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Bt in Organic Farming: Benefits and Limitations

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Abstract Bt (*Bacillus thuringiensis*) is a widely used biological pesticide known for its high specificity and safety in pest control. In organic agriculture, the application of Bt provides an effective and environmentally friendly pest control method that aligns with the principles and requirements of organic farming. However, the use of Bt in organic agriculture also faces challenges such as the risk of resistance development, environmental constraints, and regulatory issues. This study systematically reviews the mechanisms of action of Bt, its benefits and limitations in organic agriculture, and successful case studies and lessons learned. The comprehensive analysis of the current application and future prospects of Bt in organic agriculture demonstrates its significant effectiveness in pest control and environmental friendliness. Nonetheless, continuous monitoring of resistance development and the implementation of effective management strategies are essential. Additionally, innovations in Bt formulations and their integration with other organic practices are key areas for future research. This study aims to provide a scientific basis for promoting the application of Bt in organic agriculture and to guide future research and development.

Keywords Bt; Biological pesticide; Organic farming; Resistance management; Environmental benefits

1 Introduction

Bacillus thuringiensis (Bt) is a gram-positive, spore-forming bacterium that has gained prominence due to its potent insecticidal properties. During sporulation, Bt produces crystal proteins (Cry proteins) that are toxic to a wide range of insect pests, particularly those belonging to the orders Coleoptera, Diptera, and Lepidoptera (Xiao and Wu, 2019; Sánchez-Yáñez et al., 2022). These Cry proteins have been extensively utilized in both microbial insecticides and genetically modified crops to enhance pest resistance (Jouzani et al., 2017; Rajadurai et al., 2023). Bt's ability to target specific pests while being safe for humans, animals, and non-target organisms has made it the most widely used biopesticide globally (Gutiérrez et al., 2019; Rajadurai et al., 2023). Additionally, Bt has shown potential in other applications such as bioremediation, plant growth promotion, and even cancer prevention (Jouzani et al., 2017; Sánchez-Yáñez et al., 2022).

Organic farming is an agricultural practice that emphasizes the use of natural inputs and processes to enhance soil fertility, biodiversity, and ecological balance. It avoids synthetic chemicals, such as pesticides and fertilizers, to produce food in a sustainable and environmentally friendly manner. The increasing consumer demand for organic products is driven by concerns over food safety, environmental sustainability, and health benefits. Organic farming practices contribute to soil health, reduce pollution, and promote biodiversity, making it a crucial component of sustainable agriculture (Loguercio and Argôlo-Filho, 2015; Rajadurai et al., 2023). Integrating biopesticides like Bt into organic farming aligns with these principles, offering an effective and eco-friendly solution for pest management (Gomis-Cebolla and Berry, 2023; Rajadurai et al., 2023).

To evaluate the benefits and limitations of using *Bacillus thuringiensis* (Bt) in organic farming, this study assesses the efficacy of Bt as a biopesticide in controlling various insect pests in organic farming systems. It explores the potential non-insecticidal benefits of Bt, such as plant growth promotion and bioremediation. It identifies the challenges and limitations associated with the use of Bt in organic farming, including the development of pest resistance and ecological impacts. Additionally, it provides recommendations for future research and practical applications to optimize the use of Bt in organic farming. By synthesizing current knowledge and research findings, this study aims to provide a comprehensive understanding of the role of Bt in organic farming and its potential to contribute to sustainable agricultural practices.

2 Mechanisms of Bt Action

2.1 Bt toxins and their targets

Bacillus thuringiensis (Bt) produces a variety of insecticidal proteins, including Cry and Vip toxins, which target specific insect pests. These toxins are highly selective, affecting only certain insect species while being safe for humans and other non-target organisms (Gassmann and Reisig, 2022). The Cry toxins, in particular, are produced as protoxins that require activation within the insect gut to become toxic. The specificity of these toxins is due to their ability to bind to specific receptors in the insect midgut, leading to cell lysis and death (Tabashnik, 2015; Chattopadhyay and Banerjee, 2018; Heckel, 2020).

2.2 Mode of action in insect pests

The mode of action of Bt toxins involves several steps. Initially, the protoxins are ingested by the insect and activated by gut proteases, converting them into their toxic form. The activated toxins then bind to specific receptors on the midgut epithelial cells, such as cadherins and ABC transporters. This binding facilitates the formation of pores in the cell membrane, leading to cell lysis and ultimately the death of the insect (Chattopadhyay and Banerjee, 2018). Recent studies have highlighted the role of ABC transporters in the mechanism of action, suggesting that these proteins are crucial for the binding and pore formation of Cry toxins (Tabashnik, 2015; Heckel, 2020).

