Harnessing Aspergillus niger for Sustainable Biofertilizer Production: A Comprehensive Review

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Abstract—**The increasing demand for eco-friendly agricultural practices has highlighted the potential of Aspergillus niger as a promising agent in biofertilizer development. This filamentous fungus exhibits superior nutrient- solubilizing abilities, notably phosphorus and potassium, and supports plant growth through phytohormone production and biocontrol properties. This review critically explores the biology of A. niger, its nutrient- solubilization mechanisms, and its application in carrier-based biofertilizer formulations. It also assesses various carrier materials, production technologies, and storage methods that impact microbial viability and agronomic performance. Emphasis is placed on recent advances, including nanotechnology-based encapsulation and polymer-based carriers, which improve shelf life, field application, and sustainability. The review further outlines challenges in formulation consistency and environmental adaptability, advocating for innovative strategies to expand the global adoption of A. niger-based biofertilizers.**

Index Terms—**Aspergillus niger, Biofertilizer formulation, Phosphate solubilization, Carrier materials, Soil fertility Plant growth-promoting fungi (PGPF), Liquid and solid biofertilizers, Sustainable agriculture Encapsulation techniques Microbial viability**

1. INTRODUCTION

The rising demand for sustainable agricultural practices has driven significant interest in microbial biofertilizers as alternatives to synthetic fertilizers. Among these, Aspergillus niger is widely recognized for its ability to solubilize phosphorus and other nutrients, thereby enhancing soil fertility and plant growth. Formulating biofertilizers with suitable carrier materials is critical to maintaining microbial viability, ensuring prolonged shelf life, and improving field application efficiency. Various organic, inorganic, and inert carriers have been explored to optimize formulation quality, yet challenges remain in achieving consistent performance and large-scale applicability. This review aims to summarize the nutrient-solubilizing potential of A. niger strains, evaluate carrier materials and formulation strategies, and discuss production and sterilization methods critical for carrier-based biofertilizer development. Additionally, it highlights the agronomic benefits, environmental implications, and future research prospects for advancing A. niger-based biofertilizer technologies.

The increasing global population and the consequent surge in food demand have placed unprecedented pressure on the agricultural sector, exacerbated by the decreasing availability of arable land. Although conventional chemical fertilizers and farming practices have improved yields, they are associated with environmental degradation, soil fertility loss, and adverse impacts on human health. As a sustainable alternative, biofertilizers—microbial formulations that enhance nutrient availability and promote plant growth—are gaining prominence for improving agro-environmental sustainability (Aberathna et al., 2023).

Among fungal biofertilizers, Aspergillus niger is extensively studied due to its remarkable ability to solubilize phosphates, produce organic acids, and improve soil texture and fertility. Widely utilized in industrial biotechnology, this filamentous fungus is commonly cultivated in Potato Dextrose Broth (PDB) medium, though research is increasingly directed toward developing cost-effective media for large-scale production to enhance sustainability and market competitiveness. The multifaceted roles of A. niger in nutrient cycling and plant growth promotion highlight its potential as a cornerstone organism in future biofertilizer technologies.

Biofertilizers, composed of nitrogen-fixing and phosphate-solubilizing microorganisms, enhance soil fertility by increasing nutrient bioavailability, thereby reducing dependency on synthetic fertilizers and supporting sustainable crop production.

Biofertilizers are commonly formulated with carrier materials to enhance microbial viability, shelf life, and ease of application, although liquid formulations may omit carriers. Optimal carriers should be cost-effective, widely available, contaminant-free, possess >50% water retention, and be easily processed and sterilized.

This review aims to summarize the potential of Aspergillus niger strains in nutrient solubilization and their application in carrier-based biofertilizer formulations. It highlights different carrier materials, production strategies, and sterilization techniques that influence microbial viability and product efficiency. Furthermore, it evaluates the agronomic and environmental benefits of A. niger-based biofertilizers compared to synthetic inputs and identifies future research directions for improving their stability and field performance.

