous trends of crop failure and economic distress (Naranjo, 2011).

Bt cotton became a vital component of Integrated Pest Management (IPM), fitting seamlessly into broader strategies (Naranjo, 2011). Farmers were encouraged to plant refuge crops non-Bt cotton, to delay resistance among pests, although compliance varied (Malinga and Laing, 2022). Lower pesticide uses improved environmental and worker health and allowed beneficial insects like ladybugs and lacewings to thrive (Qayyum et al., 2024). Bt cotton was also combined with crop rotation, pheromone traps, handpicking of infested bolls, and timely sowing to enhance pest suppression. Importantly, public-sector agencies and research institutions like the Central Institute for Cotton Research (CICR) supported resistance monitoring and farmer training, while second-generation Bt hybrids were introduced to improve resistance to multiple pests (Alphey and Bonsall, 2018a).

Despite its success, challenges emerged. Secondary pests such as whiteflies and jassids became more prominent as bollworms were suppressed, requiring targeted management (Subramanian, 2023). Some regions reported resistance development in pink bollworm populations due to poor refuge compliance and overuse (Subramanian, 2023). Furthermore, criticisms arose over seed cost, monopolies by private companies, and uneven benefits, especially in drought-prone or rainfed regions (Azadi et al., 2022). Nonetheless, public-sector Bt varieties were developed for resource-poor farmers, and government agencies worked to ensure broader accessibility, equity, and sustainability of the technology (Fischer et al., 2015). Social and policy responses addressed the socioeconomic risks while strengthening the regulatory framework for biosafety and farmer support (Carrière et al., 2020).

Overall, the Bt cotton experience in India offers a compelling case for the role of genetic modification in sustainable agriculture (Mukherjee et al., 2022). It illustrates that GM crops, when thoughtfully integrated into IPM and backed by robust extension services, can reduce chemical dependency, enhance yields and incomes, and contribute to national food and fiber security. Lessons from India underscore the importance of managing resistance, maintaining ecological balance, ensuring affordability, and involving farmers in decision-making. Bt cotton has not only empowered millions of smallholders but has also redefined India's cotton economy, proving that genetic technologies can be powerful allies in agroecological resilience when used responsibly (Mukherjee et al., 2022).

Bt Brinjal Success Story in Bangladesh

Bangladesh made agricultural history in 2014 by becoming the first South Asian country to commercially release genetically modified (GM) eggplant, known as Bt brinjal (Quamruzzaman, 2021). Brinjal (eggplant) is a vital crop for millions of Bangladeshi farmers and consumers, but it has long been severely affected by the fruit and shoot borer (*Leucinodes orbonalis*), a destructive insect pest responsible for yield losses of up to 70% (Prodhan et al., 2018). Farmers previously relied on frequent, heavy applications of chemical pesticides, often as many as 80 to 100 sprays per season to control the pest (Mahjabeen, 2021).

This excessive use posed significant risks to human health, especially for farmers and farmworkers applying the chemicals without proper protective equipment, and also contributed to environmental pollution and pesticide resistance (Mahjabeen, n.d.). BT Brinjal was developed using a gene (*Cry1Ac*) from the bacterium *Bacillus thuringiensis*, which produces a protein toxic specifically to the fruit and shoot borer but safe for humans, animals, and non-target insects (Quamruzzaman, 2021). Field trials and early adoption demonstrated impressive results with farmers growing Bt brinjal reporting pest damage reduction of over 90%, yield increases of 40–50%, and pesticide use reductions by more than 80% (Quamruzzaman, 2021). This not only increased profitability by up to 80% in some cases, but also improved produce quality and worker safety. The adoption of Bt brinjal was supported by government extension services, NGOs, and international collaborators such as USAID and Cornell University, who provided farmer training, seed distribution, and resistance management guidelines. Farmers were also encouraged to integrate Bt brinjal with other Integrated Pest Management (IPM) practices, including crop rotation, field sanitation, and refuge planting to delay pest resistance (Shelton et al., 2018).

