

By understanding these biochemical mechanisms in depth, researchers can develop more effective resistance management strategies to mitigate and delay the development of insect resistance to Bt toxins, ensuring the continued efficacy of Bt-based pest control methods.

5 Behavioral Mechanisms of Resistance

5.1 Avoidance behavior

Avoidance behavior is a critical mechanism by which insects can resist the effects of Bt toxins. Insects may develop the ability to detect and avoid Bt-treated plants or areas, thereby reducing their exposure to the toxins. This behavior can be particularly effective in heterogeneous environments where non-Bt plants are available as refuges. For instance, the presence of abundant refuges of non-Bt host plants has been shown to favor sustained susceptibility to Bt crops by providing alternative feeding sites for pests, thereby reducing the selection pressure for resistance (Tabashnik et al., 2023).

5.2 Changes in feeding patterns

Changes in feeding patterns represent another behavioral adaptation that insects can employ to mitigate the impact of Bt toxins. Insects may alter their feeding habits, such as feeding at different times of the day or targeting different parts of the plant that have lower concentrations of Bt toxins. For example, studies have shown that the western corn rootworm, a significant pest of maize, exhibits changes in its feeding behavior when exposed to Bt-expressing maize. Resistant insects were found to maintain a more stable microbiome compared to susceptible insects, suggesting that their altered feeding patterns might help them avoid the detrimental effects of Bt toxins (Paddock et al., 2021).

5.3 Altered life cycle

Insects may also develop resistance to Bt toxins through alterations in their life cycle. This can include changes in developmental timing, such as faster or slower growth rates, which can help them avoid peak periods of Bt toxin expression in plants. For example, the larvae of *Anoplophora glabripennis*, when fed on transgenic poplar lines expressing dual Bt toxins, showed significant changes in the expression of genes related to their growth and development. These changes suggest that the larvae are adapting their life cycle to mitigate the effects of Bt toxins (Ren et al., 2021). Additionally, the nutritional environment can influence the susceptibility of insects to Bt toxins. *Helicoverpa zea*, a polyphagous pest, showed a 100-fold increase in LC50 when reared on protein-biased diets compared to carbohydrate-biased diets, indicating that diet-mediated plasticity can alter the life cycle and resistance levels of insects (Deans et al., 2017).

6 Management Strategies to Combat Resistance

6.1 Refuge strategies

Refuge strategies involve planting non-Bt crops near Bt crops to maintain a population of pests that remain susceptible to Bt toxins. This approach helps to delay the evolution of resistance by ensuring that susceptible pests can mate with potentially resistant individuals, thereby diluting resistance genes in the pest population. The high-dose/refuge strategy has been particularly successful in North America, where it has helped maintain susceptibility in major pests like the European corn borer and the pink bollworm (Huang et al., 2011). However, the effectiveness of this strategy can be compromised by non-compliance with refuge requirements and the presence of pests with non-recessive resistance (Brewer and Bonsall, 2020). Natural refuges, such as non-Bt host plants, have also been shown to delay resistance, although they may not be as effective as structured non-Bt cotton refuges (Jin et al., 2014).

6.2 Pyramiding Bt genes

Pyramiding involves stacking multiple Bt genes that produce different toxins within the same crop. This strategy aims to provide multiple modes of action against pests, making it more difficult for them to develop resistance. Pyramided Bt crops, such as those expressing both Cry and Vip3Aa toxins, have shown promise in delaying resistance. The synergistic action of multiple toxins can effectively manage pest populations even when some pests have developed resistance to one of the toxins. However, the design of these pyramids must consider