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Long-term Sustainability of Bt Transgenic Crops in Agricultural Systems

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Abstract Bt transgenic crops have achieved significant success in improving agricultural yield and pest resistance, becoming an essential part of modern agriculture. However, their long-term sustainability requires in-depth research. This study aims to comprehensively evaluate the performance of Bt crops in terms of agronomic performance, environmental impact, resistance management, socio-economic factors, regulatory and policy considerations, technological advancements and innovations, and long-term ecological and economic sustainability. The results show that Bt crops not only have advantages in increasing yield and pest resistance but also improve crop health and quality. However, the impact of Bt crops on biodiversity, soil health, and non-target organisms needs continuous monitoring and assessment. Effective resistance management strategies must be developed to ensure the long-term effectiveness of Bt technology in addressing pest resistance. On the socio-economic front, the promotion of Bt crops needs to consider farmers' acceptance and economic benefits, as well as the comprehensive impact on rural communities. The improvement of policy and regulatory frameworks will facilitate the safe use of Bt crops and international trade. Additionally, with the advancement of new Bt varieties and genetic engineering technologies, the application prospects of Bt crops are broader. This study highlights the importance of an integrated approach in assessing the long-term sustainability of Bt crops and provides scientific evidence for future research and policy formulation.

Keywords Bt transgenic crops; Long-term sustainability; Agricultural systems; Environmental impact; Resistance management

1 Introduction

Bt transgenic crops have revolutionized pest management in agriculture by providing an effective alternative to chemical pesticides. These crops, genetically engineered to express Bt toxins, target a variety of insect pests, significantly reducing the need for insecticide applications and benefiting both the environment and the economy (Xiao and Wu, 2019; Koul, 2020; Peterson et al., 2020). Bt crops such as maize, cotton, and soybean have been widely adopted globally, offering protection against major pests and contributing to increased crop yields (Fleming et al., 2018; Xiao and Wu, 2019; Koul, 2020). However, the long-term effectiveness of Bt crops is threatened by the evolution of resistance in target pest populations (Tabashnik and Carrière, 2017; Gassmann et al., 2019; Tabashnik et al., 2023).

Sustainability in agriculture is crucial for ensuring food security, environmental health, and economic viability. The overuse of chemical pesticides has led to numerous ecological issues, including biodiversity loss, pest resistance, and negative impacts on non-target species (Catarino et al., 2015; Peterson et al., 2020). Bt transgenic crops offer a more sustainable pest management solution by reducing reliance on chemical insecticides and minimizing their associated environmental impacts (Catarino et al., 2015; Xiao and Wu, 2019; Peterson et al., 2020). However, the sustainability of Bt crops is challenged by the potential for pests to develop resistance, which could undermine their long-term efficacy and necessitate a return to more harmful pest control methods (Tabashnik and Carrière, 2017; Gassmann et al., 2019; Tabashnik et al., 2023).

This study evaluates the long-term sustainability of Bt transgenic crops in agricultural systems. By analyzing the current application of Bt crops and their impact on pest management and agricultural productivity, exploring the mechanisms and prevalence of pest resistance to Bt crops, and examining possible strategies for managing and mitigating resistance, this study aims to discuss the broader ecological and economic implications of Bt crop use and resistance management. By synthesizing findings from multiple studies, the research seeks to provide a comprehensive understanding of the challenges and opportunities associated with the long-term sustainability of Bt transgenic crops in agriculture.

2 Agronomic Performance of Bt Crops

2.1 Yield benefits

Bt transgenic crops have demonstrated significant yield benefits across various agricultural systems. The introduction of Bt crops, such as Bt cotton and Bt corn, has led to increased crop yields by effectively controlling target pests. For instance, Bt crops have been shown to increase yields by 22% on average, which has also resulted in a 68% increase in farmers' profits and a 37% reduction in chemical insecticide applications (Manjunath, 2020). This reduction in insecticide use not only lowers production costs but also minimizes environmental impact, contributing to the overall sustainability of agricultural practices (Siegfried and Jurat-Fuentes, 2016).

