

Functional genomics approaches, including gene expression profiling, proteomics, metabolomics, and functional studies of specific genes, have significantly advanced our understanding of the complex regulatory networks and metabolic pathways in Bt and related *Bacillus* species. These insights are essential for harnessing the full potential of these bacteria in biotechnological and agricultural applications.

6. Ecological and Evolutionary Insights

6.1. Adaptation to environmental niches

Bacillus species exhibit remarkable adaptability to diverse environmental niches, driven by genomic variations and selective pressures. For instance, *Bacillus pumilus* group strains show distinct genomic features that facilitate their survival in marine and terrestrial environments. Marine strains are enriched with genes related to transcription, phage defense, DNA recombination, and repair, while terrestrial strains possess genes aiding survival in land-specific niches (Fu et al., 2021). Similarly, *Bacillus mycoides*, a member of the *Bacillus cereus* group, demonstrates significant genomic diversity, with adaptive genes enabling it to thrive in various ecological niches, particularly in cold climates (Fiedoruk et al., 2021). These adaptations are often facilitated by horizontal gene transfer and the presence of mobile genetic elements, which enhance the genomic plasticity of these bacteria (Du et al., 2023).

6.2 Co-evolution with hosts

The co-evolution of *Bacillus* species with their hosts is a significant driver of their evolutionary trajectory. *Bacillus thuringiensis*, for example, has evolved high virulence through the selective advantage of its *Cry* toxin genes during co-evolution with nematode hosts. This co-evolutionary process is distinct from unidirectional selection and involves the accumulation of multiple virulence factors, which enhance the pathogen's ability to infect and adapt to various hosts (Masri et al., 2015). Additionally, *Bacillus thuringiensis* has specialized to exploit multiple invertebrate hosts, with host switching occurring at both major clade and subclade levels. The transfer of plasmids carrying *cry* genes plays a crucial role in this adaptation, allowing the bacteria to target specific insect orders effectively (Zheng et al., 2017).

6.3 Implications for biocontrol and biotechnology

Insights into the ecology and evolution of *Bacillus* species are of great significance for biocontrol and biotechnology. It is known that *Bacillus amyloliquefaciens* strains with biocontrol properties possess a set of core genes involved in the production of secondary metabolites, volatile compounds, and biofilm formation, which are crucial for their beneficial interactions with plants. These genetic elements not only enhance plant growth but also induce host defense responses, making these strains valuable in agricultural applications (Magno-Pérez-Bryan et al., 2015). Moreover, the metabolic characterization of *Bacillus* species reveals their nutritional preferences and metabolic capabilities (Figure 2), information that can be used to develop targeted biocontrol strategies and enhance the efficacy of these bacteria under various environmental conditions (Chang et al., 2020). Additionally, the genomic analysis of Bt provides a theoretical basis for developing more effective biopesticides and highlights the potential of genomics in addressing insect resistance.

Chang et al. (2020) demonstrated the nutritional preferences in carbon utilization, highlighting the metabolic characteristics of *Bacillus* species. Through the analysis of utilization rates of nutrients with different chemical properties, the study revealed significant differences in the metabolic capacities of *Bacillus* species. The study showed that different strains have distinct utilization rates for carbohydrates, amino acids, and lipids. This information is crucial for developing targeted biocontrol strategies. Especially for Bt and related *Bacillus* species, analyzing their metabolic preferences and capacities under specific environmental conditions can enhance the efficacy of these bacteria in various environments, providing a scientific basis for biocontrol.

7 Applications and Implications

Bt's applications in agriculture, medicine, and industry highlight its versatility and potential for promoting sustainable practices. However, careful regulatory oversight is essential to mitigate any potential risks associated with its use.