2.3 Specificity and safety of Bt toxins

Bt toxins are highly specific to their target pests, which makes them an attractive alternative to broad-spectrum chemical insecticides. This specificity is due to the unique receptors present in the midgut of susceptible insects, which are absent in non-target organisms (Tabashnik, 2015; Chattopadhyay and Banerjee, 2018; Gassmann and Reisig, 2022). For instance, Cry1Ac and Cry2Ab toxins are effective against lepidopteran pests but have little to no effect on other insects or mammals. The safety of Bt toxins is further supported by their long history of use in agriculture without adverse effects on human health or the environment. However, the evolution of resistance in target pests poses a significant challenge, necessitating ongoing research and the development of new strategies to manage resistance (Tabashnik, 2015; Gassmann and Reisig, 2022).

Bt toxins offer a highly specific and safe method for pest control, with their mode of action involving the activation of protoxins, binding to specific midgut receptors, and subsequent cell lysis. The specificity and safety of these toxins make them a valuable tool in integrated pest management, although the evolution of resistance remains a critical issue that requires continuous monitoring and innovation.

3 Benefits of Bt in Organic Farming

Bt crops provide numerous benefits in organic farming, including effective pest control, environmental sustainability, and alignment with organic farming principles. These advantages make Bt crops a promising option for enhancing the productivity and sustainability of organic farming systems.

3.1 Pest control efficacy

3.1.1 Spectrum of activity

Bt crops have been engineered to produce insecticidal proteins from *Bacillus thuringiensis* (Bt), which are effective against a wide range of pests, particularly lepidopteran and coleopteran species. These proteins, such as Cry1 and Cry2, target specific pests while having minimal impact on non-target organisms, including beneficial insects and humans (Tabashnik, 2015; Arends et al., 2021). The narrow and selective toxicity spectrum of Bt proteins helps in managing primary pests effectively without causing significant harm to the ecosystem (Catarino et al., 2016).

3.1.2 Field application successes

The implementation of Bt crops has led to significant successes in pest control in various regions. For instance, Bt cotton and maize have been widely adopted in the United States, India, and Australia, resulting in reduced pest populations and decreased reliance on chemical insecticides (Tabashnik, 2015; Xiao and Wu, 2019; Gassmann, and Reisig, 2022). In the southwestern United States, a combination of Bt cotton and integrated pest management strategies, including the release of sterile moths, has successfully eradicated the pink bollworm, a major pest (Tabashnik and Carrière, 2019). These successes highlight the practical benefits of Bt crops in reducing pest-related crop damage and increasing agricultural productivity.

3.1.3 Resistance management

One key challenge in using Bt crops is the evolution of pest resistance. However, strategies such as planting refuges with non-Bt crops and using pyramided Bt crops that produce multiple Bt toxins have effectively delayed the development of resistance (Carrière et al., 2016). Cooperative management among government regulators, growers, and other stakeholders plays a critical role in effectively managing pest resistance (Figure 1). For example, in Australia, Bt cotton using Cry1Ac and Cry2Ab toxins helps manage resistance in the cotton bollworm (*Helicoverpa armigera*) (Tabashnik, 2015). Additionally, combining Bt crops with other pest management strategies, such as crop rotation and the use of non-Bt host plants, has been shown to enhance the sustainability of Bt crops by slowing the development of resistance (Gassmann, 2021).