2.2 Pest resistance

Despite the initial success of Bt crops in controlling pests, the evolution of pest resistance poses a significant challenge to their long-term sustainability. Studies have documented cases of practical resistance in several pest species. For example, resistance to Cry1F maize by the fall armyworm (*Spodoptera frugiperda*) has been reported in Puerto Rico, Brazil, and parts of the southeastern United States (Yang et al., 2016). Additionally, global monitoring data indicate an increase in pest resistance cases from 3 in 2005 to 26 in 2020, affecting multiple Bt toxins and pest species (Tabashnik and Carrière, 2017; Tabashnik et al., 2023). Factors such as recessive inheritance of resistance, low resistance allele frequency, and the use of multi-toxin Bt crops have been identified as critical in delaying resistance development (Carrière et al., 2015; Tabashnik and Carrière, 2017; Tabashnik et al., 2023).

2.3 Crop health and quality

The health and quality of Bt crops are generally maintained or improved due to effective pest control. Bt crops have been associated with reduced crop damage and lower levels of mycotoxin contamination, which can occur when pests damage crops and create entry points for fungal infections (Xiao and Wu, 2019). Furthermore, Bt crops have been shown to promote biological control by conserving natural enemies of pests, such as parasitoids and predators, due to reduced insecticide use (Manjunath, 2020). This integrated pest management approach enhances the overall health and resilience of the crop ecosystem.

Bt transgenic crops have provided substantial agronomic benefits, including increased yields, reduced reliance on chemical insecticides, and improved crop health and quality. However, the sustainability of these benefits is threatened by the evolution of pest resistance, necessitating ongoing monitoring and the implementation of effective resistance management strategies.

3 Environmental Impact

3.1 Biodiversity effects

The introduction of Bt transgenic crops has raised concerns regarding their potential impact on biodiversity, particularly on non-target organisms. Studies have shown that Bt crops do not significantly affect the population abundance and biomass of soil invertebrates compared to conventional crops. A systematic review and meta-analysis of 22 publications revealed no significant effect of Cry proteins on soil invertebrates, although there was considerable variation among different orders of soil invertebrates (Krogh et al., 2020). Additionally, research on nematode communities indicated that Bt rice did not alter nematode abundance and community composition but did enhance trophic connections within nematode communities, suggesting a moderate stress effect of Cry proteins (Liu et al., 2018). Overall, while some studies suggest minor changes in specific taxa, the general consensus is that Bt crops do not pose a significant threat to soil biodiversity (Yaqoob et al., 2016; Mandal et al., 2020).

3.2 Soil health and microbial activity

The impact of Bt transgenic crops on soil health and microbial activity has been extensively studied. Bt crops have been found to affect soil enzyme activity and microbial community structure to some extent (Figure 1). Although most studies have found these effects to be temporary and inconsistent, a few have recorded significant impacts, particularly under long-term cultivation conditions. The residues of Bt crops have notably affected soil microorganisms, necessitating further research to assess their long-term ecological impacts (Li et al., 2022; Lebedev et al., 2022). Studies on the soil incubation of Cry1Ac protein have shown no adverse effects on soil microbial communities, with no significant changes in the diversity and population of bacteria, fungi, and archaea within 100 days (Zhao et al., 2018). A global meta-analysis of soil enzyme activity found that certain enzymes, such as dehydrogenase and urease, increased in activity under Bt crop cultivation, while others, such as neutral phosphatase, decreased. The response ratio of soil enzymes was greater with the incorporation of Bt residues than without (Li et al., 2019).

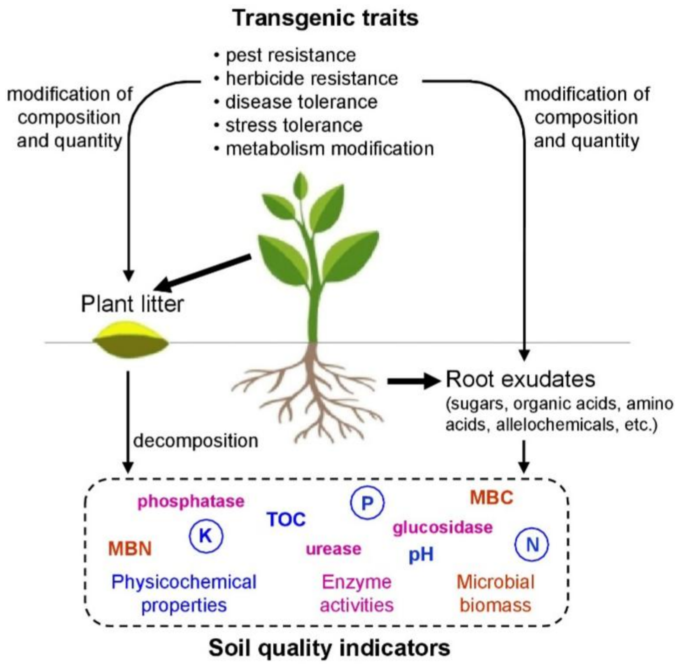

Figure 1 Potential impact of transgenic plants on soil quality indicators (Adopted from Lebedev et al., 2022)

