SVOA Microbiology

ISSN: 2634-534X

Review Article

Challenges and Opportunities in Biofertilizer Commercialization

Anurag Yadav[1]* and Kusum Yadav[2]

[1] *Department of Microbiology, C.P. College of Agriculture, Sardarkrushinagar Dantiwada Agricultural University, Sardrarkrushinagar, Dist. Banaskantha, Gujarat-385506, India.*

[2] *Department of Biochemistry, University of Lucknow, Lucknow, Uttar Pradesh-226007, India.*

***Corresponding Author:** Anurag Yadav, Department of Microbiology, C.P. College of Agriculture, Sardarkrushinagar Dantiwada Agricultural University, Sardrarkrushinagar, Dist. Banaskantha, Gujarat-385506, India.*

DOI: https://doi.org/10.58624/SVOAMB.2024.05.037

***Received:** November 02, 2023* ***Published:** January 02, 2024*

Abstract

As eco-friendly alternative to chemical fertilizers, biofertilizers have gained significance in the quest for sustainable farming. While challenges exist, such as regulatory hurdles and technical complexities, the opportunities in this field are substantial. Understanding rhizosphere engineering can enhance biofertilizers' efficiency, ensuring they provide maximum crop benefits. Genetic engineering of bioinoculants offers a pathway to tailor biofertilizers to specific crop needs, potentially increasing their effectiveness. Multi-trait, multi-strain, and multi-nutrient microbial formulations have the potential to revolutionize the biofertilizer market, allowing for customized solutions that address a range of agricultural needs. These innovations are complemented by market dynamics and the integration of nanotechnology, which can further enhance biofertilizer performance and reach. Such opportunities indicate a bright future for biofertilizer commercialization, where sustainable agriculture can benefit from advanced formulations with an improved understanding of soil-plant interactions. Biofertilizers' prospects are promising, offering a more sustainable and environmentally friendly approach to nourishing the world's growing population.

Keywords: *Biofertilizer, Commercialization, Challenges, Opportunities*

1. Introduction

Biofertilizers play a crucial role in sustainable agriculture development, offering a potential approach for enhancing crop production while minimizing the negative environmental impacts of chemical fertilizers. The importance of biofertilizers in agriculture has been recognized by governments and researchers alike. In India, for example, the government has taken steps to ensure the quality and production of biofertilizers, highlighting their significance for agriculture sector [1]. Biofertilizers have gained attention for various applications, including agriculture, bioremediation, and ecology [2]. These microbial-based fertilizers offer a promising alternative to hazardous chemical fertilizers, contributing to achieving sustainable agriculture goals [3]. Agricultural policies promoting environmentally friendly products, such as biofertilizers, have become increasingly important in recent years [4]. Additionally, biofertilizers can contribute to the maintenance of organic matter in the soil and reduce the emission of CO_2 into the atmosphere, further highlighting their significance in agricultural practices [5].

Screening rhizosphere soil samples and identifying competent microbial strains is very interesting and applicable [6]. Such strains have been isolated from various environments, including the rhizosphere, saline soil, and limestone mining regions [7-10]. This diversity of habitats suggests that biofertilizers can adapt to different conditions and be explored for various purposes.

The commercialization of biofertilizers presents opportunities for sustainable agriculture. Food production can be increased without posing any environmental risks by employing biofertilizers to inoculate seeds, crops, or soil [17]. Biofertilizer applications can enhance crop yield [18]. Bioinoculants can also exhibit other beneficial properties, such as biological nitrogen fixation, phytohormone synthesis, and stress reduction, which promote plant growth. Biofertilizers have been shown to have potential applications beyond agriculture. They can be used in bioremediation to degrade environmental pollutants, such as malathion pesticides [19].

However, the journey from laboratory research to the commercial application of such microorganisms is filled with challenges and opportunities. One of the key challenges is the effective selection of microbial strains [18]. Additionally, the performance of biofertilizers under in situ conditions is not always reliable and needs improvement [20]. Given these challenges and opportunities, there is a pressing need for multidisciplinary research to bridge the gap between laboratory findings and field applications, thereby unlocking the full potential of biofertilizers in sustainable agriculture and environmental management.

2. Challenges in Biofertilizer Commercialization

The challenges in biofertilizer commercialization include the timely supply of cultures, slow response of biofertilizers, availability of poor quality of bioinoculants in the market, limited production on an industrial scale, and the need for improved formulations and new biofertilizers (Fig. 1). Overcoming these challenges is crucial for the widespread adoption and successful commercialization of biofertilizers.

The subsequent subsections have briefed the possible challenges in biofertilizer commercialization.

Figure 1: *Opportunities and challenges in rhizosphere engineering.*

2.1 Regulatory Hurdles

2.1.1 Bio-safety Concerns

The commercialization of efficient microbial strains in biofertilizers play a pivotal role in commercial success, as they significantly enhance crop yield and soil health, thereby meeting regulatory standards and market demands effectively. Biofertilizer commercialization faces several challenges, including regulatory hurdles and bio-safety concerns. Using biofertilizers in agriculture and environmental applications raises concerns about their potential impact on ecosystems and human health. It is crucial to ensure that biofertilizer products are safe for use and do not pose any environmental or human health risks, thus requiring rigorous testing, safety evaluation, and efficacy before they can be commercialized.

However, navigating these regulations can be complex and time-consuming, hindering commercialization. It is essential to evaluate the safety and efficacy of biofertilizer products to address these challenges. Authors screened highly effective phosphate solubilizing *Pseudomonas fluorescens* PSM1 strain for promoting wheat plant growth [21]. The study demonstrated that this efficient and environmentally safe bacteria strain can solubilize tricalcium phosphate and increase the available phosphorus for plant uptake.

In addition to safety concerns, the commercialization of biofertilizers also requires addressing technical challenges. For instance, biofertilizer production and formulation must be optimized to ensure stability and effectiveness. Researchers have explored biofertilizer-based methods for improving nitrogen fixation and enhancing phosphate solubilization, through ultraviolet (UV) mutagenesis and immobilization technology [22].

2.1.2 Quality Control

The commercialization of biofertilizers, confronts many challenges with quality control a significant hurdle. One of the foremost challenges lies in the cost of production, which must be competitive with conventional fertilizers to ensure market sustainability [23]. Such economic constraint underscores the urgency for industrial standardization, which could reduce production costs and mitigate variability in product quality.

The limited commercial adoption of plant growth-promoting microbes (PGPMs) adds another layer of complexity. Existing microbial communities in agricultural settings, shaped by long-term interactions with their environment, often outcompete or exclude newly introduced PGPMs [24]. The challenge lies in developing strategies to circumvent the natural resilience, enabling the successful integration of PGPMs into existing microbial ecosystems.

Regulatory inconsistencies further exacerbate these challenges. Establishing international standards, such as International Organization for Standardization (ISO), is crucial for ensuring the quality and efficacy of biofertilizers [25]. However, efforts to establish a comprehensive regulatory framework have been insufficient in many countries. For example, the number of colony-forming units (CFU) is the primary metric for quality assessment, yet a comprehensive regulatory framework is conspicuously lacking [26].