The success of Bt brinjal in Bangladesh demonstrates how genetic modification can benefit smallholder farmers when deployed with institutional support and within a holistic IPM framework (Shelton et al., 2018). Reducing the need for hazardous pesticides it has led to safer farming environments, more sustainable pest control, and increased farmer confidence in biotechnology (Haque & Saha, 2020). Over 65,000 farmers were growing Bt brinjal by 2023, and the technology continues to expand, offering a model for neighbouring countries facing similar pest pressures (Shelton et al., 2018). The case highlights the importance of science-based regulatory decisions, strong public awareness, and continuous monitoring to ensure long-term efficacy and public trust. Bangladesh's experience with Bt brinjal sets a precedent for responsibly integrating GM crops into small-scale farming systems for food security, economic resilience, and environmental sustainability (Shelton et al., 2018).

Bt Maize in Sub-Saharan Africa

Bt maize, a genetically modified variety engineered to produce insecticidal proteins from *Bacillus thuringiensis* (Bt), has emerged as a promising solution to pest-related losses in Sub-Saharan Africa (Botha et al., 2020). It targets major maize pests such as stem borers and the highly invasive fall armyworm (*Spodoptera frugiperda*), which arrived in Africa in 2016 and has since caused significant damage to maize crops, threatening food security and livelihoods (Ajam et al., 2024). Maize is the most widely grown staple crop across the region, and yield losses from pest infestation can reach 30–50% (Sekabira et al., 2022). For smallholder farmers, pest management has been challenging due to limited access to affordable and safe pesticides (Sekabira et al., 2022; Romeis et al., 2019).

South Africa leads the region in the adoption of Bt maize, having commercialized it in 1997. Today, over 80% of the maize grown there is genetically modified, resulting in consistent yield gains and reduced pesticide use. Encouraged by this, several countries have initiated research and regulatory processes under the Water Efficient Maize for Africa (WEMA) and

TELA Maize Project, with support from institutions like the African Agricultural Technology Foundation (AATF) and CIMMYT. Kenya approved Bt maize for commercial cultivation in 2022 after extensive confined field trials, while Nigeria has also authorized its commercial release and seed production (Ongu et al., 2023). Ethiopia, Mozambique, and Tanzania have conducted advanced trials, and their regulatory processes are ongoing (Akinbo et al., 2021). These efforts reflect growing confidence in biotechnology as a tool to address pest pressures and climate challenges (Akinbo et al., 2021).

In Uganda, maize is both a key food crop and a strategic commodity, yet yields have remained low due to recurrent pest attacks and drought stress (Ajam et al., 2024). The National Agricultural Research Organization (NARO) has been conducting confined field trials of Bt maize under the TELA project, with promising results trials at research stations such as Namulonge and Kasese demonstrated that Bt maize experienced less than 10% fall armyworm damage compared to over 60% in non-Bt varieties, with yield increases of 25–40% (Otim et al., 2022). These trials were conducted under the supervision of Uganda's National Biosafety Committee and the Uganda National Council for Science and Technology (Ongu et al., 2023). However, despite scientific success, Bt maize is not yet commercially available in Uganda due to delays in passing comprehensive biosafety legislation, public debate over GM crops, and the absence of a final regulatory framework to approve environmental release (Ongu et al., 2023).

Bt maize has strong potential to strengthen Integrated Pest Management (IPM) systems across Sub-Saharan Africa, including Uganda (Otim et al., 2022). It can be used alongside ecological practices such as refuge planting, push-pull intercropping with *Desmodium*, early planting, and biological control agents, forming a robust defense against pest outbreaks (Otim et al., 2022). It reduces farmers' reliance on synthetic insecticides by over 60%, lowers production costs, and protects beneficial insect populations. To ensure long-term sustainability, resistance management strategies and farmer education are critical. For Uganda and its neighbors, Bt maize represents a viable tool for enhancing food security, resilience to pests and climate shocks, and agricultural productivity provided it is supported by enabling policies, strong regulatory systems, and inclusive public engagement (Otim et al., 2022).

False Codling Moth Management in South Africa

The False codling moth (FCM), *Thaumatotibia leucotreta*, is a highly destructive pest native to Sub-Saharan Africa (Gilligan et al., 2011). It affects a wide range of economically important crops, including citrus, avocados, peppers, cotton, and stone fruits (Shikoshi et al., 2025). In South Africa's fruit export industry, especially citrus, FCM poses a significant threat because the presence of even a single larva in a consignment can result in the rejection of entire shipments under stringent phytosanitary regulations, especially in European Union (EU) markets (Adom et al., 2021). Historically, farmers relied heavily on chemical insecticides to control pests, which led to environmental concerns, pesticide resistance, and damage to beneficial insect populations (Adom et al., 2021). The need for a

more effective, sustainable, and residue-free method of controlling FCM prompted researchers to explore genetic and biological approaches to pest management (Shikoshi et al., 2025).