2. BIOLOGY AND CHARACTERISTICS OF ASPERGILLUS NIGER

Aspergillus niger is a filamentous fungus extensively explored for biofertilizer production due to its ability to solubilize insoluble nutrients such as phosphorus, potassium, and zinc, thereby improving their plant availability (Aberathna et al., 2023). This organism secretes organic acids that reduce soil pH and mobilize phosphates, along with hydrolytic enzymes like cellulases and amylases that aid in organic matter decomposition and nutrient release (Mundim et al., 2022). Furthermore, A. niger synthesizes phytohormones that enhance plant growth and has demonstrated biocontrol activity against soil-borne pathogens, including Fusarium wilt in guava (Gangaraj et al., 2023). Despite these advantages, strain selection must account for potential mycotoxin production to ensure safety and effectiveness in agricultural applications.

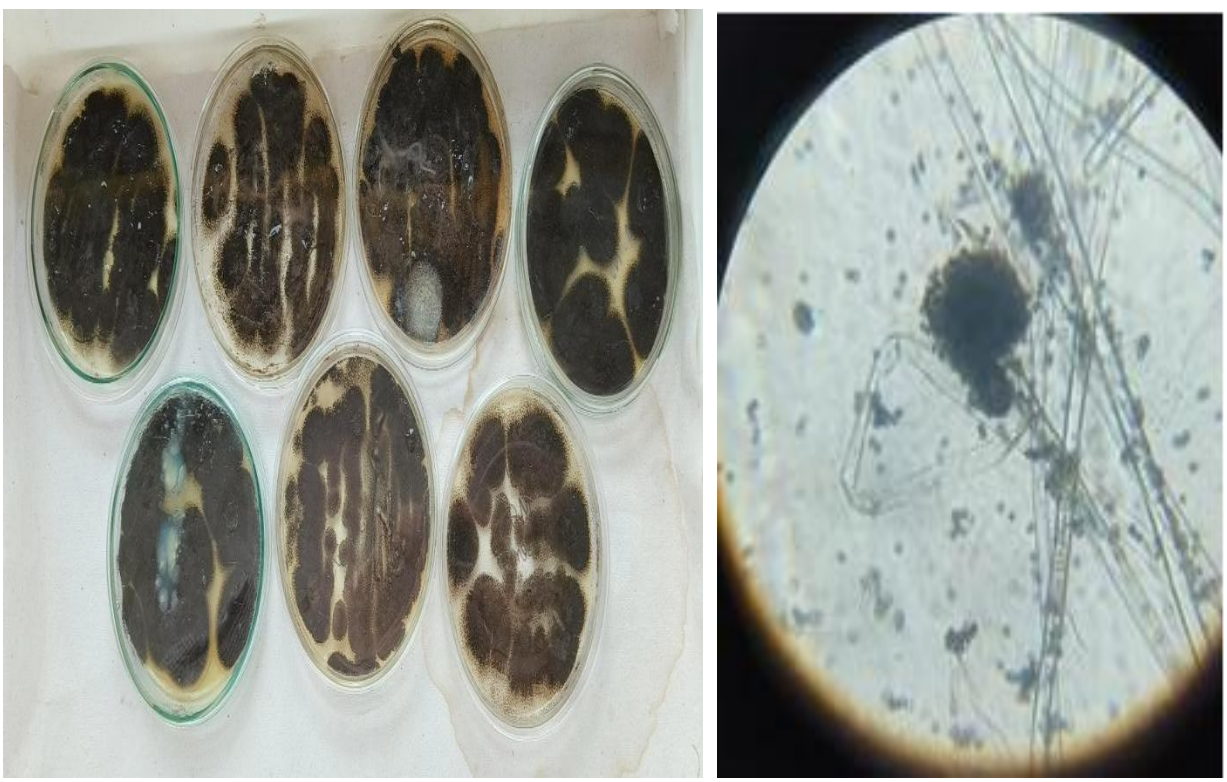

Figure 2.1 *Aspergillus niger* grown on PDA petri plates and its microscopic analysis. (Adopted from Pal et al., 2025)

The solubilization of potassium ions (K^+) and the optimization of conditions to enhance the ability of Aspergillus niger to release K^+ by promoting organic acid production, thereby reducing pH levels and particle size. (Ashrafi-Saiedlou, Rasouli-Sadaghiani, Barin, & Sepehr, 2024)

Aberathna et al. (2023) discussed insights into the prospects of *Aspergillus* biofertilizers. Biofertilizers are commonly formulated in four primary forms: solid, liquid, granular, and freeze-dried powders. Among these, *Aspergillus*-based biofertilizers are most frequently developed in solid and liquid formulations due to their feasibility in terms of production, storage, transportation, and field application.