Finally, quality control issues extend to the formulation and storage of biofertilizers. Many products are propagated without a robust quality control scheme, leading to inconsistent formulations and limited information on optimal storage conditions and application methods [27]. Moreover, commercial biofertilizers often feature a narrow range of microbial species despite natural ecosystems interacting with diverse microorganisms. The lack of diversity and quality control hampers the efficacy and usability of biofertilizers.

2.2 Technical Challenges

Applying biofertilizers in agricultural fields require understanding their interactions with plants and other microorganisms in the rhizosphere. Biofertilizers engage with plants through metabolic interactions, such as producing extracellular amino acids [28]. These interactions can influence plant growth and nutrient uptake, highlighting the importance of studying the complex microbial communities in the rhizosphere. Apart from this, the following factors add to the technical challenges.

2.2.1 Strain Stability

The commercialization of biofertilizers presents many technical challenges, one of the most critical being microbial strain stability. The efficacy of biofertilizer strains during storage and application is paramount for successful integration into agricultural practices. Genetic variability within bacterial populations poses a significant hurdle in maintaining the stability of biofertilizer strains. Different strains of biofertilizers can manifest varying degrees of plant growth promotion, influencing their performance under diverse soil conditions [29]. Therefore, it becomes imperative to identify and select strains that exhibit stable and consistent plant growth promotion capabilities for practical agricultural applications. Environmental factors, including pH, temperature, and nutrient availability, further complicate the stability of biofertilizer strains [30]. These variables can differ substantially across soil types and agricultural practices, leading to inconsistent performance of biofertilizer strains [31]. A comprehensive understanding of the optimal environmental conditions conducive to the growth and activity of biofertilizers is essential, and strategies must be developed to maintain these conditions to ensure strain stability. Interactions with other soil microorganisms present another layer of complexity. Biofertilizer strains often compete with other soil bacteria, fungi, and actinomycetes for nutrients and space, which can result in a decline in their population and activity [32]. Strategies to enhance the competitiveness of biofertilizer strains against other microorganisms are vital for maintaining their stability and effectiveness.

Long-term survival and persistence of microbial strains in the soil is crucial for providing sustained benefits to plants. However, predation, nutrient depletion, and changing soil conditions can adversely affect their survival and persistence [33]. Therefore, understanding the mechanisms that govern the survival and persistence of biofertilizers in different soil environments is critical for enhancing their long-term stability.

Addressing these challenges necessitates a multi-pronged approach. Rigorous strain selection and screening processes can identify microbial strains with stable and consistent plant growth promoting traits, considering genetic stability and adaptability to different soil conditions [34]. Genetic manipulation techniques, including genetic engineering and mutagenesis, offer promising avenues for enhancing the stability and performance of biofertilizer strains, although ethical considerations and potential risks must be carefully weighed.

Microbial consortia, comprising multiple strains of bacteria and other beneficial microorganisms, can offer synergistic benefits that enhance strain stability and effectiveness [35]. The selection of compatible strains within such consortia should be based on their complementary functions and compatibility. Finally, implementing appropriate soil management practices, such as organic matter addition, crop rotation, and balanced nutrient management, can create a conducive environment for the growth and activity of biofertilizers, thereby promoting their stability [20].

2.2.2 Bioformulation

The appropriate formulation is crucial in developing suitable biofertilizer carriers to ensure long-term microbial viability and commercial success [36,37]. The viability of biofertilizers is essential for their efficacy as microbial inoculants [37]. Various techniques have been explored to develop carriers that enhance the stability and viability of biofertilizers during long-term storage [36]. One common approach involves encapsulating the microbial suspension or pellet with a protective shell [36]. The protective capsule can consist of fats, proteins, (poly)saccharides, or other coating materials that enhance the stability and viability of biofertilizers. Coated and expanded clay particles have also been investigated as potential carriers for biofertilizers in biological concrete, aiming to ensure the long-term viability of bacteria embedded in the concrete [38].

The choice of carrier material is crucial for maintaining the viability of biofertilizers. Powder-based carriers such as peat and talc maintain bioinoculant viability for extended periods. These carriers contain high concentrations of organic material and essential nutrients, which contribute to the viability of microbes [39]. For example pine sawdust biochar has been identified as a suitable biofertilizer carrier, promoting nutrient mobilization and growth in *Allium cepa* L. [40]. Also, expanded clay has been used as a carrier to protect bacteria from the harsh internal environment of concrete, ensuring their effectiveness [41].

The viability of biofertilizers can be assessed using various methods, including serial dilutions on agar plates [42]. The survival of biofertilizers in carriers can be influenced by cryoprotectant formulations, which enhance the viability of bioinoculants during long-term storage [43]. The effectiveness of carriers in maintaining bacterial viability can be observed through microscopy, which confirms the presence of microbes within the carrier material [41]. The long-term viability of biofertilizers is crucial for application in agricultural fields [44]. The viability of biofertilizers in carriers is also crucial for bioremediation, as they can contribute to the stabilization of pollutants [45]. The successful application of viable biofertilizers in carriers can significantly contribute to sustainable agricultural practices, aiding in the reduction of environmental impacts associated with synthetic fertilizer use [46.47].

2.2.3 Stability with chemical fertilizers

Combining biofertilizers with conventional fertilizers presents both hurdles and opportunities in the journey toward commercialization. Such an approach can offer synergistic benefits, enhancing nutrient uptake, improving soil health, and potentially reducing the amount of chemical fertilizers needed, which aligns with sustainable agricultural practices and adds a unique selling proposition for biofertilizers in the market. Our research has shown that multi-trait bacterial consortia, combined with chemical fertilizers, can significantly enhance plant growth and yield [48].

However, the hurdles are non-trivial. The interaction between biofertilizers and chemical fertilizers is complex and can vary depending on the fertilizers used, soil conditions, and the crops involved. Such complexities make it challenging to provide consistent guidelines for farmers, an essential requirement for commercial success. Additionally, regulatory agencies may require more stringent safety and efficacy data for such combined products, prolonging the time-to-market and increasing costs. The variability resulting due to these interactions can also pose challenges in gaining farmer trust, which is crucial for commercial adoption.

2.3 Market Challenges

2.3.1 Consumer Acceptance

The commercialization of biofertilizers faces a complex landscape of challenges, particularly in consumer acceptance. One of the most pressing issues is the prevailing negative perception of agrochemicals, especially pesticides and herbicides.

Such skepticism is not without reason; it stems from the fact that more and more people are becoming aware of the health risks of traditional farming methods. [49]. Legal actions against agrochemical companies have further fueled the distrust, inadvertently creating a window of opportunity for biofertilizers to gain market traction.