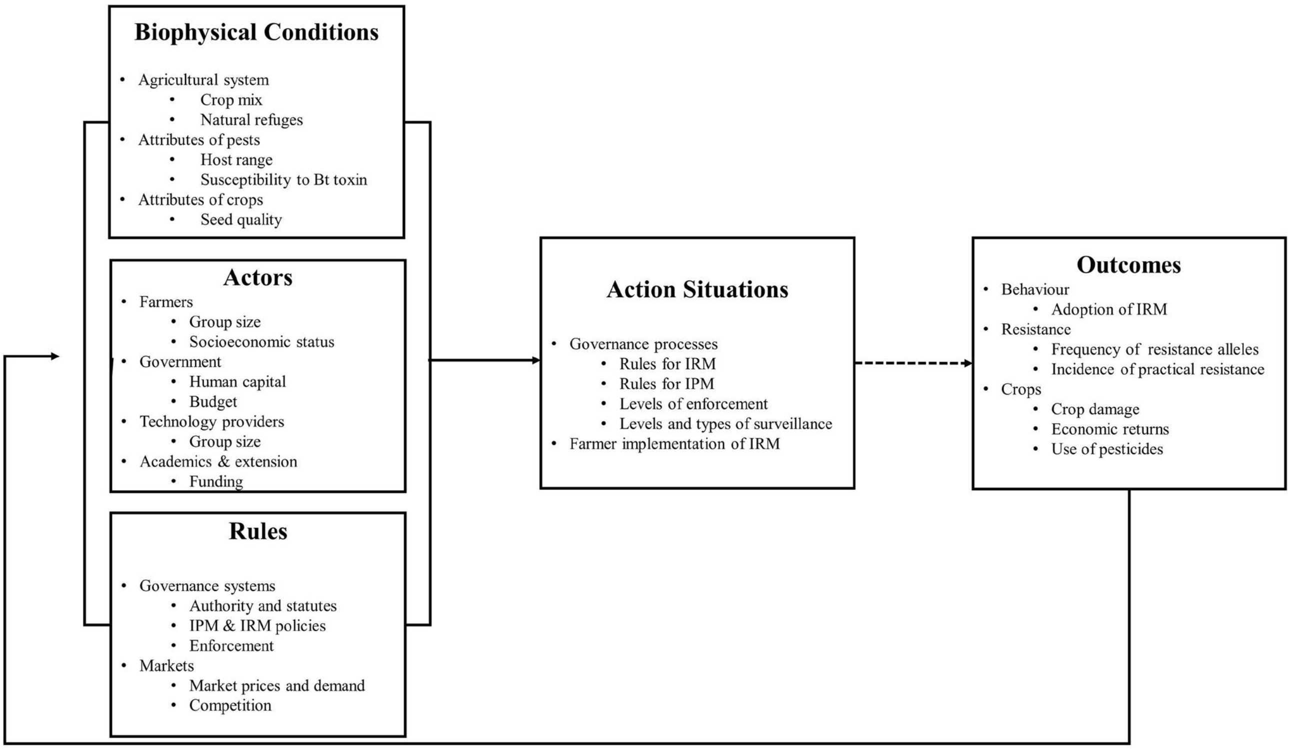

Figure 1 Overview of the Institutional Analysis and Development framework for governance of Bt crops (Adopted from Carrière et al., 2016)

The Institutional Analysis and Development (IAD) framework for the governance of Bt crops demonstrates how biophysical conditions, rules, and the actions of different stakeholders interact to influence resistance outcomes. Figure 1 emphasizes the importance of considering ecological and socio-economic factors when formulating and implementing resistance management policies. It underscores the integrated roles of government agencies, growers, and the industry in managing resistance to Bt crops to ensure sustainable pest control and long-term agricultural productivity.

3.2 Environmental benefits

Bt crops offer significant environmental benefits by reducing the need for chemical insecticides, which can have harmful effects on non-target organisms and the environment. The adoption of Bt crops has led to a decrease in insecticide use, thereby reducing the environmental footprint of agricultural practices (Xiao and Wu, 2019; Gassmann and Reisig, 2022). Moreover, Bt crops contribute to biodiversity conservation by preserving beneficial insect populations and reducing the risk of pesticide runoff into water bodies (Arends et al., 2021). The environmental safety of Bt crops has been well-documented, with studies showing no adverse effects on non-target organisms, including mammals, birds, and beneficial insects (Koch et al., 2015).

3.3 Compatibility with organic farming principles

Bt crops align well with the principles of organic farming, which emphasize sustainable and environmentally friendly agricultural practices. The use of Bt crops can reduce the reliance on synthetic chemical insecticides, which are generally prohibited in organic farming (Xiao and Wu, 2019). Additionally, Bt crops can be integrated into organic farming systems as part of a broader integrated pest management strategy, which includes crop rotation, biological control, and the use of natural refuges (Carrière et al., 2016). This compatibility makes Bt crops a valuable tool for organic farmers seeking to manage pests effectively while adhering to organic farming standards.

