

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.