

benefits of SynComs while safeguarding ecological integrity, providing valuable insights for researchers, policymakers, and practitioners.

2 Background on Synthetic Microbial Communities

2.1 Definition and characteristics of SynComs

Synthetic microbial communities (SynComs) are deliberately constructed consortia of microorganisms designed to perform specific functions within a host or environment. Unlike natural microbial communities, which are complex and often unpredictable, SynComs are engineered to have defined compositions and functionalities (Parnell et al., 2023). These communities are typically assembled using microorganisms that have been selected for their beneficial traits, such as the ability to promote plant growth, enhance nutrient acquisition, or protect against pathogens (Souza et al., 2020). The design of SynComs often involves advanced computational methods, including machine learning and artificial intelligence, to identify the optimal combination of microbial species for a desired outcome (Martins et al., 2023).

2.2 Current applications of SynComs in agricultural systems

SynComs have been increasingly applied in agricultural systems to improve crop health and productivity. One of the primary applications is enhancing nutrient efficiency and yield. For instance, SynComs constructed from root-associated microbes have been shown to significantly promote plant growth and nutrient acquisition in soybean, leading to increased yields (Wang et al., 2021). Additionally, SynComs are used to combat biotic stresses by protecting plants from pathogens. For example, SynComs derived from rhizosphere soil have been effective in protecting wheat against soilborne fungal pathogens (Yin et al., 2022). Another promising application is the use of SynComs to engineer seedling microbiota, which can improve plant health from the early stages of development (Arnault et al., 2023). These applications demonstrate the potential of SynComs to provide sustainable solutions for modern agriculture by reducing dependency on chemical fertilizers and enhancing crop resilience against environmental stressors (Pradhan et al., 2022; Sai et al., 2022).

2.3 Comparison with natural microbial communities

Natural microbial communities are inherently complex and dynamic, often consisting of thousands of microbial species interacting in intricate ways. These communities are shaped by various factors, including the host plant, soil type, and environmental conditions. In contrast, SynComs are simplified and controlled systems designed to mimic the beneficial functions of natural communities while minimizing their unpredictability (Wang et al., 2023). While natural communities are assembled through ecological processes and evolutionary pressures, SynComs are constructed based on scientific knowledge and technological advancements, such as next-generation sequencing and omics approaches. This allows for a more targeted and efficient manipulation of microbial functions to achieve specific agricultural goals. However, one of the challenges with SynComs is ensuring their stability and long-term efficacy in the field, as they may undergo changes due to microbial interactions and environmental factors.

SynComs represent a promising tool for enhancing agricultural sustainability by leveraging the beneficial traits of microorganisms in a controlled and targeted manner. Their applications in improving nutrient efficiency, combating biotic stresses, and engineering plant microbiota highlight their potential to address some of the key challenges faced by modern agriculture. However, further research is needed to optimize their design and ensure their stability and effectiveness in diverse agricultural settings.

3 Mechanisms of SynComs in Agriculture

3.1 Biological pathways and interactions within SynComs

Synthetic microbial communities (SynComs) are not randomly assembled; instead, they follow ecological theories that suggest a defined phylogenetic organization structured by community assembly rules. SynComs can form biofilms, produce secondary metabolites, and induce plant resistance, which are crucial for their stability and effectiveness under environmental stressors (Martins et al., 2023). Additionally, SynComs can modulate plant physiological traits, such as reducing leaf temperature and improving water usage, which are vital for plant resilience to stress conditions like drought. The interactions within SynComs and between SynComs and plants