4 Limitations of Bt in Organic Farming

4.1 Development of resistance

4.1.1 Mechanisms of resistance development

The development of resistance to Bt crops in organic farming is a significant limiting factor. Resistance mechanisms typically involve genetic mutations in target pests. For instance, mutations in genes encoding ATP-binding cassette (ABC) transporters have been associated with *Helicoverpa zea* resistance to the Cry2Ab toxin (Tabashnik, 2015). Additionally, resistance may also result from mutations in other genes that affect toxin binding sites or are involved in the mode of action of Bt toxins (Xiao and Wu, 2019; Jurat-Fuentes, 2021). The development of resistance is promoted by factors such as the inheritance of non-recessive resistance traits, low fitness costs associated with resistance, and continuous exposure to Bt crops (Gassmann, 2021). The introduction of Bt maize and Bt cotton has significantly suppressed pest populations in some regions, reducing the need for traditional insecticides and increasing farmers' profits. However, the evolution of pest resistance to Bt traits remains a critical challenge, leading to reduced effectiveness of Bt crops (Figure 2).

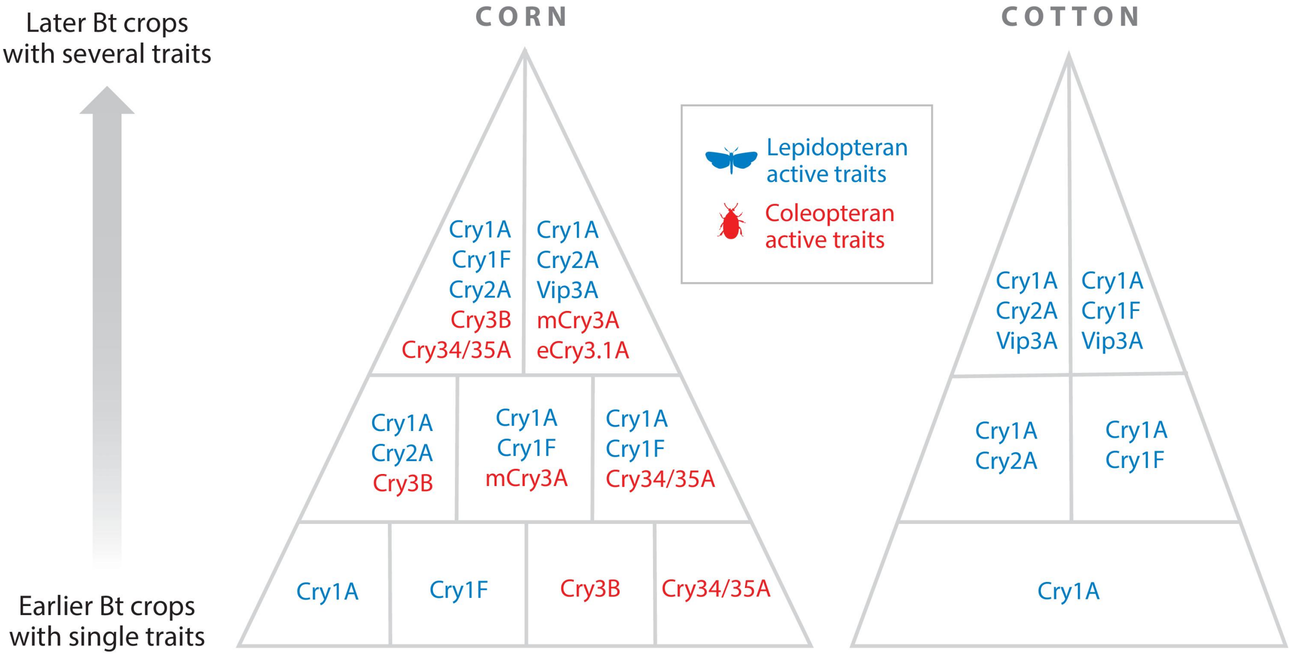

Figure 2 Pattern of pyramiding and stacking of *Bacillus thuringiensis* (Bt) traits over time for Bt corn and Bt cotton in the United States (Adopted from Gassmann, 2021)

Image caption: Subdivisions within larger triangles represent an array of Bt traits found within an individual crop plant. All past and current trait combinations are displayed for cotton, but only a subset of trait combinations are provided for corn. While lepidopteran traits target pests in multiple families, coleopteran traits are only used to manage species in the genus Diabrotica (Chrysomelidae) (Adopted from Gassmann, 2021)

The figure from Gassmann (2021) details the combination of different Bt toxins within a single crop, highlighting the cumulative effect of multiple Bt toxins on the same pest. This pyramiding strategy aims to delay the evolution of pest resistance by using multiple toxins, but the figure also reveals that cross-resistance and antagonism between the toxins can impact the effectiveness of resistance management. Therefore, optimizing the combination of Bt toxins is crucial for improving pest control efficacy.