However, the road to consumer acceptance of biofertilizers is fraught with obstacles, including the critical safety issue. The microorganisms utilized in biofertilizers must be rigorously vetted for their impact on human health, not just for the end consumers but also for those involved in the manufacturing process [50]. While certain microbial strains from *Azospirillum, Gluconacetobacter, Bacillus,* and *Azotobacter* genera have been safely commercialized for non-leguminous crops, there remains a pressing need for additional research to unequivocally establish the safety of biofertilizers across a broader spectrum of crops. Another challenge concerns food technology neophobia or the fear of novel food technologies [51]. Such neophobia is particularly prevalent among consumers who are already concerned about the sustainability of their food choices. Addressing such challenges requires effective marketing and comprehensive educational initiatives to elucidate biofertilizers' safety and environmental benefits.

The demand for functional foods containing health-protecting bioactive compounds is rising [52]. Biofertilizers, particularly those using plant probiotics, are seen as a viable alternative to chemical fertilizers in producing such functional foods. However, the scientific literature is scant regarding the impact of biofertilizers on the yield and bioactive compound content in functional foods, necessitating further research to bolster consumer confidence.

Moreover, the efficacy of biofertilizers is not universal but varies depending on the cultivar of the crop. For instance, strawberries' response to bacterial inoculation is highly cultivar-dependent [53]. This calls for targeted breeding programs focusing on yield, fruit quality, and adaptability to various growing systems, enhancing consumer acceptance. Lastly, the role of socio-demographic factors in consumer acceptance cannot be overlooked. Consumer preferences for biofertilizers are influenced by many factors, including cultural background and socio-demographic characteristics [54]. A nuanced understanding of these factors is essential for tailoring marketing strategies that can effectively break down the barriers to consumer acceptance.

2.3.2 Cost Competitiveness

Although the biofertilizer market is growing, the higher production and utilization costs remain a significant challenge, particularly for small-scale farmers [55]. The production process of biofertilizers involves isolating and formulating beneficial microorganisms, which can be labor-intensive and require specialized facilities [25]. Additionally, the cost of scaling up production and ensuring consistent quality can be a barrier to cost competitiveness [55]. To address the challenge, research and development efforts should optimize production processes and explore cost-effective alternatives for biofertilizer formulation.

3. Opportunities in Biofertilizer Commercialization

The commercialization of biofertilizers presents a promising avenue for sustainable agriculture and environmental stewardship. As the world grapples with the need for more sustainable agricultural practices, the opportunities in biofertilizer commercialization have never been more significant. This burgeoning industry not only addresses the growing demand for organic and environmentally friendly farming solutions but also holds the potential to revolutionize how we nourish our crops, improve soil health, and reduce the environmental impact of agriculture. In this context, exploring the prospects and challenges within the biofertilizer commercialization sector becomes essential for farmers and investors seeking to contribute to a greener and more resilient future for our planet. Fig. 2 illustrates the various methods of rhizosphere engineering.

The following subsections brief the various opportunities lying in biofertilizer commercialization.

3.1 Understanding Rhizosphere Engineering

Rhizosphere engineering, the targeted manipulation of soil-microbe-plant interactions, offers a transformative approach to biofertilizer commercialization, but it also comes with its own set of hurdles and opportunities. On the positive side, rhizosphere engineering can optimize the soil environment to enhance the efficacy of biofertilizers, including their combined use with conventional fertilizers, leading to more robust, efficient, and targeted biofertilizer products tailored to specific crops or soil types. Our research has explored the prospects and bottlenecks in rhizosphere engineering, particularly in semiarid tropics, and has shown that microbial interventions can significantly improve soil health and crop yields [56].

Rhizosphere engineering requires a deep understanding of complex soil-microbe-plant interactions, which are influenced by many factors, including soil pH, organic matter, and seasonal changes. Such complexity makes it challenging to develop universally effective biofertilizer products. Commercializing such engineered solutions would also require rigorous field testing and regulatory approvals, which could be time-consuming and costly. The variability introduced by rhizosphere engineering could also make it challenging to gain farmers' trust, who often seek consistency and reliability in agricultural inputs.

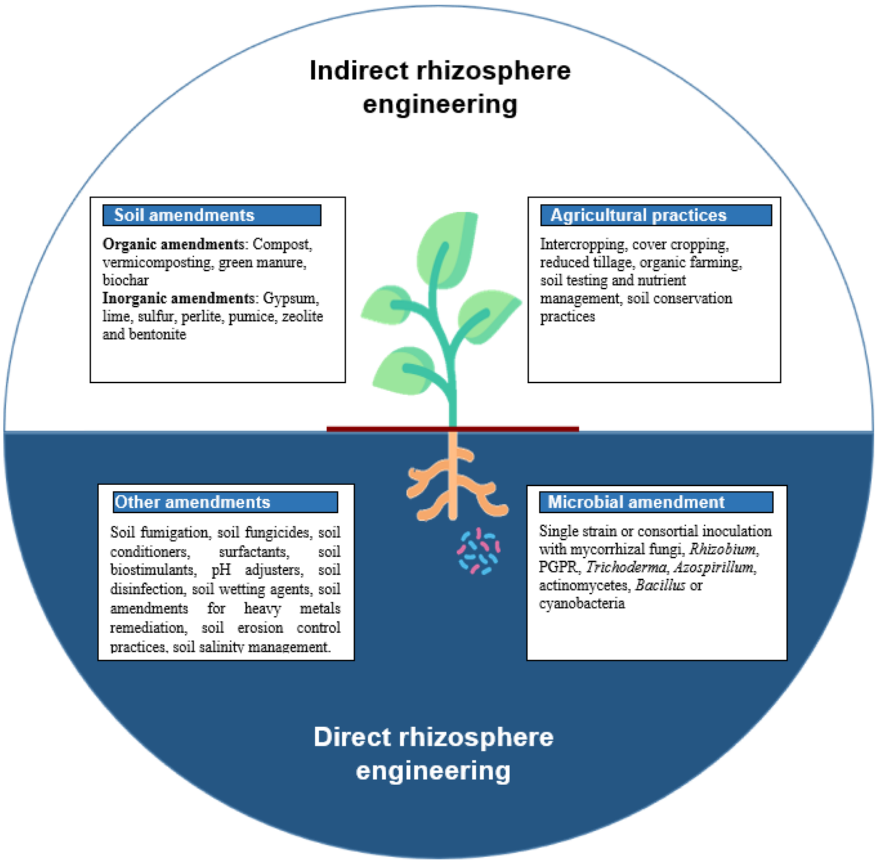

Figure 2: *Methods of rhizosphere engineering.*

3.2 Genetic Engineering

Genetic engineering of PGPMs for biofertilizer commercialization is a promising approach in sustainable agriculture. Genetic engineering techniques allow modifying PGPMs to enhance their beneficial traits and tailor them for specific agricultural applications. Genetic modification can involve the transfer of desirable traits into selected rhizobacterial strains or populations using mobile genetic elements [57]. This approach enables the development of engineered PGPMs with improved efficacy and stability in the rhizosphere [58].

