

potential cross-resistance and antagonism between toxins, which can reduce their effectiveness (Carrière et al., 2015). Products like SmartStax and PowerCore have demonstrated improved resistance management benefits compared to single-toxin products, allowing for smaller refuges and less dependence on high mortality rates among susceptible pests (Storer et al., 2012).

6.3 Integrated pest management (IPM)

Integrated Pest Management (IPM) combines multiple control tactics to manage pest populations sustainably. This approach includes the use of Bt crops, refuges, biological control agents, and cultural practices. IPM aims to reduce the reliance on any single control method, thereby delaying the evolution of resistance. For instance, combining Bt crops with the release of sterile insects or transgenic insects has been proposed as a method to manage pest populations and resistance simultaneously (Zafar et al., 2020; Brewer and Bonsall, 2020). Additionally, IPM strategies can be tailored to regional pest pressures, ensuring that Bt crops are used where they are most beneficial and reducing their use in areas with low pest pressure. By integrating various control methods, IPM can enhance the sustainability of Bt crops and delay the development of resistance in pest populations (Gassmann and Reisig, 2022).

7 Case Studies

7.1 Successful management of resistance

The successful management of resistance to Bt toxins in insect populations has been achieved through various strategies. One notable example is the implementation of proactive resistance management strategies such as the refuge strategy and the pyramid strategy. These strategies have been effective in sustaining the control of target pests for nearly two decades (Wu, 2014). Additionally, the use of multi-toxin Bt crops has been shown to delay resistance evolution by providing redundant killing mechanisms, which is supported by field outcomes and theoretical predictions (Tabashnik et al., 2013). In the United States, regional suppression of pest populations and even pest eradication have been achieved in some cases, leading to reduced reliance on conventional insecticides and increased profits for farmers (Gassmann and Reisig, 2022).

7.2 Challenges faced in different regions

Despite the successes, several challenges have been encountered in different regions. For instance, practical resistance to Bt crops has been documented in some populations of 11 pest species across seven countries, affecting nine widely used Bt toxins (Tabashnik et al., 2023). In the United States, pests have evolved resistance to multiple Bt traits, compromising the effectiveness of Bt crops and leading to increased crop damage (Gassmann and Reisig, 2022). The spatial heterogeneity of Bt crop deployment in small-holder farm systems has also been identified as a factor that can accelerate the regional evolution of resistance, highlighting the need for spatially explicit resistance management strategies (Huang et al., 2017). Furthermore, the genetic diversity of resistance mechanisms, including mutations in ABC transporters and enhanced immune responses in insects, poses additional challenges for understanding and managing resistance (Gahan et al., 2010; Heckel et al., 2012; Tay et al., 2015; Xiao et al., 2023).

7.3 Lessons learned

Several lessons have been learned from the management of Bt resistance in insect populations. The importance of maintaining abundant refuges of non-Bt host plants has been underscored as a key factor in delaying resistance evolution (Tabashnik et al., 2013; Tabashnik et al., 2023). Understanding the molecular genetic basis of resistance, such as the role of ABC transporters in toxin mode of action, is crucial for developing effective resistance detection methods and management strategies (Gahan et al., 2010; Heckel et al., 2012; Tay et al., 2015). The integration of multiple strategies, including the use of multi-toxin Bt crops and spatially explicit deployment patterns, can enhance the sustainability of Bt technology (Tabashnik et al., 2013; Huang et al., 2017). Finally, continuous monitoring and proactive adaptation of resistance management strategies are essential to address the evolving threat of resistance and ensure the long-term success of Bt crops (Wu, 2014; Gassmann and Reisig, 2022).