

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).

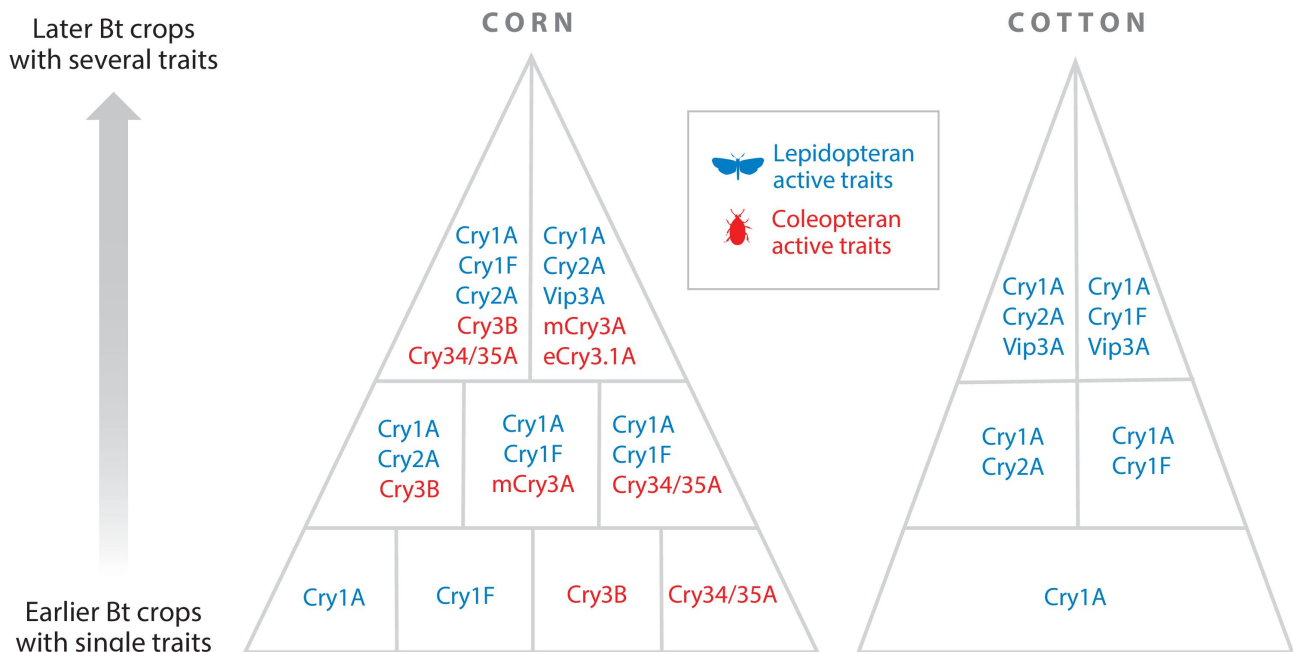


Figure 2 Pattern of pyramiding and stacking of *Bacillus thuringiensis* (Bt) traits over time for Bt corn and Bt cotton in the United States (Adopted from Gassmann, 2021)

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)