One of the main challenges in the genetic engineering of PGPMs for biofertilizer commercialization is translating laboratory results to field conditions. While genetic engineering techniques have shown promising results in controlled laboratory settings, their effectiveness in field conditions remains limited [59]. Field trials and large-scale studies are necessary to evaluate genetically engineered PGPMs performance and ecological impact in real-world agricultural systems [60].

Another important consideration in the genetic engineering of PGPMs is the selection of suitable traits for modification. Genetically engineered PGPMs should possess stability, high expression, tolerance, and survival capacity in the plant rhizosphere [58]. These traits are crucial for ensuring biofertilizer formulations' long-term effectiveness and sustainability.

Furthermore, genetic engineering and synthetic biology approaches can enable the development of exclusive coupling of plant-bacteria interactions in the field. Such an approach can optimize various aspects of engineered PGPMs ecology, including enrichment, plant growth promotion efficacy, and biocontainment [57]. By harnessing the signalling mechanisms between plants and bacteria, it is possible to establish targeted and efficient interactions that enhance plant growth and nutrient uptake.

3.3 Opportunities in Multi-trait, Multi-strain and Multi-nutrient Formulations

Using biofertilizers as part of multi-trait microbial consortia offers exciting opportunity. Such consortia can provide multiple benefits to crops, including enhanced nutrient uptake, disease resistance, and stress tolerance. Developing multi-trait microbial formulations could revolutionize biofertilizers [48]. Using multi-strain and multi-nutrient formulations in biofertilizer commercialization also offers several advantages. Multi-strain formulations involve the combination of different strains of biofertilizer, which can enhance plant growth compared to single-strain formulations. The synergistic interactions between strains can increase nutrient availability and improve plant performance. Additionally, multi-nutrient formulations incorporate other essential nutrients, such as nitrogen, potassium, micronutrients, and biofertilizers. This approach ensures a balanced nutrient supply to plants and further enhances crop productivity.

3.3.1 Drivers for Biofertilizer Market Expansion

3.3.1.1 Growing Awareness

The increasing awareness about sustainable agriculture is creating a favorable market for biofertilizers. The market value of biofertilizers has been increasing, driven by the demand for chemical-free food products and the need for sustainable agricultural practices [25]. Biofertilizers are shown to enhance crop yield and provide environmentally friendly nutrition [61]. However, the adoption of biofertilizers remains limited, likely due to inappropriate formulations and a lack of quality control capacity in some regions [62]. It is crucial to conduct adequate research to promote the production of quality biofertilizers by implementing effective regulatory frameworks and providing adequate extension programs [26].

3.3.1.2 Government Support

Government support is essential for the research and development of biofertilizer-based products. Research studies have shown that biofertilizer strains isolated from various sources, such as the rhizosphere of wild potatoes [9], sugarcane [63], and wheat [9], have demonstrated significant plant growth promoting abilities. However, further research is needed to optimize biofertilizer-based products' formulation and application methods for different crops and soil conditions [17].

Government funding can facilitate research projects to understand the mechanisms of plant growth promotion by biofertilizer and their interactions with plants. This knowledge can help develop more effective and efficient biofertilizers. Additionally, government support can enable the establishment of research facilities and laboratories with advanced technologies to isolate, identify, and characterize biofertilizer strains [4]. Government support is also crucial in establishing a regulatory framework for commercializing biofertilizer-based products. The regulatory framework should ensure these products' safety, efficacy, and quality. Government authorities can work with research institutions and industry players to set guidelines and standards for producing, labelling, and marketing biofertilizers containing biofertilizers [17].

Quality control measures should be adopted to ensure that biofertilizer-based products meet the standards. Such measures can include testing biofertilizer strains' viability and purity and quantifying their plant growth promotion abilities. Government support can facilitate the establishment of quality control laboratories and certification processes to ensure the reliability and consistency of biofertilizer-based products [17].

Government support can also be provided through financial incentives and subsidies to promote farmers adoption of biofertilizers. These incentives can include tax breaks, grants, and subsidies for producing, distributing, and purchasing biofertilizer-based products. By reducing the financial burden on farmers, government support can encourage the widespread use of biofertilizers, improving soil health and increasing crop productivity [17].

Government support is also essential in raising awareness and educating farmers about the benefits of using biofertilizers. Government agencies can collaborate with agricultural extension services to conduct training programs, workshops, and field demonstrations to inform farmers about using and applying biofertilizer-based products. These programs can also provide information on biofertilizers' environmental and economic benefits, further incentivizing their adoption [17].

3.3.2 Integration of Nanotechnology with Biofertilizers

Nanotechnology has emerged as a promising field with applications in various sectors, including agriculture. In agriculture, nanotechnology offers opportunities to enhance crop productivity, improve nutrient uptake, and mitigate environmental stresses [64]. Nanoparticles can be used as carriers for the controlled release of fertilizers and biofertilizers, improving their efficiency and longevity [65,66]. Additionally, nanosensors can detect plant pathogens, enabling early disease diagnosis and management [66,67]. Integrating nanotechnology with biofertilizers holds excellent potential for improving the shelf life of biofertilizers and overall effectiveness.

One approach to improve the shelf life of biofertilizers is through nanoencapsulation. Nanoencapsulation involves the encapsulation of biofertilizers within nanomaterials, which provide protection against environmental factors and enhance their stability [66,67]. For example, essential oils have been nanoencapsulated and used as insecticides to control pests in agriculture. The controlled release of essential oils from nanoparticles was reported to maximize their insecticidal effects at low concentrations, reducing the need for frequent applications and minimizing environmental impact [67]. Similarly, biofertilizers can be encapsulated within nanoparticles to protect the microorganisms from adverse conditions and extend their viability [65]. Furthermore, nanotechnology can facilitate the delivery of bioactive compounds produced by biofertilizers, such as phytohormones and vitamins, to plants, thereby promoting growth and development [68].

4. Current Scenario

The burgeoning interest in sustainable agriculture has paved the way for innovative practices to enhance crop productivity while mitigating the environmental repercussions of conventional farming methods [56]. One groundbreaking approach involves merging biofertilizers within the integrated nutrient management (INM) framework. This amalgamation offers a comprehensive solution for sustainable agriculture, addressing various facets such as nutrient availability, soil health, environmental sustainability, and crop yield and quality.

Biofertilizers, comprising beneficial microbial inoculants like rhizobacteria and mycorrhizal fungi, are vital in soil nutrient cycling and mineralization [69,70]. Farmers can secure a consistent nutrient supply to crops when biofertilizers are integrated into INM—a strategy that judiciously combines organic and inorganic fertilizers. This synergistic interaction elevates nutrient availability and fosters robust plant growth [71].

The integration of biofertilizers with INM also has profound implications for soil health. INM practices, when complemented by biofertilizers, can significantly improve the soil's physical and physicochemical properties [72]. Biofertilizers enrich the microbiome, enhancing soil structure, nutrient cycling, and water-holding capacity [73]. This microbial diversity catalyzes the proliferation of beneficial soil organisms, reducing the dependency on chemical inputs and contributing to sustainable soil management.