4.1.2 Monitoring and detection

Effective monitoring and detection of resistance are crucial for managing Bt resistance. Techniques such as the F2 screen and genetic linkage analysis have been employed to detect resistance alleles in field populations . Regular surveillance and bioassays are essential to identify early signs of resistance and implement timely management strategies (Carrière et al., 2019). For example, monitoring data from Australia showed no significant increase in Cry2Ab resistance over eight years, highlighting the importance of robust monitoring programs (Tabashnik, 2015).

4.1.3 Strategies to mitigate resistance

Several strategies can mitigate the development of resistance to Bt crops. One approach is the use of multi-toxin Bt crops, which produce multiple Bt toxins to delay resistance (Tabashnik, 2015). Another strategy is the implementation of refuges, where non-Bt crops are planted to maintain a population of susceptible pests (Arends et al., 2021; Gassmann, 2021). Additionally, integrated pest management (IPM) practices, such as crop rotation and the use of non-Bt insecticides, can help manage resistance (Gassmann, 2021; Gassmann and Reisig, 2022). The success of these strategies depends on coordinated efforts among farmers, regulators, and other stakeholders (Carrière et al., 2019).

4.2 Environmental constraints

Environmental factors can also limit the effectiveness of Bt in organic farming. The interaction between Bt crops and the surrounding ecosystem can influence the development of resistance. For example, the local abundance of non-Bt crops and natural refuges can affect the effectiveness of resistance management strategies (Arends et al., 2021). Moreover, the nutritional status of insect herbivores can impact their susceptibility to Bt toxins, with optimal diets potentially reducing the efficacy of Bt crops (Deans et al., 2016). Understanding these environmental constraints is essential for developing sustainable pest management practices.

4.3 Regulatory and market challenges

Regulatory and market challenges pose additional limitations to the use of Bt in organic farming. Regulatory frameworks vary across countries, affecting the implementation of resistance management measures (Carrière et al., 2019). In some regions, the lack of mandatory refuges and insufficient monitoring can exacerbate resistance issues (Tabashnik and Carrière, 2019). Market acceptance of Bt crops also varies, with some consumers and organic certification bodies opposing genetically modified organisms (GMOs) (Xiao and Wu, 2019). Addressing these challenges requires harmonized regulations, effective communication among stakeholders, and public education on the benefits and risks of Bt crops.

5 Case Studies and Field Applications

5.1 Successful implementations

The adoption of *Bacillus thuringiensis* (Bt) crops has shown significant success in various agricultural settings. For instance, widespread Bt maize adoption in the Mid-Atlantic United States has led to marked decreases in the number of recommended insecticidal applications, insecticides applied, and damage to vegetable crops. This regional pest suppression has benefited not only Bt crop fields but also non-Bt crop fields, including those managed organically (Dively, 2018). Additionally, Bt crops have been associated with increased profits for farmers due to reduced conventional insecticide use and enhanced pest control.

5.2 Lessons learned

While Bt crops have demonstrated substantial benefits, there are critical lessons to be learned from their implementation. One significant challenge is the evolution of pest resistance to Bt traits. In some cases, pests have developed resistance, leading to increased crop damage and reduced effectiveness of Bt crops. To mitigate this, strategies such as increasing the prevalence of refuges and integrating pest management practices are essential. These measures can help delay resistance and sustain the efficacy of Bt crops over time (Gassmann and Reisig, 2022).

5.3 Comparative analysis with other organic methods

When comparing Bt crops with other organic farming methods, several factors come into play. Organic farming generally outperforms conventional systems economically due to lower production costs and higher market prices, despite lower yields (Durham and Mizik, 2021). However, the integration of Bt crops can enhance pest control and reduce the need for insecticides, which is beneficial for both conventional and organic systems (Dively, 2018; Gassmann and Reisig, 2022).

Moreover, organic farming practices, such as crop rotations and the use of organic fertilizers, contribute to soil fertility and environmental sustainability (Kolbe, 2022). However, the yield gap between organic and conventional farming remains a challenge, with organic systems producing on average 25% lower yields (Alvarez, 2021). The combination of Bt crops with organic practices could potentially bridge this gap by improving pest control and reducing crop damage, thereby enhancing overall productivity and sustainability.