Figure 2.2 Procurement of dry spores of *Aspergillus niger* for use in biofertilizer formulation. (Adopted from Pal et al ., 2025)

The formulation process relies heavily on the choice of carrier materials, which may include culture media, organic residues (e.g., agricultural wastes and underutilized by-products), and fertilizers (both organic and inorganic) . Carrier selection is influenced by factors such as availability, compatibility with microbial strains, cost-effectiveness, and absence of toxicity. Therefore, optimization of carrier materials is essential to ensure efficient microbial survival, high inoculant quality, and enhanced field performance of *Aspergillus* biofertilizers.

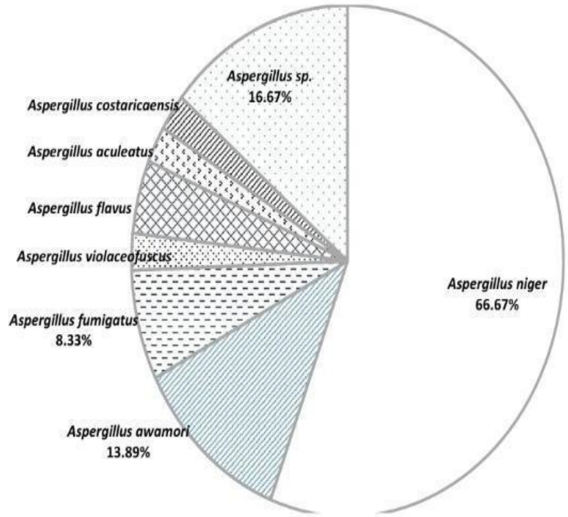

Figure 2.3 The graph of reported *Aspergillus* species for biofertilizer

(Adopted from Aberathna et.al., 2023)

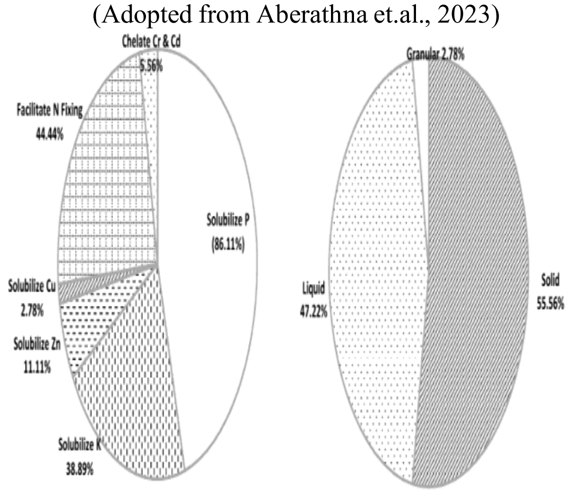

Figure 2.4 The graph of Type of minerals, make available to plants by *Aspergillus* biofertilizers and various formulations used in production of *Aspergillus* biofertilizers

(Adopted from Aberathna et.al ., 2023)

3. MECHANISM IN BIOFERTILIZER ACTION

With the growing demand for food production, nitrogen-fixing biofertilizers have become increasingly vital in enhancing soil fertility, reducing reliance on chemical fertilizers, and minimizing environmental impacts. Their adoption is crucial for ensuring the long-term sustainability of Indian agriculture. The rising focus on eco-friendly and sustainable farming practices is expected to drive further growth and innovation in the Indian biofertilizer market.

Among the various application methods, seed treatment currently dominates the Indian market. This popularity stems from farmers' growing awareness of its benefits, including improved seed germination, healthier plant growth, and higher yields. Soil treatment is also witnessing significant expansion, driven by the demand for organic produce and the need to maintain soil health. In contrast, the 'others' category of biofertilizer applications remains relatively smaller in scale.

In terms of formulations, solid biofertilizers—available as granules or powders—utilize organic or inorganic carriers. Talc-based powders are particularly favored due to their low moisture absorption and hydrophobic properties, which enhance storage stability by preventing hydrate bridge formation (Martínez-Álvarez et al., 2016). Biofertilizers can be applied via root dipping, soil incorporation, or seed inoculation, using either liquid or dry formulations depending on crop and soil requirements (Mahanty et al., 2017).

