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Microbial biotechnology in sustainable agriculture

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Abstract
Sustainable agricultural practices are necessary to meet the increasing food requirements of growing global population without damaging the environment. Microbial biotechnology allows the use of beneficial microorganisms as an ecofriendly alternative to enhance soil fertility and crop production. Biofertilizers, biopesticides, bioremediation and stress resilient are all key applications of these microbes. These microbes reduce the dependency on chemical inputs in agricultural system for sustainability. These positive benefits are further optimized through advances in microbial genetic engineering. Integrating microbial biotechnology in farming systems is vital for ensuring food security and resource conservation during climate change challenges.

Keywords: Biofertilizers, biopesticides, sustainable agricultural

Introduction

The world's population is expected to reach nearly 10 billion people by year 2050 and this will increase the total food demand globally by 60% (FAO, 2017) [5]. The conventional farming practices are mainly dependent on use of chemical fertilizer and insecticides. These chemicals have caused severe environmental degradation like acidifying soil, loss of native microbial biodiversity and water pollution (Tilman *et al*., 2011) [20]. Therefore these practices are unsustainable and have been found to pose a great threat to future agricultural productivity. Also, production and utilization of these chemicals contribute significantly to greenhouse gas emissions in climate change (Masson-Delmotte IPCC, 2019) [11]. Sustainable agriculture is important to ensure food security and conservation of the environment to meet the challenges of population increase in climate change scenario. Moreover, Sustainable agricultural practices utilize biological pest control which decreases synthetic pesticides effects on beneficial microbes and insects (Potts *et al*., 2016) [14].

The application of genetic engineering on microbes is not only important in the improvement of the quality and yield of crops but also in the improvement of plant-microbe interactions dynamics. By genetic engineering, researchers can create more effective PGPR to colonize plant roots more effectively that can help the plant to become healthier and more productive (Adenle *et al*., 2012) [1]. Microbial biotechnology can be considered as a more environment friendly sustainable approach for harnessing beneficial microorganisms, such as plant growth-promoting rhizobacteria (PGPR), mycorrhizal fungi, and endophytes, to optimize plant health and reduce dependence on chemicals in agriculture (Glick, 2012) [7]. Beneficial microbes such as nitrogen-fixing bacteria (*Rhizobium*, *Azospirillum*), phosphate-solubilizing bacteria (*Pseudomonas*, *Bacillus*) and mycorrhizal fungi improve nutrient availability (Oldroyd, 2013; Rodríguez & Fraga, 1999) [13, 15]. Microbial Biopesticides such as *Bacillus thuringiensis* and *Trichoderma* control pests and diseases without harming the environment (Glare *et al*., 2012) [6]. Also, the microbes assist in regulating the stress-related genes for drought and salinity tolerance (Sandhya *et al*., 2009; Etesami & Beattie, 2018) [4, 16]. Microbial biotechnology also plays a key role in bioremediation, where bacteria and fungi degrade pollutants and restore soil health (Das & Chandran, 2011) [3]. The application of microbial inoculants in biofertilizers increases the soil microbial population (Bashan *et al*., 2014) [2]. As global food demand rises, integrating microbial biotechnology into farming systems is crucial for ensuring food security, conserving natural resources, and mitigating climate change impacts (Glick, 2012; Ladha *et al*., 2016) [7, 10]. The key microbial groups contributing to sustainable agriculture include:

Biofertilizers: Enhancing Soil Fertility and Nutrient Uptake

One of the most important areas of application of the plant-microbe interactions in biotechnology is the production of biofertilizers. Biofertilizers are substances which contain useful microbes which help in the availability of nutrients in the soil and therefore minimize the use of chemical fertilizers. Nitrogen fixing bacteria like *Rhizobium*, *Azospirillum* and *Azotobacter* are very important in fixing nitrogen from atmosphere to ammonia which can be used by the plants (Oldroyd, 2013) [13]. This biological nitrogen fixation increases the production of legumes and also improve the fertility of the soil for increased production of nonlegume crops.