Figure 1 from Lebedev et al. (2022) illustrates the potential impacts of transgenic plants on soil quality indicators. The figure emphasizes how root exudates and plant residues from Bt crops can alter soil microbial communities and enzyme activity. It highlights the complexity of soil-plant interactions, showing that changes in soil enzyme activity and microbial biomass are influenced by various biotic and abiotic factors. This detailed description aids in understanding the multifaceted impacts of Bt crops on soil health, stressing the need for integrated management practices to mitigate any adverse effects on soil ecosystems.

3.3 Non-target organisms

The potential effects of Bt crops on non-target organisms, including beneficial insects and soil organisms, have been a major focus of biosafety assessments. A comprehensive review of 76 articles on non-target plant-associated insects and soil organisms found no significant harmful impacts from approved GM events, although critical risk assessments are still recommended before commercialization (Yaqoob et al., 2016). Additionally, studies on the rhizosphere of transgenic rice indicated no significant changes in the population and activity of soil organisms such as bacteria, fungi, and nematodes, nor in the physicochemical properties of the soil (Sahoo et al., 2015). These results are supported by findings that Bt crops do not significantly alter the microbial communities in the rhizosphere, root endosphere, or leaf endosphere over multiple years (Wu et al., 2021). Overall, the evidence suggests that Bt transgenic crops do not pose significant risks to non-target organisms in agricultural systems (Mandal et al., 2020; Li et al., 2022).

4 Resistance Management

4.1 Development of pest resistance

The widespread adoption of Bt transgenic crops has significantly improved pest management and reduced reliance on chemical insecticides. However, the evolution of pest resistance to Bt toxins poses a major challenge to the long-term sustainability of these crops. Over the past two decades, the number of cases of pest resistance to Bt crystal proteins (Cry proteins) has increased significantly, from three cases in 2005 to 16 cases in 2016 (Tabashnik and Carrière, 2017). Similarly, a comprehensive analysis of global resistance monitoring data over 25 years has shown substantial resistance in some pest populations to nine widely used Cry toxins, spanning 11 pests in seven countries (Tabashnik et al., 2023). Research indicates that the development of pest resistance primarily stems from mutations affecting Bt toxin activation, toxin-binding genes, and regulation of the pest immune system. These mechanisms enable pests to survive Bt crops, gradually accumulating resistance genes and spreading within populations, as seen in the evolution of resistance in pink bollworm (PBW) to Bt cotton (Figure 2). In the long term, the evolution of resistance may significantly reduce the efficacy of Bt crops. Therefore, understanding the mechanisms behind resistance development and implementing integrated management strategies are crucial (Xiao and Wu, 2019).