South Africa pioneered the use of genetically modified sterile insect technique (GM-SIT) to manage FCM, marking a breakthrough in area-wide pest suppression (Barnes et al., 2015). The approach involved rearing large numbers of male FCM moths that were genetically modified to carry a self-limiting gene and a fluorescent marker (Ajinkya Tanaji et al., 2018). The gene causes the moths' female offspring to die in early larval stages, effectively suppressing future generations. These GM moths, developed using precision genetic tools, were mass-reared and released into the environment in targeted agricultural zones (Ajinkya Tanaji et al., 2018). When the sterile males mated with wild females, no viable female offspring survived, leading to a steady decline in FCM populations without the use of insecticides. The fluorescence marker allowed for easy tracking and monitoring of released moths in the field, improving the precision of pest control operations.

The program, implemented by Oxitec in collaboration with Citrus Research International (CRI) and South African agricultural authorities, showed strong success in early pilot trials and commercial-scale operations. In citrus farms across the Eastern Cape and Western Cape, where FCM pressure is typically high, the release of GM sterile males resulted in up to 90% suppression of wild FCM populations within a few growing seasons (Adom et al., 2021). This greatly reduced the risk of crop rejection for exports, and many farmers reported substantial reductions in pesticide applications, lowering costs and enhancing compliance with export residue standards. Furthermore, the GM-SIT approach allowed for more targeted and environmentally safe pest control, aligning with integrated pest management (IPM) principles. The absence of chemical residues also improved the quality and marketability of fresh produce (Adom et al., 2021).

The success of GM-SIT against FCM in South Africa has attracted international attention and is regarded as a global model for sustainable pest control in horticulture (Shikoshi et al., 2025). By integrating cutting-edge genetic tools with traditional pest management strategies, South Africa has demonstrated how innovation can address complex agricultural challenges in an export-driven economy (Ngongolo and Mmbando, 2025a). The case also highlights the importance of regulatory support, stakeholder engagement, and public-private partnerships in scaling genetically engineered solutions. As a result, South Africa has not only protected its multi-billion-rand citrus industry from quarantine pests but has also laid the groundwork for broader adoption of genetically based pest control systems across Africa and other regions facing similar phytosanitary threats (Ngongolo and Mmbando, 2025a). The FCM management story exemplifies how genetic pest control, when implemented responsibly within IPM frameworks, can achieve high impact in both productivity and sustainability (Shikoshi et al., 2025).

Emerging Patterns in GM-IPM Integration Across the Case Studies

Across all four cases, several consistent patterns emerge. First, GM technologies deliver the greatest benefits when addressing clearly defined, high-impact pests that significantly

constrain yields. Secondly, successful integration depends on institutional support, including regulatory clarity, farmer training, and resistance management enforcement. Also, resistance evolution becomes a tangible risk when stewardship systems weaken, as seen in aspects of the Indian experience. Lastly, public-sector leadership and transparent communication enhance social legitimacy, as demonstrated in Bangladesh and South Africa.

Collectively, these cases show that GM crops are most effective within IPM when they are treated not as stand-alone solutions but as components of diversified pest management strategies supported by policy coherence, monitoring systems, and farmer engagement. Where governance structures are strong and stewardship is enforced, GM–IPM integration succeeds; where regulatory uncertainty, weak compliance, or limited public trust persist, progress slows or sustainability is compromised.

Discussion of the Findings.

This review synthesizes multidisciplinary evidence demonstrating that genetically modified (GM) technologies can significantly enhance Integrated Pest Management (IPM) systems when embedded within diversified agronomic and institutional frameworks. Across transgenic crops, genetically modified insects, and engineered microorganisms, the dominant pattern in the literature is conditional effectiveness: GM tools deliver strong agronomic and environmental benefits where stewardship, monitoring, and regulatory systems are functional. For instance, Bt crops consistently reduce insecticide applications, increase yields, and support conservation biological control by minimizing harm to natural enemies (Romeis et al., 2019; Naranjo et al., 2019). Empirical studies from India and Bangladesh show that Bt cotton and Bt eggplant substantially improved farm profitability while reducing pesticide exposure and associated environmental risks (Subramanian, 2023; Prodhon et al., 2018). In Sub-Saharan Africa, confined field trials of Bt maize in Uganda reported less than 10% fall armyworm damage compared to over 60% in non-Bt varieties, with yield gains of 25–40% (Otim et al., 2022), reinforcing the crop's compatibility with ecological IPM practices such as refuge planting and push–pull systems.