From an environmental standpoint, biofertilizers are emerging as eco-friendly alternatives to chemical fertilizers. Their renewable nature and minimal environmental footprint make them an attractive option for sustainable agriculture [74]. Using biofertilizers reduces the danger of nutrient leaching and groundwater pollution while lowering greenhouse gas emissions from manufacturing and using synthetic fertilizers [73]. Therefore, their integration with INM can substantially contribute to the environmental sustainability of agricultural systems.

Moreover, the amalgamation of biofertilizers and INM has significantly enhanced crop yield and quality. Numerous studies corroborate that this integration augments plant nutrient uptake, root development, and stress tolerance, culminating in elevated yields and superior crop performance [71,75]. Furthermore, biofertilizers can enrich crops' nutritional profiles by elevating essential nutrients and bioactive compounds [76].

5. Challenges and Future Directions

Understanding rhizosphere dynamics is a critical factor that poses hurdles in commercializing biofertilizers. The rhizosphere is a complex and dynamic environment influenced by many factors, including soil type, plant species, and microbial interactions. Seasonal changes further complicate this dynamic by affecting soil moisture, temperature, and microbial activity. These fluctuations can impact the efficacy of biofertilizers, making it challenging to develop a one-size-fits-all solution [30].

While integrating biofertilizers with INM holds great promise for sustainable agriculture, several challenges must be addressed before biofertilizer commercialization. These include the development of cost-effective production methods for biofertilizers, ensuring their quality and efficacy, and promoting adoption among farmers [77]. Additionally, more research is needed to understand the interactions between biofertilizers and other components of INM, such as organic and inorganic fertilizers, to optimize nutrient management strategies [78].

Future biotechnology and microbial ecology advancements may lead to novel biofertilizers with enhanced nutrient mobilization and plant growth-promoting properties [79]. Furthermore, integrating biofertilizers with precision agriculture techniques, such as remote sensing and data analytics, could enable targeted nutrient management and improve resource use efficiency [80]. Overall, the prospects of biofertilizer integration with INM are promising and offer a sustainable solution for enhancing agricultural productivity while minimizing environmental impacts.

6. Status of Biofertilizers in Global Market

The biofertilizer market is expected to grow exponentially with increasing food demand globally. Biofertilizers, particularly nitrogen-fixing strains from *Rhizobium*, *Azotobacter*, and *Azospirillum* genera, represents the global biofertilizer market [81]. The global market for N_2-fixing biofertilizers was worth USD 800 million in 2016 and is predicted to reach USD 3 billion by 2024, expanding at a compound annual growth rate (CAGR) of around 14.3% [81]. The market for *Azotobacter*-based biofertilizers alone was valued at USD 212.2 million in 2017 and is predicted to show a CAGR of 8.7% from 2020-2025 [81]. These figures indicate the significant market potential and growth opportunities for biofertilizers in the coming years. Several factors are driving the growth of the global biofertilizer market. Firstly, Farmers and consumers are becoming more aware of the environmental and health risks of excessive chemical fertilizers and pesticides [82]. Secondly, the increasing demand for organic and sustainable food products has created a favorable biofertilizer market environment. Consumers increasingly seek products produced using environmentally friendly practices, and biofertilizers can help meet this demand. Additionally, government initiatives and regulations promoting sustainable agriculture and reducing chemical inputs have further boosted the adoption of biofertilizers [3].

7. Conclusion

The exploration into biofertilizer commercialization has unveiled a landscape riddled with challenges while presenting opportunities for advancement. Regulatory hurdles, prominently featuring bio-safety concerns and quality control issues, stand as formidable barriers to be addressed. Alongside these, technical challenges encompassing strain stability, bioformulation complexities, and the need for compatibility with chemical fertilizers present significant impediments to large-scale adoption. Moreover, market challenges such as consumer acceptance and cost competitiveness further complicate the path to widespread biofertilizer usage. Conversely, amidst these challenges, opportunities arise. Understanding rhizosphere engineering, leveraging genetic engineering, and exploring the potential in multi-trait, multi-strain, and multi-nutrient formulations pose promising avenues for enhancing biofertilizer efficacy. The integration of nanotechnology and an understanding of market dynamics present additional openings for optimizing biofertilizer utilization.

The review has highlighted the intricate balance between challenges and opportunities in biofertilizer commercialization. Overcoming regulatory, technical, and market hurdles while capitalizing on the potential openings is imperative for the effective implementation and widespread acceptance of biofertilizers in agricultural practices, driving toward a more sustainable and eco-friendly future in agriculture.

Author Contributions

Author 1 was responsible for drafting and writing the manuscript, while Author 2 revised and proofread it.

References

1. Debnath S, Rawat D, Mukherjee AK, Adhikary S, Kundu R. Applications and constraints of plant beneficial microorganisms in agriculture. In: Radhakrishnan R, Mirmajlessi SM, eds. *Biostimulants in Plant Science*. IntechOpen; 2020.

2. Mahanty T, Bhattacharjee S, Goswami M, et al. Biofertilizers: a potential approach for sustainable agriculture development. *Environ Sci Pollut Res Int*. Feb 2017, *24(4)*, 3315-3335. doi:10.1007/s11356-016-8104-0