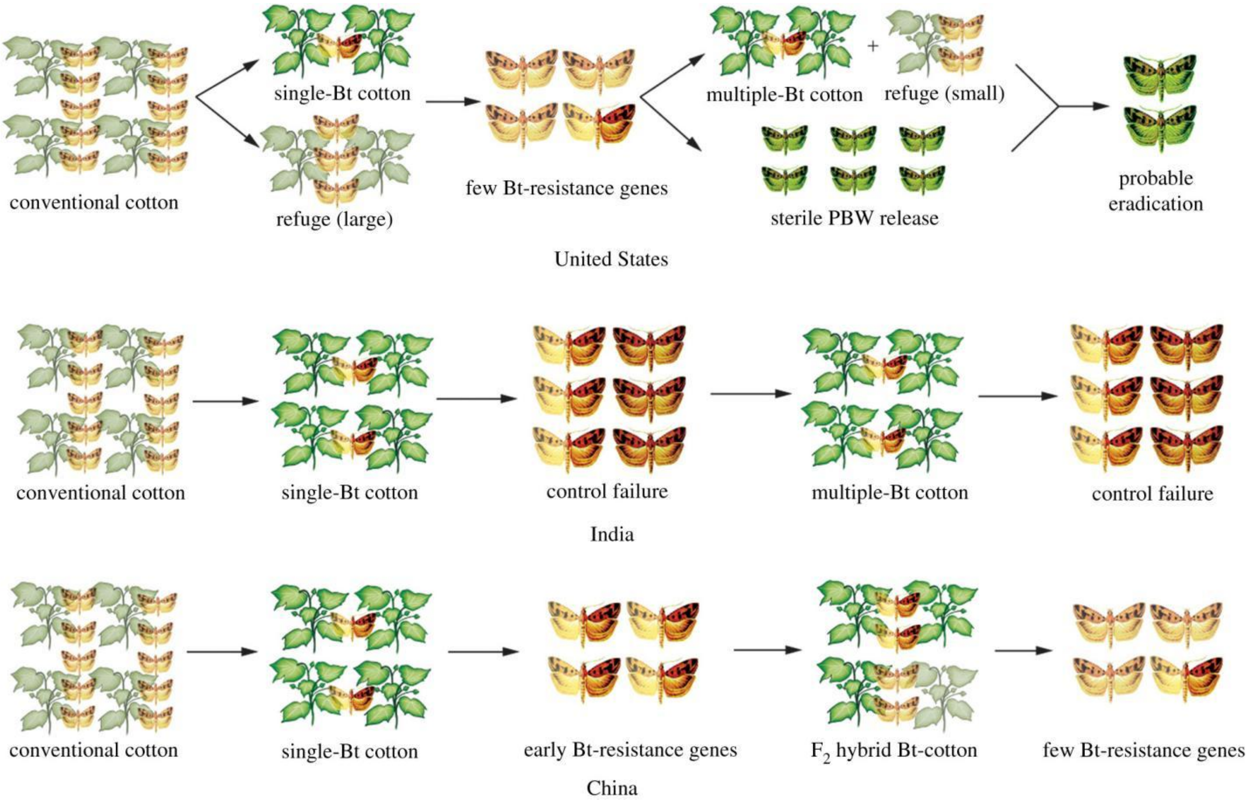

Figure 2 Models of the evolution of pink bollworm (PBW) Bt resistance (Adopted from Xiao and Wu, 2019)

Figure 2 illustrates the resistance evolution model of pink bollworm (PBW) to Bt cotton. In the United States, by effectively implementing a high-dose/refuge strategy, Bt cotton successfully delayed the spread of resistance genes, almost eliminating the resistant population after the introduction of multi-toxin Bt cotton. In India, poor refuge management led to the rapid development of Cry1Ac resistance in single-toxin Bt cotton, with resistance gradually increasing in subsequent multi-toxin Bt cotton. In China, the mixed refuge strategy with F2 generation

Bt cotton seeds effectively delayed the development of resistance. This figure emphasizes the importance of appropriate refuge strategies in managing resistance.

4.2 Strategies for resistance management

To mitigate the risk of resistance development, several strategies have been proposed and implemented. One of the primary strategies involves the use of refuges, which are areas planted with non-Bt crops to maintain a population of susceptible pests. This approach helps to delay resistance by promoting the survival of pests that are not exposed to Bt toxins, thereby reducing the selection pressure for resistant individuals (Carrière et al., 2016). Another effective strategy is the deployment of pyramided Bt crops, which produce multiple Bt toxins targeting the same pest. This approach has been shown to delay resistance more effectively than single-toxin crops, although issues such as cross-resistance and antagonism between toxins need to be carefully managed (Carrière et al., 2015). Additionally, integrating Bt crops with other pest management tactics, such as crop rotation and biological control, can further enhance the sustainability of Bt technology (Gassmann and Reisig, 2022).

4.3 Case studies of resistance management programs

Some case studies have demonstrated successful implementations of resistance management programs. The study by Carrière et al. (2019) compared resistance management strategies in Australia, Brazil, India, and the United States. Effective governance relies on a shared understanding among regulators, growers, and stakeholders, supported by robust coordination and monitoring systems to ensure compliance and rapid remediation. Successful Bt resistance management projects combine regulatory guidelines with collaborative efforts from all parties involved (Figure 3). Effective governance requires monitoring growers' compliance with resistance management requirements and promptly implementing remediation measures. In Australia, a proactive resistance management program for Bt cotton targeting Helicoverpa species has been in place for over 20 years. This program includes rigorous monitoring of resistance allele frequencies and strong stakeholder support, with results showing no significant changes in resistance allele frequencies in field populations (Knight et al., 2021). In the United States, the use of Bt crops has led to regional suppression of pest populations and, in some cases, even pest eradication. However, instances of resistance evolution have also been recorded, emphasizing the necessity for ongoing monitoring and adaptive management (Gassmann and Reisig, 2022).

