Plant Sci. Arc.
Plant Science Archives
An International Journal of Plant Biology

Short Communication
ISSN 2518-6965
www.plantarc.com

Advancements in Biofertilizers for Pulse Crops: From Single-Strain Inoculants to Microbiome-Based Technologies

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Citation: S. Anbarasan, Kanchan Sharma, Ashwini A. Waoo, Kushal Sachan (2024). Advancements in Biofertilizers for Pulse Crops: From Single-Strain Inoculants to Microbiome-Based Technologies. *Plant Science Archives.* **23-25. DOI: https://doi.org/10.51470/PSA.2024.9.2.23**

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Received 26 February 2024 | Revised 27 March 2024 | Accepted 4 May 2024 | Available Online July 10 2024

ABSTRACT

The application of biofertilizers in pulse crop agriculture has garnered significant attention as an eco-friendly and sustainable alternative to conventional chemical fertilizers. This comprehensive review aims to elucidate the progression of biofertilizer technologies from traditional single-strain inoculants to contemporary microbiome-based strategies. Pulse crops, such as beans, lentils, chickpeas, and peas, are pivotal in global agriculture due to their high protein content, nitrogen-fixing ability, and role in improving soil health. However, optimizing their productivity necessitates effective nutrient management, where biofertilizers play a crucial role. Initially, biofertilizer development concentrated on single-strain inoculants, predominantly Rhizobium species, which establish symbiotic relationships with leguminous plants to enhance nitrogen fixation and improve crop yields. Despite their proven benefits, single-strain inoculants often exhibit variable performance influenced by soil conditions, climatic factors, and interactions with indigenous soil microbiota. This variability highlights the need for more consistent and resilient biofertilizer solutions. Recent advances in microbiome research have paved the way for the development of microbiome-based biofertilizers. These advanced formulations leverage the synergistic interactions among diverse microbial communities, including bacteria, fungi, and archaea, to provide a more comprehensive and stable enhancement of soil fertility and plant growth. Microbiome-based approaches recognize the complexity of plant-microbe-soil interactions, offering improved nutrient cycling, increased plant stress resilience, and better adaptation to various environmental conditions. The benefits of microbiome-based biofertilizers are manifold, encompassing enhanced nutrient availability, improved plant health, and sustainable soil management. However, their development and application pose several challenges, including understanding the intricate dynamics of microbiome interactions, developing precise formulation and application methods, and navigating regulatory landscapes. Addressing these challenges requires multidisciplinary research and innovation, integrating genomics, metagenomics, and advanced data analytics to unravel the complexities of soil microbiomes. This includes the potential for personalized biofertilizer formulations tailored to specific soil and crop conditions, enhancing the efficacy and scalability of biofertilizer technologies.

Keywords: *Biofertilizers, Pulse Crops, Single-Strain Inoculants, Microbiome, Sustainable Agriculture, Soil Health, Nitrogen Fixation*

Introduction

Pulse crops, encompassing a variety of legumes such as beans, lentils, chickpeas, and peas, are integral to global agricultural systems due to their high nutritional value, ability to improve soil health through biological nitrogen fixation, and their role in sustainable farming practices [1-2]. These crops contribute significantly to food security and are a primary source of protein, especially in developing countries. Furthermore, pulse crops enhance soil fertility by fixing atmospheric nitrogen through symbiotic relationships with root-nodulating bacteria, thus reducing the dependency on synthetic nitrogen fertilizers. Traditional agricultural practices have heavily relied on chemical fertilizers to meet the nutrient demands of crops [3-4]. However, the excessive use of these fertilizers has led to several environmental issues, including soil degradation, water pollution, and greenhouse gas emissions [5]. These concerns have spurred the search for sustainable alternatives that can maintain or even improve crop yields while mitigating adverse environmental impacts. Biofertilizers have emerged as a promising solution in this context, leveraging the natural capabilities of microorganisms to enhance soil fertility and plant growth. Initially, the development of biofertilizers focused on single-strain inoculants, particularly Rhizobium species, which form symbiotic relationships with leguminous plants. These single-strain inoculants have demonstrated their effectiveness in enhancing nitrogen fixation, improving nutrient uptake, and boosting crop yields [6]. Despite their success, the performance of single-strain inoculants can be inconsistent due to various factors such as soil type, climatic conditions, and interactions with native soil microbial communities. These limitations underscore the need for more resilient and versatile biofertilizer solutions. In recent years, advancements in microbiome research have revolutionized our understanding of soil ecosystems and plant-microbe interactions. The soil microbiome comprises a complex network of microorganisms, including bacteria, fungi, archaea, and viruses, that interact with each other and with plant roots [7]. These interactions play a crucial role in nutrient cycling, disease suppression, and stress tolerance. Harnessing the potential of the entire soil microbiome, rather than relying on single-strain inoculants, presents a novel approach to developing more effective and resilient biofertilizers. Microbiome-based biofertilizers utilize diverse microbial communities to create a more robust and stable enhancement of soil fertility and plant growth. These advanced formulations aim to replicate and amplify the natural processes occurring in the soil, leading to improved nutrient availability, enhanced plant resilience to biotic and abiotic stresses, and better adaptation to varying environmental conditions [8-9]. The integration of microbiome strategies into biofertilizer development represents a significant shift towards a more holistic approach to sustainable agriculture. The benefits of microbiome-based biofertilizers extend beyond nutrient management. They have the potential to promote plant health by suppressing soil-borne diseases, improving soil structure, and enhancing root growth. Additionally, these biofertilizers can contribute to climate change mitigation by reducing the need for chemical fertilizers and lowering greenhouse gas emissions associated with fertilizer production and application.