Phosphate solubilizing bacteria include *Pseudomonas* and *Bacillus* which dissolve insoluble phosphate and make it available to the plants (Rodríguez & Fraga, 1999) [15]. Arbuscular mycorrhizal fungi (AMF) are the mutualistic fungi which establish a mutual relationship with plant roots and enhance the uptake of nutrients and water (Smith & Read, 2008). The biotechnology has recently been used to genetically manipulate these microorganisms in order to increase their PGPR traits. Furthermore, new technologies like nano encapsulated biofertilizers provide the possibility of extending the shelf life and controlling the delivery of microbial inoculants (Bashan *et al*., 2014) [2].

Biopesticides: Natural Pest and Disease Control

Biopesticides derived from microbial sources offer an environmentally friendly alternative to chemical pesticides. These microbes protect the plant against insect pests, fungal and bacterial diseases. Among bacterial biopesticides, *Bacillus thuringiensis* (Bt) is the most popular because it produces insectical toxins that are specific to pests such as caterpillars and beetles (Glare *et al*., 2012) [6]. Fungal biopesticides such as *Beauveria bassiana* and *Trichoderma* spp. act as natural antagonists to plant pathogens by outcompeting them for resources and producing antimicrobial compounds (Harman *et al*., 2004) [9]. Viruses such as *Baculoviruses* are also employed in pest management, as they selectively infect and kill insect pests (Gupta & Dikshit, 2010) [8].

The effectiveness of biopesticides has been improved by genetic engineering in the recent past. This has led to the development of Bt strains that can control a wider variety of pests. The formulations include the use of microbial biofilms and encapsulation techniques to enhance the persistence and stability of biopesticides. CRISPR-based genome editing has also been used to help scientists design better microbes (Mishra *et al*., 2023).

Stress Tolerance and Climate-Resilient Agriculture

As climate change threatened the global food security, microbial biotechnology is being increasingly used to develop climate-resilient agricultural systems. Plant-associated microbes help mitigate the effects of various abiotic stresses such as drought, salinity and extreme temperatures. Some rhizobacteria such as *Pseudomonas* and *Bacillus* produce exopolysaccharides that improves soil moisture retention and plant drought tolerance (Sandhya *et al*., 2009) [16]. Halotolerant microbes assist plants in saline conditions by regulating ion homeostasis and by producing osmoprotectants (Etesami & Beattie, 2018) [4]. Additionally, some thermotolerant rhizobacteria secrete heat-shock proteins which protect plants from high temperatures (Sessitsch *et al*., 2002) [17]. Through the study of genomics, we have recognized the genes that control stress tolerance in the microbes.

Microbial genetic engineering has emerged as a valuable transformative technique for yield and quality of crops through the modification of microbes to enhance their efficiency in delivering various benefits to plants growth, nutrient uptake, and stress resilience. With the help of tools like CRISPR-Cas9 and synthetic biology, researchers engineer microbes like rhizobia, mycorrhizal fungi, and plant growth-promoting rhizobacteria (PGPR) to optimize their symbiotic functions. For instance, microbes can be engineered to overproduce phytohormones (e.g., auxins, cytokinins) or stress-alleviating compounds (e.g., ACC deaminase), which promote root development and drought tolerance (Bashan *et al*., 2014) [2]. Furthermore, microbial consortia are designed to solubilize phosphorus, sequester heavy metals, or secrete antimicrobial agents, reducing dependency on synthetic fertilizers and pesticides (Singh *et al*., 2016). These innovations not only boost agricultural productivity but also align with sustainable practices by minimizing environmental footprints. However, challenges such as regulatory hurdles, ecological risks and public acceptance of genetically modified organisms (GMOs) must be addressed to ensure safe and scalable deployment.

Conclusion

The applications of plant-microbe interactions in biotechnology are vast and transformative. Microbes are sources of biofertilizers and biopesticides, bioremediation, and genetic engineering and offer sustainable solutions for global challenges in agriculture, environmental management and agricultural industry. As research continues to unlock the potential of these beneficial microbes, their integration into mainstream agriculture and industrial processes will play a crucial role in shaping a more sustainable and resilient future.

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