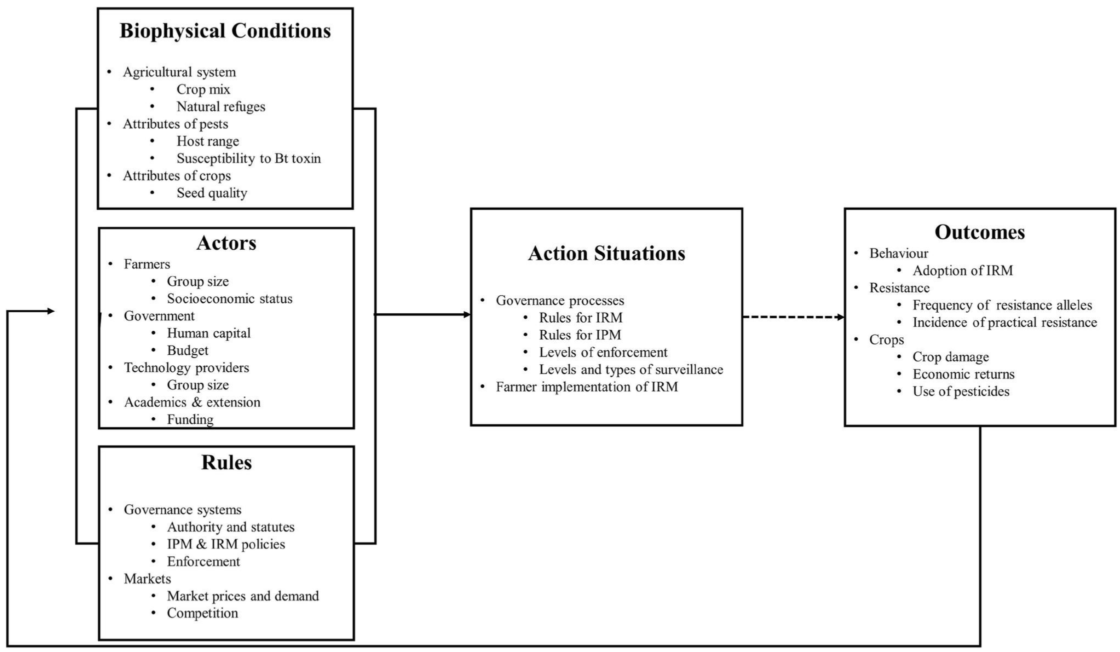

Figure 3 Overview of the Institutional Analysis and Development framework for governance of Bt crops (Adopted from Carrière et al, 2019)

Figure 3 from Carrière et al. (2019) presents the Institutional Analysis and Development (IAD) framework for Bt resistance governance. This framework identifies how environmental attributes, actor behavior, and institutional rules interact to influence resistance management outcomes. Key factors include pest biology, agricultural practices, and socioeconomic conditions. The figure highlights the importance of feedback loops, where growers' practices impact the evolution of pest resistance, which in turn affects the incentives for resistance management. This holistic approach underscores the necessity of combining regulations, monitoring, and stakeholder cooperation in effectively managing Bt resistance.

5 Socioeconomic Factors

The long-term sustainability of Bt transgenic crops in agricultural systems is influenced by a complex interplay of socioeconomic factors, including farmer adoption and acceptance, economic benefits and costs, and the broader impact on rural communities. Addressing these factors through improved regulation, public education, and integrated pest management strategies can enhance the sustainability and benefits of Bt crops.