However, the findings also reveal structural vulnerabilities. Resistance evolution emerges as the most consistently documented risk, particularly in contexts of weak refuge compliance and limited regulatory enforcement (Anderson et al., 2019; Alphey & Bonsall, 2018). Experiences from Brazil highlight how inadequate stewardship can erode long-term efficacy despite strong initial performance. Regulatory uncertainty and public skepticism further shape adoption patterns, particularly in African countries where biosafety legislation remains incomplete or politically contested (Sadikiel Mmbando, 2024; Ongu et al., 2023).

The literature also differentiates adoption dynamics across GM categories. While transgenic crops can be adopted at the farm level, GM insect technologies require area-wide coordination and institutional oversight to achieve suppression thresholds (Reeves & Phillipson, 2017; Boersma, 2021). Evidence regarding GM microorganisms remains

promising but comparatively limited, with scholars emphasizing the need for expanded field validation and biosafety assessment (Romeis et al., 2019).

Collectively, the review advances understanding by demonstrating that GM technologies do not replace IPM but strengthen it when aligned with resistance management, ecological diversification, regulatory capacity, and participatory farmer engagement (Sekabira et al., 2022 Anderson et al., 2019).

Future Directions

Development of Multi-Trait GM Crops: Future GM crops are likely to incorporate multiple traits such as resistance to insects, viruses, and drought in a single variety (Anderson et al., 2019). These stacked traits will broaden pest protection and reduce selection pressure, thereby enhancing durability (Romeis et al., 2019). This approach responds directly to documented resistance failures in countries such as Brazil and India, where reliance on single modes of action accelerated pest adaptation. Future research must prioritize the development of multi-mechanism pest suppression systems that combine distinct biological pathways to reduce selection pressure and prolong trait durability. The urgency of this direction lies in the growing incidence of cross-resistance among lepidopteran pests and the expansion of invasive species such as fall armyworm across Africa.

Synthetic Biology and Designer Biocontrol Agents: Advances in synthetic biology may lead to the development of designer organisms tailored for pest control (Xin et al., 2018). These could include engineered fungi, viruses, or symbiotic bacteria with enhanced pest-killing capabilities (Haq et al., 2024). Customizable biocontrol agents can complement existing IPM tactics (Chaudhary et al., 2024). However, significant scientific gaps remain, particularly regarding long-term ecological behaviours, gene flow containment, and reversible deployment mechanisms. Current literature highlights uncertainty regarding reversibility, containment, and cross-border spread of engineered organisms. Future investment should focus on reversible or self-limiting gene drive systems and robust molecular confinement strategies to address biosafety and ethical concerns. Without such safeguards, public resistance and regulatory hesitation will likely delay deployment regardless of technical readiness.

Integration with Digital and Precision Agriculture: emerging researches are combining genetic tools with digital technologies such as remote sensing, drones, mathematics and AI-based diagnostics can enable site-specific pest control (Aziz et al., 2025, Alphey and Bonsall, 2018a). Resistance management failures have often been attributed to weak monitoring and delayed response, which Precision agriculture offers an opportunity to correct. This precision IPM approach can reduce inputs, monitor resistance, and improve decision-making (Gossen and McDonald, 2020). However, it's limited by access to digital infrastructure among smallholder farmers and insufficient interoperability programming between biotech stewardship programs and digital advisory platforms. This limitation can be addressed by investment in mobile-based extension tools tailored to smallholder contexts in Africa that are critical for ensuring equitable integration of biotechnology and digital agriculture.

Strengthening Policy, Ethics, and Governance: Robust legal frameworks and ethical oversight are essential to guide the responsible use of GM technologies (Mahanayak, 2024). This includes ensuring informed consent, benefit sharing, and environmental safeguards. Global cooperation is also vital, especially in managing transboundary pests and harmonizing biosafety regulations (Ngongolo & Mmbando, 2025b). Future progress requires harmonized regional biosafety frameworks across African economic blocs to reduce duplication and facilitate cross-border trade. Also, establishing time-bound regulatory review processes with transparent scientific criteria would enhance investor confidence while maintaining precautionary safeguards.