Despite the promising potential of microbiome-based biofertilizers, several challenges must be addressed to realize their full benefits. These include understanding the complex interactions within the soil microbiome, developing precise and reproducible formulation and application methods, and ensuring regulatory compliance and acceptance by farmers and stakeholders [10-12]. Addressing these challenges requires a multidisciplinary approach, integrating expertise from microbiology, agronomy, soil science, and data analytics. This review aims to provide a comprehensive overview of the advancements in biofertilizer technologies for pulse crops, tracing the evolution from traditional single-strain inoculants to cutting-edge microbiome-based strategies. It will explore the mechanisms through which biofertilizers enhance soil fertility and plant growth, examine the benefits and limitations of different biofertilizer approaches, and discuss future directions for research and development. By highlighting the potential of microbiome-based biofertilizers, this review seeks to contribute to the ongoing efforts to promote sustainable agriculture and ensure food security for a growing global population.

Traditional Single-Strain Inoculants

Historically, biofertilizer development has primarily focused on single-strain inoculants, with Rhizobium spp. being the most prominent example. Rhizobium species form symbiotic relationships with leguminous plants, facilitating the process of biological nitrogen fixation. This symbiosis allows the plants to convert atmospheric nitrogen into a form that is readily available for their growth, significantly enhancing soil fertility and improving pulse crop yields. The effectiveness of Rhizobium inoculants in promoting plant growth and increasing agricultural productivity has been well-documented, making them a staple in biofertilizer applications for pulse crops [13-14]. However, despite their proven benefits, single-strain inoculants often exhibit variable performance. Several factors contribute to this inconsistency, including soil conditions, climatic factors, and the complex interactions between introduced inoculants and the native soil microbiota. Soil pH, nutrient availability, temperature, and moisture levels can all influence the efficacy of Rhizobium inoculants. Additionally, the presence of indigenous microbial communities can either compete with or complement the introduced strains, further affecting their performance.

Variability in the success of single-strain inoculants highlights the need for more adaptable and resilient biofertilizer solutions. While Rhizobium spp. and other single-strain inoculants have laid the groundwork for biofertilizer use in agriculture, their limitations underscore the importance of exploring more holistic approaches that can overcome these challenges and provide more consistent benefits across diverse environmental conditions. This realization has paved the way for the development of microbiome-based biofertilizers, which aim to leverage the full spectrum of beneficial microorganisms present in the soil.

Advancements in Microbiome-Based Technologies

Recent research has shifted towards utilizing entire microbial communities or microbiomes to develop more resilient and effective biofertilizers [15]. These microbiome-based approaches recognize the complex interactions between plants and diverse soil microorganisms, including bacteria, fungi, and archaea. By harnessing these interactions, microbiome-based biofertilizers can offer a more holistic and robust solution to nutrient management in pulse crops.

Benefits and Challenges

Microbiome-based biofertilizers offer several advantages over traditional inoculants, including improved nutrient cycling, enhanced plant resilience to stress, and better adaptation to diverse environmental conditions [16-19. However, challenges such as the complexity of microbiome interactions, the need for precise formulation and application techniques, and regulatory considerations must be addressed to realize their full potential.

The future of biofertilizers in pulse crop agriculture lies in integrating advanced technologies such as genomics, metagenomics, and machine learning to better understand and manipulate soil microbiomes and continued research and innovation will be essential to develop effective, scalable, and sustainable biofertilizer solutions that can meet the growing global demand for food while preserving environmental health [20-22].

Conclusion

The transition from single-strain inoculants to microbiome-based technologies represents a significant advancement in the field of biofertilizers for pulse crops. By leveraging the power of diverse microbial communities, these innovative approaches can provide more robust and consistent enhancements in crop productivity and soil health. Microbiome-based biofertilizers offer a holistic solution to nutrient management, addressing the limitations of traditional single-strain inoculants and promoting sustainable agricultural practices. These advanced biofertilizers not only improve nutrient availability and plant growth but also enhance soil resilience to environmental stresses and reduce dependency on chemical fertilizers. As research and development continue to unravel the complexities of soil microbiomes, the potential for tailored and efficient biofertilizer formulations grows, promising significant benefits for pulse crop agriculture. The future of biofertilizers lies in the integration of cutting-edge technologies such as genomics, metagenomics, and machine learning to better understand and manipulate soil microbiomes. Continued innovation and interdisciplinary collaboration will be essential to develop scalable and effective biofertilizer solutions that can meet the global demand for sustainable food production while preserving environmental health. By embracing microbiome-based technologies, we can pave the way for a more resilient and sustainable agricultural future.

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