5.1 Farmer adoption and acceptance

The adoption and acceptance of Bt transgenic crops by farmers are influenced by various factors, including perceived benefits, regulatory environments, and social pressures. In China, for instance, despite the development of multiple Bt rice lines that have shown negligible environmental risks and safety as food, commercial production has been stalled due to politicized decision-making and low consumer acceptance of GM crops. This indicates that enhancing public understanding and acceptance of GM crops is crucial for their adoption (Li et al., 2016). Similarly, in Pakistan, the adoption of Bt cotton has been complicated by a poorly regulated market where farmers often misidentify Bt and non-Bt crops, affecting their pesticide use strategies and health outcomes. Improved regulation and accurate identification of Bt crops could enhance adoption and maximize benefits (Kouser et al., 2019).

5.2 Economic benefits and costs

The economic benefits of Bt transgenic crops are significant, primarily due to reduced pesticide use and increased crop yields. For example, Bt cotton in the United States has led to regional suppression of pest populations, reduced conventional insecticide use, and increased profits for farmers (Gassmann and Reisig, 2022). However, the economic advantages can be offset by the rise of secondary pests, which may require additional insecticide applications or other management strategies. This has been observed in Bt maize, where secondary pests have become key pests, necessitating further measures to maintain economic benefits (Catarino et al., 2016). The health cost savings associated with reduced pesticide use in Bt cotton cultivation in Pakistan have been estimated at around US$ 7 million annually, highlighting the economic and health benefits of Bt crops (Kouser et al., 2019).

5.3 Impact on rural communities

The impact of Bt transgenic crops on rural communities extends beyond economic benefits to include health and environmental aspects. In Pakistan, the reduced need for pesticide sprays in Bt cotton cultivation has been associated with significant health benefits for farmers, reducing pesticide-induced illnesses and associated costs (Kouser et al., 2019). However, the uneven distribution of benefits and risks among different regions and communities can lead to disparities. For instance, in the southeastern USA, Bt cotton adoption has resulted in increased abundance of non-target pests like stink bugs, necessitating continued use of synthetic insecticides and potentially negating some of the environmental and economic benefits. Therefore, a comprehensive understanding of the ecological and socioeconomic dynamics is essential for maximizing the positive impacts of Bt crops on rural communities.

6 Regulatory and Policy Considerations

The regulatory and policy considerations for Bt crops are multifaceted and require a balanced approach that addresses biosafety, public perception, and international trade dynamics. Effective governance, robust regulatory frameworks, and proactive policy support are essential for the long-term sustainability of Bt transgenic crops in agricultural systems.

6.1 Regulatory frameworks for Bt crops

The regulatory frameworks for Bt crops vary significantly across different countries, reflecting diverse approaches to biosafety, environmental impact, and agricultural sustainability. In China, for instance, the regulatory system for genetically modified (GM) plants, including Bt rice, is well-developed and includes comprehensive risk assessment and management protocols. However, the decision-making process for commercial production approval has been heavily influenced by political and social factors, delaying the adoption of Bt rice despite its demonstrated safety and potential benefits (Li et al., 2016).

In the United States, the regulatory framework for Bt crops involves multiple agencies, including the Environmental Protection Agency (EPA), which oversees the environmental safety of Bt crops, and the United States Department of Agriculture (USDA), which assesses their agricultural impact. This multi-agency approach aims to ensure that Bt crops are safe for the environment and effective for pest management (Gassmann and Reisig, 2020).

Australia, Brazil, and India also have regulatory systems in place for Bt crops, with varying degrees of success in managing pest resistance. Effective governance in these countries relies on a shared understanding of resistance risks among regulators, growers, and other stakeholders, as well as robust monitoring and compliance mechanisms (Carrière et al., 2019).

6.2 Policy support and public perception

Policy support for Bt crops is crucial for their long-term sustainability. In many countries, government policies have promoted the adoption of Bt crops by providing subsidies, technical support, and educational programs for farmers. For example, in Latin America, government vigilance in monitoring Bt-susceptibility and implementing corrective measures has been essential in maintaining the effectiveness of Bt crops (Blanco et al., 2016).

Public perception of Bt crops, however, remains a significant challenge. In China, the low level of understanding and acceptance of GM crops among consumers has hindered the commercialization of Bt rice, despite its potential benefits (Li et al., 2016). This highlights the need for better communication and education about the science and safety of GM crops to gain public trust and support.

6.3 International trade and regulations

International trade regulations for Bt crops are complex and often involve stringent biosafety assessments to ensure that these crops do not pose risks to importing countries. The global trade of Bt crops is influenced by varying regulatory standards and public perceptions in different regions. For instance, the European Union has strict regulations and labeling requirements for GM crops, which can affect the export potential of Bt crops from countries with more permissive regulatory environments (Carrière et al., 2019).