Capacity Building and Participatory Research: Empowering local researchers, extension workers, and farmers through training and participatory research will ensure that GM technologies are contextually relevant and widely adopted (Kotey et al., 2016). It's been noted that biotechnology innovation alone cannot ensure sustainability without farmer knowledge and institutional competence. To add to this, evidence from confined field trials indicates that farmer training significantly improves adoption outcomes and public trust. Regional innovation hubs can support the co-creation of GM solutions tailored to specific agroecology and socio-economic contexts. For these reasons, future research programs should adopt participatory breeding and on-farm co-design models to ensure GM traits address locally prioritized pest challenges. These structures will determine not only the success of GM technologies in enhancing pest management but also their societal acceptance, ecological sustainability, and regulatory compliance.

Recommendations

This review identifies several priority research actions necessary to ensure that genetically modified (GM) technologies contribute sustainably to Integrated Pest Management (IPM) systems in Africa. First, long-term and region-specific resistance surveillance must be institutionalized before and during commercialization. Resistance evolution has been widely documented in Bt systems (Anderson et al., 2019), and field evidence on fall armyworm dynamics in Africa further underscores the urgency of proactive monitoring (Ajam et al., 2024). Establishing coordinated national and regional surveillance systems to track resistance development and ecological impacts would help prevent the durability failures observed elsewhere (Abd & Masaad, 2018). In parallel, resistance management research should advance gene stacking and refuge strategies as outlined by (Alphey & Bonsall, 2018), ensuring that GM crops remain effective within broader IPM frameworks. Second, future research must shift from evaluating single GM traits in isolation toward system-level IPM assessments. Evidence from Sub-Saharan Africa demonstrates that Bt maize performs best when integrated with ecological practices such as refuge planting and biological control (Otim et al., 2022, Botha et al., 2020). Therefore, multi-season, landscape-scale trials comparing conventional, GM-only, and fully integrated GM-IPM systems are essential (Ngongolo & Mmbando, 2025c). These trials should incorporate ecological indicators and risk benefit modeling tools to guide decision-making (Zhou et al.,

2024) , thereby generating policy-relevant evidence rather than isolated agronomic performance data.

Third, robust socioeconomic and participatory research must accompany technological deployment. Interdisciplinary assessments examining income distribution, gender dynamics, labor shifts, and market access are necessary to address equity concerns (Ala-Kokko et al., 2021). Community-based participatory trials have proven effective in evaluating farmer acceptance and scalability under real-world conditions (Cascone et al., 2024), while farmer training and capacity building strengthen informed adoption and stewardship (Anderson et al., 2019).

Finally, regulatory and innovation systems research should address structural bottlenecks limiting responsible adoption. Comparative analyses of African biosafety systems highlight the importance of harmonized, science-based regulatory frameworks (Akinbo et al., 2021, Anderson et al., 2019). Investment in next-generation tools, including CRISPR-based editing and synthetic biology applications must proceed alongside rigorous gene drive safety studies (El-Awaad & Merzendorfer, 2025). Collectively, these targeted research priorities respond directly to the empirical gaps identified in this review and provide a focused pathway for strengthening GM integration within sustainable IPM systems.

Conclusion

The synthesis of evidence across crops, insects, and microbial applications demonstrates that genetic modification technologies can strengthen Integrated Pest Management (IPM) when implemented within ecologically diversified and institutionally supported systems. Findings consistently show that Bt crops reduce insecticide applications, enhance yields, and contribute to farm profitability while supporting conservation of beneficial living organism. These outcomes affirm the technical compatibility of GM tools with core IPM principles of ecological sustainability and economic efficiency.

At the same time, the literature makes clear that technological performance alone does not guarantee long-term success. Resistance evolution, regulatory fragmentation, public trust deficits, and uneven biosafety capacity significantly shape adoption trajectories. Comparative case studies reveal that where refuge compliance, monitoring systems, and policy continuity are weak, initial gains may erode.

Overall, this review contributes to the scholarship by demonstrating that GM technologies function most effectively as complementary components within adaptive, well-governed IPM frameworks rather than as stand-alone solutions.

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