

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