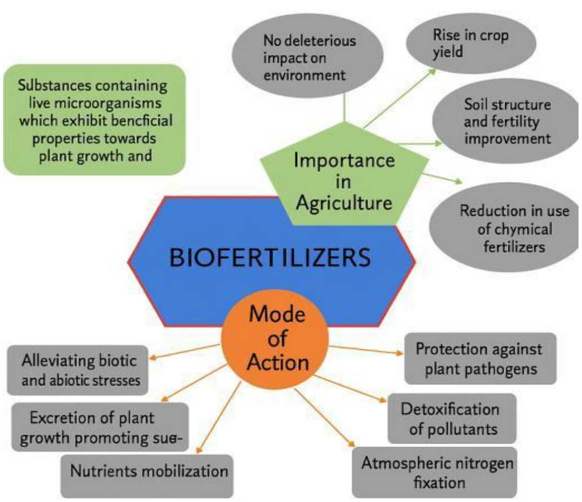

Figure 3.1 Contribution of Biofertilizers to Sustainable Agriculture

(Adopted from Kataria, Sharma, & Jhamaria, 2022)

4. PRODUCTION TECHNOLOGY

The preparation of biofertilizers involves sequential steps starting with isolation of beneficial microorganisms from soil or plant tissues, followed by pure culture growth and screening for plant growth- promoting traits such as nutrient solubilization, phytohormone production, and biocontrol activity. The best- performing strains are then selected for inoculum preparation using shakers or fermenters. Carrier materials are sterilized and optimized for pH and texture before blending with the inoculum. The formulated biofertilizers are evaluated under laboratory, pot, or field conditions for their effects on germination, biomass, stress tolerance, and yield, and subsequently packaged for storage and application (Satish et al., 2022).

Various application methods for biofertilizers include seed inoculation, root dipping, and soil application, using either liquid or dry formulations (Mahanty et al., 2017). Certain precautions are essential during application—prepared microbial suspensions should not be stored overnight, and direct sunlight exposure must be avoided. Ideal storage temperatures range between 0°C and 35°C.

For seed or soil application, dry bioinoculants are rehydrated prior to use (Malusá et al., 2012; Berninger et al., 2017), whereas liquid formulations can be applied directly without rehydration. In seed inoculation, the carrier-based biofertilizer is mixed with water or jaggery to form a slurry, which is then uniformly coated onto sterilized seeds and air-dried before sowing (Lawal & Babalola, 2014). In the root dipping method, seedlings are dipped in a diluted biofertilizer suspension before transplantation. For soil application, the biofertilizer is either sprayed or broadcast prior to sowing (Lawal & Babalola, 2014).