1. Nosheen S, Ajmal I, Song Y. Microbes as biofertilizers, a potential approach for sustainable crop production. *Sustainability*. 2021, *13(4)*, 1868. doi:10.3390/su13041868
2. Bahadir PS, LİAqat F, Eltem R. Plant growth promoting properties of phosphate solubilizing Bacillus species isolated from the Aegean Region of Turkey. *Turkish Journal of Botany*. 2018, *42(2)*, 183-196. doi:10.3906/bot-1706-51
3. Oliveira Filho JdS, Viana TVdA, Azevedo BMd, Sousa GGd, Pereira MG. Phosphorus forms and lability of organic matter during anaerobic digestion of swine manure. *Semina: Ciências Agrárias*. 2019, *40(5Supl1)*, 2107-2119. doi:10.5433/1679-0359.2019v40n5Supl1p2107
4. Malboobi MA, Owlia P, Behbahani M, et al. Solubilization of organic and inorganic phosphates by three highly efficient soil bacterial isolates. *World Journal of Microbiology and Biotechnology*. 2009, *25(8)*, 1471-1477. doi:10.1007/s11274-009-0037-z
5. Tjahjoleksono A, Mubarik NR, Fitriyanti D. Characterization of phosphate solubilizing bacteria and nitrogen fixing bacteria from limestone mining region. *Malaysian Journal of Microbiology*. 2017, *13(3)*, 147-155. doi:10.21161/mjm.95016
6. Mubarik NR, Mursyida E, Tjahjoleks A. Selection and identification of phosphate-potassium solubilizing bacteria from the area around the limestone mining in Cirebon Quarry. *Research Journal of Microbiology*. 2015, *10(6)*, 270-279. doi:10.3923/jm.2015.270.279
7. Pantigoso HA, He Y, Manter DK, Fonte SJ, Vivanco JM. Phosphorus-solubilizing bacteria isolated from the rhizosphere of wild potato *Solanum bulbocastanum* enhance growth of modern potato varieties. *Bulletin of the National Research Centre*. 2022, *46(1)*, 1-10. doi:10.1186/s42269-022-00913-x
8. Tarigan DM, Barus WA, Munar A, Lestami A. Exploration and morphological characterization of phosphate-solubilizing and nitrogen-fixing bacteria in saline soil. *SABRAO Journal of Breeding and Genetics*. 2023, *52(2)*, 550-563. doi:10.54910/sabrao2023.55.2.27
9. Klein A-M, Vaissière BE, Cane JH, et al. Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society B: Biological Sciences*. 2006, *274(1608)*, 303-313. doi:10.1098/rspb.2006.3721
10. Peris D, Pérez-de la Fuente R, Peñalver E, Delclòs X, Barrón E, Labandeira CC. False Blister Beetles and the Expansion of Gymnosperm-Insect Pollination Modes before Angiosperm Dominance. *Current Biology*. 2017, *27(6)*, 897-904. doi:10.1016/j.cub.2017.02.009
11. Garratt MPD, Bishop J, Degani E, et al. Insect pollination as an agronomic input: Strategies for oilseed rape production. *Journal of Applied Ecology*. 2018, *55(6)*, 2834-2842. doi:10.1111/1365-2664.13153
12. Bola Adelabu D, Bredenhand E, van der Merwe S, Franke AC. Soil fertilization synergistically enhances the impact of pollination services in increasing seed yield of sunflower under dryland conditions. *The Journal of Agricultural Science*. 2021, *159(3-4)*, 258-271. doi:10.1017/s0021859621000514
13. Omar NA, ZarİMan NA, Nurul Huda A. Pollination in the Tropics: Role of Pollinator in Guava Production. *International Journal of Life Sciences and Biotechnology*. 2021, *4(3)*, 623-639. doi:10.38001/ijlsb.907696

16. Ehlers BK, Bataillon T, Damgaard CF. Ongoing decline in insect-pollinated plants across Danish grasslands. *Biology Letters*. 2021, *17(11)*, doi:10.1098/rsbl.2021.0493
17. Alori ET, Glick BR, Babalola OO. Microbial Phosphorus Solubilization and Its Potential for Use in Sustainable Agriculture. *Front Microbiol*. 2017, *8*, 971. doi:10.3389/fmicb.2017.00971
18. Patel G, Singh S, Saxena DSK, Kaur DKJ. Isolation, biochemical characterization and production of biofertilizer from *Bacillus megaterium*. *The International Journal of Life-Sciences Scientific Research*. 2016, *2(6)*, 749-752. doi:10.21276/ijlssr.2016.2.6.16
19. Chakma P, Chowdhury S, Bari L, Hoque S. A Feasible Way of Degrading Malathion Pesticide under Laboratory Condition Using Phosphate Solubilizing Bacteria. *Journal of Geoscience and Environment Protection*. 2019, *07(01)*, 1-12. doi:10.4236/gep.2019.71001
20. Sharma SB, Sayyed RZ, Trivedi MH, Gobi TA. Phosphate solubilizing microbes: sustainable approach for managing phosphorus deficiency in agricultural soils. *Springerplus*. 2013, *2*, 587. doi:10.1186/2193-1801-2-587

21. Yadav A, Yadav K, Vashistha A. Phosphate solubilizing activity of *Pseudomonas fluorescens* PSM1 isolated from wheat rhizosphere. *Journal of Applied and Natural Sciences*. 2016, *8(1)*, 93-96.

22. Walpola BC, Kim AY, Jeon JH, Yoon M-H. Application of immobilization technology in solubilization of rock phosphate. *Korean Journal of Soil Science and Fertilizer*. 2014, *47(4)*, 249-253. doi:10.7745/kjssf.2014.47.4.249

23. Malusa E, Sas-Paszt L, Ciesielska J. Technologies for beneficial microorganisms inocula used as biofertilizers. *ScientificWorldJournal*. 2012, *2012*, 491206. doi:10.1100/2012/491206

24. Ke J, Wang B, Yoshikuni Y. Microbiome Engineering: Synthetic Biology of Plant-Associated Microbiomes in Sustainable Agriculture. *Trends Biotechnol*. Mar 2021, *39(3)*, 244-261. doi:10.1016/j.tibtech.2020.07.008

25. Soumare A, Boubekri K, Lyamlouli K, Hafidi M, Ouhdouch Y, Kouisni L. From Isolation of Phosphate Solubilizing Microbes to Their Formulation and Use as Biofertilizers: Status and Needs. *Front Bioeng Biotechnol*. 2019, *7*, 425. doi:10.3389/fbioe.2019.00425

26. Kassem HS, Alotaibi BA, Aldosri FO, Muddassir M. Exploring the relationship between information-seeking behavior and adoption of biofertilizers among onion farmers. *Agronomy*. 2021, *11(6)*, 1258. doi:10.3390/agronomy11061258

27. Lauriano-Barajas J, Vega-Frutis R. Infectivity and effectivity of commercial and native arbuscular mycorrhizal biofertilizers in seedlings of maize (*Zea mays*). *Botanical Sciences*. 2018, *96(3)*, 395-404. doi:10.17129/botsci.1855

28. Smirnova I, Sadanov A, Baimakhanova G, Faizulina E, Tatarkina L. Metabolic interaction at the level of extracellular amino acids between plant growth-promoting rhizobacteria and plants of alfalfa (*Medicago sativa* L.). *Rhizosphere*. 2022, *21*, 100477. doi:10.1016/j.rhisph.2022.100477

29. Oteino N, Lally RD, Kiwanuka S, et al. Plant growth promotion induced by phosphate solubilizing endophytic Pseudomonas isolates. *Front Microbiol*. 2015, *6*, 745. doi:10.3389/fmicb.2015.00745

30. Yadav A, Yadav K. Seasonal population dynamics of rhizosphere and non-rhizosphere soil microorganisms of chir pine seedlings (*Pinus roxburghii* Sarg.). *British Microbiology Research Journal*. 2013, *3(4)*, 664-667.

