

2015; 2017). Bt strains have been utilized in both sprayable pesticide formulations and transgenic crops to protect against insect damage. The diversity of Bt strains and their respective insecticidal proteins allows for targeted pest control, reducing the need for broad-spectrum chemical insecticides (Li et al., 2022; Yamamoto, 2022).

2.2 Types of insecticidal proteins produced by Bt

Bt produces several classes of insecticidal proteins, each with distinct target specificities and modes of action. The primary types include:

Cry Proteins: These are the most extensively studied and utilized Bt toxins. They are crystalline proteins that target specific insect midgut receptors, leading to cell lysis and insect death. Examples include Cry1Ac, Cry1Ab, and Cry2Ab, which are used in transgenic crops like cotton and corn to control pests such as the tobacco budworm and European corn borer (Bravo et al., 2017; Rathinam et al., 2019; Yamamoto, 2022).

Vip Proteins: Vegetative insecticidal proteins (Vip) are produced during the vegetative growth phase of Bt. They have a different mode of action compared to Cry proteins and can target a broader range of insect pests.

Cyt Proteins: Cytolytic proteins (Cyt) are less commonly used but are effective against certain insect orders and nematodes. They work by forming pores in the cell membranes of the target insects (Bravo et al., 2015; 2017).

2.3 Mechanisms of action of insecticidal proteins

The insecticidal proteins produced by Bt operate through several mechanisms to exert their toxic effects on target pests:

Cry Proteins: These proteins bind to specific receptors in the insect midgut, such as cadherin-like proteins, leading to pore formation in the gut epithelial cells. This results in cell lysis, gut paralysis, and ultimately, insect death. The specificity of Cry proteins to their receptors is a key factor in their effectiveness and safety (Bravo et al., 2017; Liu et al., 2018; Rathinam et al., 2019).

Vip Proteins: Vip proteins also target the insect midgut but have a different binding mechanism compared to Cry proteins. They can be effective against insects that have developed resistance to Cry proteins, providing an alternative mode of action (Bravo et al., 2015; 2017).

Cyt Proteins: These proteins form pores in the cell membranes of target insects, leading to cell lysis and death. Their mode of action is similar to that of Cry proteins but involves different target sites within the insect (Bravo et al., 2015; 2017).

The continuous evolution of insect resistance to Bt proteins necessitates ongoing research and development of new proteins and engineering of existing ones to maintain their efficacy. Strategies such as protein engineering, domain swapping, and bioconjugation have been employed to enhance the insecticidal activity and broaden the spectrum of Bt proteins (Pan et al., 2019; Rathinam et al., 2019; Yamamoto, 2022).

3 Metabolic Pathways in Bt

3.1 Primary metabolic pathways

Bacillus thuringiensis (Bt) primarily relies on standard bacterial metabolic pathways for its growth and survival. These include glycolysis, the tricarboxylic acid (TCA) cycle, and oxidative phosphorylation, which are essential for energy production and biosynthesis of cellular components. The primary metabolism in Bt is crucial for providing the necessary precursors and energy required for the synthesis of secondary metabolites, including insecticidal proteins.

3.2 Secondary metabolic pathways

3.2.1 Pathways leading to toxin production

The production of insecticidal proteins in Bt, such as Cry and Vip toxins, is a hallmark of its secondary metabolism. These proteins are synthesized during the sporulation phase of Bt and are encoded by specific genes