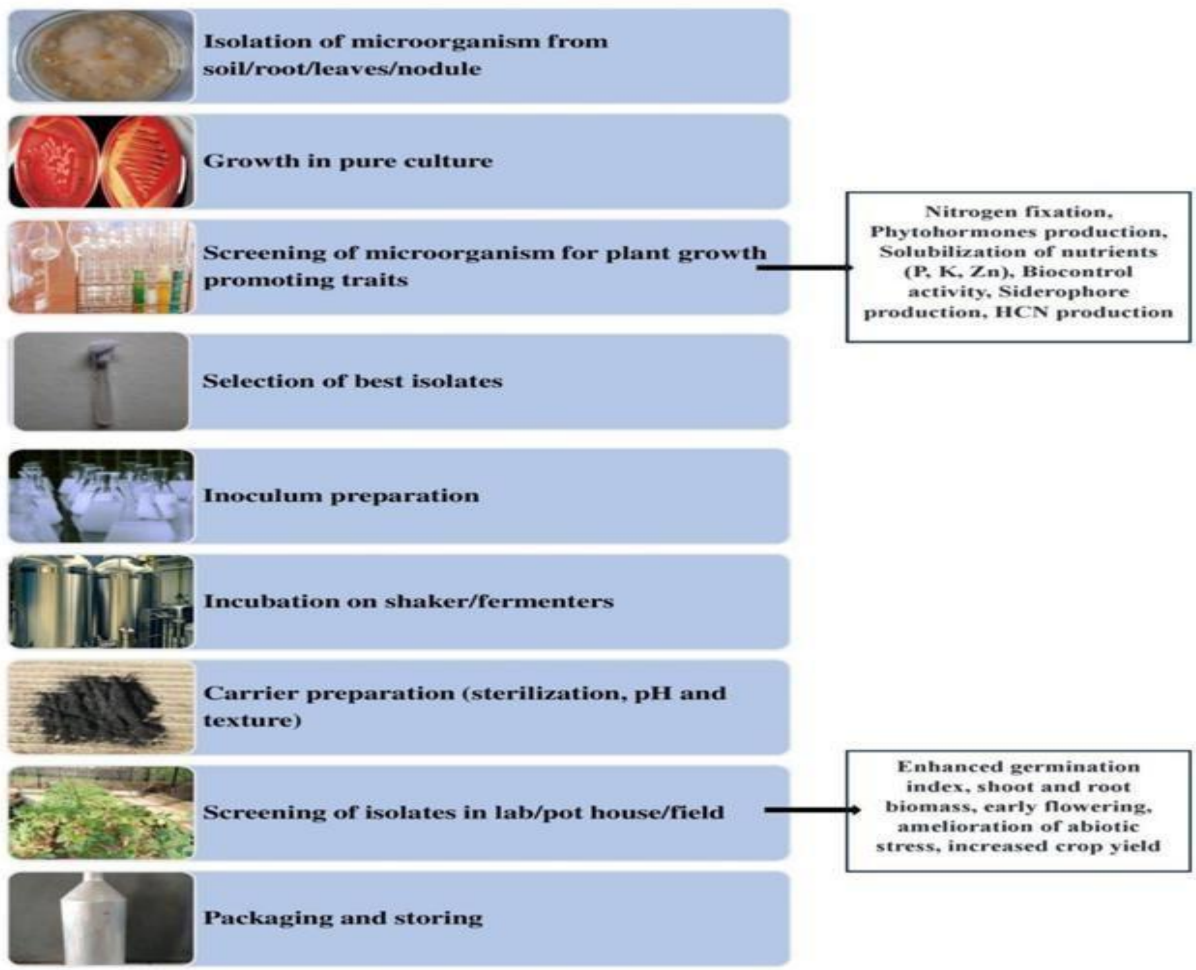

Figure 4.1 Flow chart illustrating the selection of beneficial microbial strains and sequential steps involved in biofertilizer preparation.
(Adopted from Satish et.al.,2022)

5. FORMULATION AND CARRIER MATERIALS

Kataria, Sharma, and Jhamaria (2022) reviewed liquid biofertilizers and highlighted their study on Carrier- based biofertilizers embed beneficial microbes in solid carriers, ensuring easy transport, longer shelf life, sustained viability, and improved field performance. A variety of carrier materials have been explored for biofertilizer development, including peat, lignite, talc, farmyard manure, compost, bagasse, and fly ash (Tilak et al., 1979; Samra et al., 2003). Recent studies highlight biochar, sugarcane filter cake, rice husk ash, nanoclays, and polymer-based matrices as cost-effective alternatives that improve microbial viability, nutrient retention, and field performance (Kumar et al., 2022; Singh et al., 2023). Carriers protect microbes from environmental stress, maintain viability during storage and transport, and support effective soil colonization (Fuentes-Ramírez & Caballero-Mellado, 2005).

Novel carriers such as alginate beads, guar gum hydrogels, and CMC/starch blends provide high porosity,
controlled microbial release, and extended shelf life ($>10^7$ CFU g^{-1} for up to 180 days) (Doe et al., 2023;
Yuliani et al., 2024). Agro-residues like pea fiber and gum outperform rigid materials like rice straw in
sustaining cell viability. Sterilization methods, including gamma irradiation and autoclaving, are

crucial to ensure pathogen-free formulations (Sarbani et al., 2022). Overall, integrating advanced carrier systems enhances stability, ease of application, and agronomic efficacy, promoting sustainable crop production.