31. Purwaningsih S, Sutisna E, Nugroho AA. Characterization, diversity, and effectiveness phosphate solubilizing bacteria from the soil and rhizosphere on the growth of *Glycine max* L. in greenhouse. *IOP Conference Series: Earth and Environmental Science*. 2022, *976(1)*, 012030. doi:10.1088/1755-1315/976/1/012030

32. Dandessa C, Bacha K. Review on role of phosphate solubilizing microorganisms in sustainable agriculture. *International Journal of Current Research and Academic Review*. 2018, *6(11)*, 48-55. doi:10.20546/ijcrar.2018.611.006

33. Mahdi I, Fahsi N, Hafidi M, Allaoui A, Biskri L. Plant growth enhancement using rhizospheric halotolerant phosphate solubilizing bacterium *Bacillus licheniformis* QA1 and *Enterobacter asburiae* QF11 isolated from *Chenopodium quinoa* willd. *Microorganisms*. Jun 24 2020, *8(6)*, 948. doi:10.3390/microorganisms8060948

34. Motamedi H. Screening cabbage rhizosphere as a habitat for isolation of phosphate-solubilizing bacteria. *Environmental and Experimental Biology*. 2016, *14(4)*, 173-181. doi:10.22364/eeb.14.24

35. Smirnova I, Sadanov A, Baimakhanova G, Faizulina E, Tatarkina L. Use of a consortium of agronomically important microorganisms for growing soybean (*Glycine max* (L.) Merr.). *The Open Agriculture Journal*. **2023**, *17(1)*, e187433152302140. doi:10.2174/18743315-v17-230223-2022-42

36. Broeckx G, Vandenheuvel D, Claes IJ, Lebeer S, Kiekens F. Drying techniques of probiotic bacteria as an important step towards the development of novel pharmabiotics. *Int J Pharm*. **2016**, *505(1-2)*, 303-318. doi:10.1016/j.ijpharm.2016.04.002

37. Safari M, Motamedi E, Kari Dolatabad H, Modarres Sanavy SAM. Nano-carriers effects on the viability and efficiency of Pseudomonas strains as phosphate solubilizing bacteria. *Heliyon*. Oct **2020**, *6(10)*, e05076. doi:10.1016/j.heliyon.2020.e05076

38. Jakubovskis R, Jankute A, Guobuzaite S, Boris R, Urbonavicius J. Prolonging Bacterial Viability in Biological Concrete: Coated Expanded Clay Particles. *Materials (Basel)*. May 21 2021, *14(11)*, 2719. doi:10.3390/ma14112719

39. Ruiz-Valdiviezo VM, Canseco LM, Suarez LA, Gutierrez-Miceli FA, Dendooven L, Rincon-Rosales R. Symbiotic potential and survival of native rhizobia kept on different carriers. *Braz J Microbiol*. Jul-Sep 2015, *46(3)*, 735-42. doi:10.1590/S1517-838246320140541

40. Blanco-Vargas A, Chacon-Buitrago MA, Quintero-Duque MC, et al. Production of pine sawdust biochar supporting phosphate-solubilizing bacteria as an alternative bioinoculant in Allium cepa L., culture. *Sci Rep*. Jul 27 2022, *12(1)*, 12815. doi:10.1038/s41598-022-17106-1

41. Han S, Choi EK, Park W, Yi C, Chung N. Effectiveness of expanded clay as a bacteria carrier for self-healing concrete. *Applied Biological Chemistry*. 2019, *62(1)*, 1-5. doi:10.1186/s13765-019-0426-4\

42. Yahya M, Rasul M, Sarwar Y, et al. Designing synergistic biostimulants formulation containing autochthonous phosphate-solubilizing bacteria for sustainable wheat production. *Front Microbiol*. 2022, *13*, 889073. doi:10.3389/fmicb.2022.889073

43. Gul LB, Gul O, Yilmaz MT, Dertli E, Con AH. Optimization of cryoprotectant formulation to enhance the viability of *Lactobacillus brevis* ED25: Determination of storage stability and acidification kinetics in sourdough. *Journal of Food Processing and Preservation*. 2020, *44(4)*, e14400. doi:10.1111/jfpp.14400

44. Wang Z, Zhang H, Liu L, et al. Screening of phosphate-solubilizing bacteria and their abilities of phosphorus solubilization and wheat growth promotion. *BMC Microbiol*. Dec 9 2022, *22(1)*, 296. doi:10.1186/s12866-022-02715-7

45. Topolska J, Latowski D, Kaschabek S, Manecki M, Merkel BJ, Rakovan J. Pb remobilization by bacterially mediated dissolution of pyromorphite $Pb_5(PO_4)_3Cl$ in presence of phosphate-solubilizing *Pseudomonas putida*. *Environ Sci Pollut Res Int*. Jan 2014, *21(2)*, 1079-1089. doi:10.1007/s11356-013-1968-3

46. Yadav A, Yadav K, Gupta S. The combined use of chemical fertilizers with multi-trait *Pseudomonas fluorescens* enhanced bell pepper growth. *Journal of Environment and Bio-Sciences*. 2015, *29(2)*, 383-387.

47. Zhang Q, White JF. Bioprospecting desert plants for endophytic and biostimulant microbes: a strategy for enhancing agricultural production in a hotter, drier future. *Biology (Basel)*. Sep 26 2021, *10(10)*, 961. doi:10.3390/biology10100961

48. Garcia-Fraile P, Carro L, Robledo M, et al. Rhizobium promotes non-legumes growth and quality in several production steps: towards a biofertilization of edible raw vegetables healthy for humans. *PLoS One*. 2012, *7(5)*, e38122. doi:10.1371/journal.pone.0038122

49. Siegrist M, Hartmann C. Consumer acceptance of novel food technologies. *Nat Food*. Jun 2020, *1(6)*, 343-350. doi:10.1038/s43016-020-0094-x

50. Flores-Felix JD, Silva LR, Rivera LP, et al. Plants probiotics as a tool to produce highly functional fruits: the case of phyllobacterium and vitamin C in strawberries. *PLoS One*. 2015, *10(4)*, e0122281. doi:10.1371/journal.pone.0122281

51. Tomic JM, Milivojevic JM, Pesakovic MI. The response to bacterial inoculation is cultivar-related in strawberries. *Turkish Journal of Agriculture and Forestry*. 2015, *39*, 332-341. doi:10.3906/tar-1410-16

52. Shamal S, Mohan BC. Consumer behaviour in fortified food choice decisions in India. *Nutrition & Food Science*. 2017, *47(2)*, 229-239. doi:10.1108/nfs-05-2016-0065

53. Marois J, Lerch TZ, Dunant U, Farnet Da Silva AM, Christen P. Chemical and microbial characterization of fermented forest litters used as biofertilizers. *Microorganisms*. Jan 24 2023, *11(2)*, 306. doi:10.3390/microorganisms11020306

54. Yadav A, Yadav K, Ahmad R. Rhizosphere engineering for semiarid tropics: Prospects and bottlenecks. *Academia Biology*. 2023, *1*, 1-18.