Moreover, the development of pest resistance to Bt crops can have significant implications for international trade. Countries that effectively manage resistance through regulatory frameworks and compliance measures are better positioned to maintain the efficacy of Bt crops and their competitiveness in the global market (Carrière et al., 2016; Tabashnik and Carrière, 2017; Tabashnik et al., 2023).

7 Technological Advances and Innovations

7.1 New Bt varieties and traits

The development of new Bt varieties and traits has been a significant focus in the field of agricultural biotechnology. The first generation of Bt transgenic crops primarily included traits such as herbicide tolerance and resistance to insects and viruses. These traits have been successfully integrated into crops like cotton, maize, and soybean, leading to increased yields and reduced reliance on chemical pesticides (Rios, 2015; Koul, 2020). Recent advancements have introduced traits that enhance resistance to a broader range of pests and environmental stresses, improve food and feed quality, and increase input efficiency (Rios, 2015). For instance, the introduction of Bt vegetative insecticidal proteins (Vip) in transgenic corn has shown promise in maintaining pest susceptibility where other Bt proteins have failed (Tabashnik and Carrière, 2017; Tabashnik et al., 2023).

7.2 Integration with other biotechnologies

The integration of Bt transgenic crops with other biotechnologies has been pivotal in enhancing their effectiveness and sustainability. Combining Bt traits with other genetic modifications, such as RNAi-based traits for viral resistance, has been shown to improve pest and disease management (Anderson et al., 2019). Additionally, the use of Bt crops within diversified Integrated Pest Management (IPM) systems has proven beneficial. IPM strategies that incorporate Bt crops can reduce the need for chemical insecticides, thereby lowering environmental impact and promoting agricultural sustainability (Mabubu et al., 2016; Anderson et al., 2019). The use of hybrid genes, gene pyramiding, and sterile insect techniques are some of the strategies employed to delay pest resistance and maintain the efficacy of Bt crops (Carrière et al., 2015; Koul, 2020).

7.3 Advances in genetic engineering

Advances in genetic engineering have significantly contributed to the development and sustainability of Bt transgenic crops. Techniques such as cisgenesis, intragenesis, zinc-finger nuclease technology, and oligonucleotide-directed mutagenesis (ODM) have enabled more precise genetic modifications, enhancing the performance and safety of transgenic crops (Rios, 2015). The use of Agrobacterium-mediated plant transformation has been particularly effective in developing stable transgenics, which are crucial for long-term sustainability (Koul, 2020). Moreover, the application of meta-analysis in evaluating the performance of transgenic crops has provided robust evidence of their benefits over conventional crops, including higher yields, lower production costs, and reduced pesticide use (Rios, 2015). These technological advancements underscore the importance of continued innovation and regulatory support to maximize the potential of Bt transgenic crops in sustainable agriculture.

8 Long-term Ecological and Economic Sustainability

8.1 Evaluating long-term ecological impact

The long-term ecological impact of Bt transgenic crops is a critical area of study, given their widespread adoption and the potential for unintended consequences on non-target organisms and soil health. Research has shown that while Bt crops have been effective in reducing the reliance on chemical pesticides, they also pose risks such as the development of pest resistance and potential impacts on soil enzymatic activities and non-target organisms.

For instance, studies have documented an increase in pest resistance to Bt crops over time, with cases of resistance rising significantly from 2005 to 2020 (Carrière et al., 2015; Tabashnik and Carrière, 2017) . This resistance can undermine the ecological benefits of Bt crops by necessitating the use of additional pest control measures, potentially leading to increased chemical pesticide use and associated environmental impacts.

Moreover, the impact of Bt crops on soil health has been a subject of extensive research. A global meta-analysis revealed that Bt crops can alter soil enzymatic activities, with significant increases in enzymes such as dehydrogenase and urease when Bt residues are incorporated into the soil (Gassmann and Reisig, 2022). These changes in soil enzyme activities can affect nutrient cycling and soil fertility, which are crucial for long-term agricultural sustainability.

Additionally, the effects of Bt crops on non-target soil invertebrates have been systematically reviewed, showing no significant overall impact on their population abundances and biomasses (Krogh et al., 2020). However, the variability among different invertebrate orders and the heterogeneity of study results suggest that more research is needed to fully understand the long-term ecological consequences of Bt crop cultivation.