The integration of Bt crops in organic farming presents a promising approach to address some of the limitations of organic systems, particularly in pest management. However, careful consideration of pest resistance and the adoption of integrated pest management strategies are crucial to ensure the long-term success and sustainability of Bt crops in organic farming systems.

6 Future Perspectives

6.1 Innovations in Bt formulations

Innovations in Bt formulations are crucial for enhancing the efficacy and sustainability of Bt crops in organic farming. Recent studies have highlighted the importance of developing transgenic crop pyramids that produce multiple Bt toxins to delay the evolution of pest resistance. For instance, research has shown that pyramided Bt crops, which produce two or more Bt toxins targeting the same pest, can be more effective in managing pest resistance compared to single-toxin Bt crops (Carrière et al., 2015). However, the effectiveness of these pyramids can be compromised by cross-resistance and antagonism between the toxins, which are often related to the similarity in their amino acid sequences (Carrière et al., 2015). Therefore, future innovations should focus on optimizing the combination of Bt toxins to minimize these issues and enhance pest control.

6.2. Integration with other organic practices

Integrating Bt crops with other organic farming practices can further improve pest management and sustainability. Organic agriculture, known for its environmental benefits and profitability, can be complemented by Bt crops to reduce pesticide use and enhance crop yields (Reganold and Wachter, 2016). For example, the use of refuges—areas planted with non-Bt crops—alongside Bt crops has been shown to delay pest resistance by allowing susceptible pests to survive and mate with resistant ones, thereby reducing the overall resistance in the pest population (Carrière et al., 2016). Additionally, combining Bt crops with other pest management tactics, such as crop rotation and biological control, can create a more robust and sustainable pest management system (Carrière et al., 2016; Gassmann and Reisig, 2022).

6.3 Research and development priorities

Future research and development should prioritize understanding the long-term impacts of Bt crops and improving resistance management strategies. Studies have shown that while Bt crops can initially reduce pesticide use and increase profits, the evolution of pest resistance can lead to increased pesticide use and reduced effectiveness of Bt crops over time (Kranthi and Stone, 2020). Therefore, it is essential to focus on developing new Bt traits and improving existing ones to delay resistance. This includes increasing the prevalence of refuges and using integrated pest management strategies (Gassmann and Reisig, 2022). Additionally, research should explore the socio-economic impacts of Bt crops on farmers and communities to ensure that the benefits of Bt technology are equitably distributed (Reganold and Wachter, 2016; Kranthi and Stone, 2020).

7 Concluding Remarks

The application of *Bacillus thuringiensis* (Bt) crops has shown significant benefits in pest management and agricultural sustainability. The widespread adoption of Bt maize has led to regional pest suppression, reducing the need for insecticidal applications and decreasing crop damage in both Bt and non-Bt fields, including vegetable crops. Bt crops have also reduced insecticide usage and increased farmers' profits. However, the evolution of pest resistance to Bt traits remains a critical challenge, necessitating integrated pest management strategies to delay resistance. Additionally, while Bt crops have shown efficacy in pest control, their performance can be compromised under environmental stress conditions.

Bt crops play a crucial role in sustainable agriculture by reducing the reliance on chemical insecticides, thereby promoting environmental health and biocontrol services. They help lower pest management costs and increase crop yields, thus boosting farmers' profits. Bt crops have also been proven to provide indirect benefits to neighboring non-Bt crops by reducing pest pressure, which is particularly beneficial for organic farming systems. Despite the lower yields and higher variability in organic farming, integrating Bt crops can enhance the overall sustainability of agricultural practices by balancing productivity with environmental and economic benefits.

Future research should focus on several key areas to enhance the benefits of Bt crops in organic farming and reduce their limitations. Investigate and develop strategies to delay pest resistance to Bt crops, such as increasing the prevalence of refuges and employing integrated pest management practices. Conduct comprehensive studies to understand the impact of various environmental stressors on the efficacy of Bt crops and develop robust predictive models for their performance under extreme climatic conditions. Additionally, explore the interactions between Bt crops and non-target organisms, including beneficial insects and aquatic ecosystems, to ensure that Bt crop adoption does not inadvertently harm these populations. By addressing these research areas, we can optimize the use of Bt crops in organic farming systems, ensuring their benefits are maximized while minimizing potential drawbacks.

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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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