55. Haskett TL, Tkacz A, Poole PS. Engineering rhizobacteria for sustainable agriculture. *ISME J*. Apr 2021, *15(4)*, 949-964. doi:10.1038/s41396-020-00835-4

56. Chandran H, Meena M, Swapnil P. Plant growth-promoting rhizobacteria as a green alternative for sustainable agriculture. *Sustainability*. 2021, *13(19)*, 10986. doi:10.3390/su131910986

57. Saghafi D, Delangiz N, Lajayer BA, Ghorbanpour M. An overview on improvement of crop productivity in saline soils by halotolerant and halophilic PGPRs. *3 Biotech*. Jul 2019, *9(7)*, 261. doi:10.1007/s13205-019-1799-0

58. Pastor-Bueis R, Mulas R, Gómez X, González-Andrés F. Innovative liquid formulation of digestates for producing a biofertilizer based on *Bacillus siamensis*: Field testing on sweet pepper. *Journal of Plant Nutrition and Soil Science*. 2017, *180(6)*, 748-758. doi:10.1002/jpln.201700200

59. Ji SH, Kim JS, Lee CH, et al. Enhancement of vitality and activity of a plant growth-promoting bacteria (PGPB) by atmospheric pressure non-thermal plasma. *Sci Rep*. Jan 31 2019, *9(1)*, 1044. doi:10.1038/s41598-018-38026-z

60. Deodatus K, Moses T, Ernest S, Susan I, Balthazar M, Cargele M. Maize response to chemical and microbial products on two Tanzanian soils. *Journal of Agricultural Science*. 2019, *11(2)*, 71-81. doi:10.5539/jas.v11n2p71

61. Rodrigues AA, Forzani MV, Soares RdS, Sibov ST, Vieira JDG. Isolation and selection of plant growth-promoting bacteria associated with sugarcane. *Pesquisa Agropecuária Tropical*. 2016, *46(2)*, 149-158. doi:10.1590/1983-40632016v4639526

62. Shalaby T, Bayoumi Y, Eid Y, et al. Can nanofertilizers mitigate multiple environmental stresses for higher crop productivity? *Sustainability*. 2022, *14(6)*, 3480. doi:10.3390/su14063480

63. Shanware AS, Taiwade LH. Nano-biofertilizers: Progressive evolution for sustainable agriculture. *Biological Sciences*. 2022, *02(02)*, 166-171. doi:10.55006/biolsciences.2022.2201

64. Yadav A, Yadav K, Abd-Elsalam KA. Nanofertilizers: Types, delivery and advantages in agricultural sustainability. *Agrochemicals*. 2023, *2*, 296–336.

65. Christofoli M, Costa ECC, Bicalho KU, et al. Insecticidal effect of nanoencapsulated essential oils from Zanthoxylum rhoifolium (Rutaceae) in Bemisia tabaci populations. *Industrial Crops and Products*. 2015, *70*, 301-308. doi:10.1016/j.indcrop.2015.03.025

66. Cruz-Méndez AS, Ortega-Ramírez E, Lucho-Constantino CA, et al. Bamboo biochar and a nopal-based biofertilizer as improvers of alkaline soils with low buffer capacity. *Applied Sciences*. 2021, *11(14)*, 6502. doi:10.3390/app11146502

67. Ritika B, Utpal D. Biofertilizer, a way towards organic agriculture: A review. *African Journal of Microbiology Research*. 2014, *8(24)*, 2332-2343. doi:10.5897/ajmr2013.6374

68. Schutz L, Gattinger A, Meier M, et al. Improving Crop Yield and Nutrient Use Efficiency via Biofertilization-A Global Meta-analysis. *Front Plant Sci*. 2017, *8*, 2204. doi:10.3389/fpls.2017.02204

69. Mishra S, Nayak NJ, Nayak RK, et al. Influence of nutrient management practices on growth, flowering and yield attributes of cucumber (*Cucumis sativus*). *International Journal of Environment and Climate Change*. 2022, 493-503. doi:10.9734/ijecc/2022/v12i1130999

70. Sree SP, Rao CS, Latha M, Madhurya P. Effect of integrated nutrient management on physical and physico-chemical properties of soil. *International Journal of Plant & Soil Science*. 2022, 1028-1033. doi:10.9734/ijpss/2022/v34i242733

71. Milton M, Bisary D, Kumar V, Singh AK, Mehta CM. Microbial fertilizers: Their potential impact on environment sustainability and ecosystem services. *International Journal of Chemical Studies*. 2020, *8(6)*, 2308-2315. doi:10.22271/chemi.2020.v8.i6ag.11120

72. Maleva M, Borisova G, Koshcheeva O, Sinenko O. Biofertilizer based on silicate solubilizing bacteria improves photosynthetic function of *Brassica juncea*. *Agrofor*. 2018, *2(3)*, 13-19. doi:10.7251/agreng1703013m

73. Thangasamy A, Lawande KE. Effect of integrated nutrient management on garlic yield, nutrient uptake and pungency. *Agropedology*. 2018, *28(1)*, 8-13. doi:10.47114/j.agroped.2018.jun2

74. Otaiku AA. Biofertilizer impacts on cassava (*Manihot esculenta* crantz) cultivation: improved soil health and quality, Igbariam, Nigeria. *World Journal of Agriculture and Soil Science*. 2019, *3(1)*, 1-15. doi:10.33552/wjass.2019.04.000578

75. Aloo BN, Makumba BA, Mbega ER. Plant growth promoting rhizobacterial biofertilizers for sustainable crop production: the past, present, and future. *Preprints*. 2020, 1-31. doi:10.20944/preprints202009.0650.v1

76. Kumar A, Pandita VK. Effect of integrated nutrient management on seed yield and quality in cowpea. *Legume Research - An International Journal*. 2015, *39(OF)*, 448-452. doi:10.18805/lr.v0iOF.6785

77. Panazai GM. Biozote-N performance in peas production under the influence of compost application Gul Muhammad Panazai. *Pure and Applied Biology*. 2019, *8(1)*, 931-941. doi:10.19045/bspab.2019.80035

78. Yadav A, Yadav K, Ahmad R, Abd-Elsalam KA. Emerging frontiers in nanotechnology for precision agriculture: Advancements, hurdles and prospects. *Agrochemicals*. 2023, *2*, 220-256.

79. Aasfar A, Bargaz A, Yaakoubi K, et al. Nitrogen fixing *Azotobacter* species as potential soil biological enhancers for crop nutrition and yield stability. *Front Microbiol*. 2021, *12*, 628379. doi:10.3389/fmicb.2021.628379

80. Arjjumend H, Koutouki K, Neufeld S. Comparative advantage of using biofertilizers in indian agroecosystems: an analysis from the perspectives of stakeholders. *European Journal of Agriculture and Food Sciences*. 2021, *3(2)*, 26-36. doi:10.24018/ejfood.2021.3.2.243

81. Kumar S, Diksha, Sindhu SS, Kumar R. Biofertilizers: An ecofriendly technology for nutrient recycling and environmental sustainability. Current Research in Microbial Sciences. 2021, 20(3), 100094. doi: 10.1016/j.crmicr.2021.100094

82. Mahapatra DM, Kanhu Satapathy KC, Panda B. Biofertilizers and nanofertilizers for sustainable agriculture: Phycoprospects and challenges. Science of the Total Environment. 2022, 803, 149990. doi: 10.1016/j.scitotenv.2021.149990.

Citation: Yadav A, Yadav K. Challenges and Opportunities in Biofertilizer Commercialization. *SVOA Microbiology 2024,* 5:1, 01-14.