8.2 Assessing economic viability over time

The economic viability of Bt transgenic crops over the long term is influenced by several factors, including pest resistance management, crop yields, and the costs associated with implementing integrated pest management (IPM) strategies. Bt crops have been shown to provide economic benefits by reducing the need for chemical pesticides and increasing crop yields, which can lead to higher profits for farmers (Gassmann and Reisig, 2022)).

However, the evolution of pest resistance to Bt crops poses a significant challenge to their economic sustainability. As pests develop resistance, the effectiveness of Bt crops diminishes, potentially leading to increased crop damage and reduced yields. This necessitates the adoption of additional pest management strategies, such as the use of refuges of non-Bt host plants and the development of pyramided Bt crops that produce multiple toxins to delay resistance (Carrière et al., 2015; Ni et al., 2017).

The economic viability of Bt crops also depends on their ability to maintain high yields under changing environmental conditions. For example, studies have shown that inoculation with arbuscular mycorrhizal fungi (AMF) can enhance the yield and insect resistance of Bt maize, particularly under elevated CO_2 conditions, which are expected due to climate change (Wang et al., 2021). This suggests that integrating Bt crops with other sustainable agricultural practices can help ensure their long-term economic viability.

8.3 Case studies on sustainability

Several case studies highlight the sustainability of Bt transgenic crops in different agricultural systems. In the United States, the use of Bt corn and cotton has led to regional suppression of pest populations and even pest eradication in some areas, resulting in reduced use of conventional insecticides and increased profits for farmers (Gassmann and Reisig, 2022). These positive outcomes demonstrate the potential for Bt crops to contribute to sustainable pest management and economic gains.

In contrast, other case studies have documented instances where pests evolved resistance to multiple Bt traits, leading to increased crop damage and the need for additional pest control measures (Gassmann and Reisig, 2022). These cases underscore the importance of implementing effective resistance management strategies to sustain the benefits of Bt crops.Another case study from China demonstrated the effectiveness of pyramided cotton combining Bt toxins and RNA interference (RNAi) in delaying pest resistance and maintaining high crop yields (Ni et al., 2017). This approach highlights the potential for combining multiple pest control technologies to enhance the sustainability of Bt crops.

9 Concluding Remarks

The long-term sustainability of Bt transgenic crops in agricultural systems has been extensively researched. Studies indicate that while Bt crops have significantly improved pest management and reduced reliance on chemical insecticides, the evolution of pest resistance poses a substantial threat to their efficacy. Research has documented an increase in pest resistance to Bt proteins over time, with practical resistance observed in several pest species across multiple countries. However, certain factors such as the recessive inheritance of resistance, abundant refuges of non-Bt host plants, and the use of pyramided Bt crops have been shown to delay resistance development. The incorporation of Bt residues in soil has been found to influence soil enzymatic activities, which could have implications for soil health and crop sustainability.

The sustainability of Bt transgenic crops cannot rely solely on genetic modifications. Integrated pest management (IPM) strategies that combine Bt crops with other control methods are crucial. For instance, planting refuges of non-Bt crops alongside Bt crops has proven effective in delaying resistance. Moreover, the development of next-generation transgenic crops that combine Bt toxins with RNA interference (RNAi) technology shows promise in countering resistance. The use of arbuscular mycorrhizal fungi (AMF) to enhance the yield and resistance of Bt crops under elevated CO_2 conditions is another innovative approach that could contribute to the long-term sustainability of these crops. These integrated approaches help manage resistance and maintain ecological balance and soil health.

Future research should focus on understanding the mechanisms of resistance to Bt proteins at a molecular level to develop more effective resistance management strategies. Continuous monitoring of pest resistance and the effectiveness of Bt crops in different regions is necessary to adapt management practices accordingly. Policymakers should consider mandating the use of refuges and promoting the adoption of pyramided Bt crops and other integrated pest management strategies to prolong the efficacy of Bt technology. Additionally, research into the environmental impacts of Bt crops, particularly on soil health and non-target organisms, should be prioritized to ensure the overall sustainability of agricultural systems. International collaboration and data sharing among researchers, growers, and policymakers will be essential in addressing the global challenge of pest resistance to Bt crops.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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