Table 5.1. Carrier materials with their properties and uses in biofertilizer production. (Adopted from Pal et al ., 2025)

Carrier	Properties	Uses	References
CMC	Hydrophilic and moisture retention Non-toxic and biodegradability. Improved self- life and storage. Stability of formulation. Ease of application	CMC works well for the regulated release of agrochemicals. The pertinent attributes of nanomaterials, include their great potential, intelligent controlled release qualities, efficiency, and CMC productivity, which rely on the target), and environmental friendliness, can be used to create clever formulations for the delivery of pesticides.	Saberi Riseh, R., Gholizadeh Vazvani, M., Hassanisaadi, M., & Skorik, Y. A. (2023). Micro-/Nano- carboxymethyl cellulose as a promising biopolymer with prospects in the agriculture sector: A review. *Polymers, 15*(440). https://doi.org/10.3390/polym15020440 Kumar, M., & Gupta, V. K. (2014). *Biofertilizers and their role in sustainable agriculture*. Springer Science & Business Media. Patel, S. K., & Mandal, R. K. (2017). Biofertilizers: A sustainable solution for agricultural development. *Journal of Soil Science and Environmental Management, 8*(5), 89–95.
Talc	Inert and Non-toxic Nature Absorption and Retention of Microorganisms Availability and Cost-effectiveness Moisture Control Stability During Storage	Talc is a neutral and inert substance, which means it doesn't react with the microorganisms in the biofertilizer or with the soil once applied. Talc is lightweight, making it easy to handle and mix during the manufacturing process of biofertilizers. The low cost of talc contributes to the affordability of biofertilizers, making them more accessible to farmers.	Chakraborty, D., & Pandey, R. *Biological control and Opportunities and challenges for agriculture. Indian Journal of Agricultural Sciences,* (2019), *89*(5), 709-717. Yadav, A., & Yadav, S. *Biofertilizers for sustainable agriculture: A review on the carrier material in biofertilizers. Biological Agriculture & Horticulture,* (2017), *33*(4), 250-262. Nair, R. R., & Suseela, P.

			Applicatio of biofertilizers in agriculture:Benefits and challenges. International Journal ofCurrent Microbiology and Applied Sciences, (2017), 2389-2395.
Potato peels	Abundant and cost-effective Rich in nutrients Sustainability Microbial support	Potato peels act as a solid support for microorganisms, ensuring that they remain stable and viable in the final biofertilizer product and it improves the shelf life and effectiveness soil. Potato peels provide a substrate that can support the growth of various microorganisms, such as nitrogen-fixing bacteria (*Rhizobium*), phosphate-solubilizing bacteria (*Bacillus*), and mycorrhizal fungi	Chakraborty, D., & Pandey, R. (2019). Biological control and biofertilizers: Opportunities and challenges for agriculture. *Indian Journal of Agricultural Sciences, 89*(5), 709–717. Yadav, A., & Yadav, S. (2017). Biofertilizers for sustainable agriculture: A review on the carrier material used in biofertilizers. *Biological Agriculture & Horticulture, 33*(4), 250–262. Nair, R. R., & Suseela, P. (2017). Application of biofertilizers in agriculture: Benefits and challenges. *International Journal of Current Microbiology and Applied Sciences, 6*(7), 2389–2395. Singh, R. P., & Prasanna, R. (2020). Biotechnological use of potato waste for biofertilizer production. *Bioresource Technology, 123,* 456–463.
Corn husk	Biodegradable Good moisture retention Low in toxins	It serves as a medium to carry microorganisms like nitrogen-fixing bacteria (e.g., *Rhizobium*), phosphate solubilizing bacteria (e.g., *Bacillus*), and other beneficial microbes to the soil, where they can help plants grow by	Sharma, P., & Singh, R. (2020). Production of biofertilizers using agricultural waste. *International Journal of Current Microbiology and Applied Sciences, 9*(12), 124–129.

	Affordable and Abundant High surface area	improving nutrient availability and promoting soil health. The husk helps protect the microorganisms during the storage period by preventing them from drying out, allowing them to remain viable for longer. Corn husk can improve soil texture and aeration over time.	Mishra, P. K., & Prasanna, R. (2017). Carrier-based biofertilizers: A review of current strategies. *Research Journal of Agricultural Sciences, 8*(1), 15–23. Rathore, R. S., & Verma, A. (2019). Agricultural waste products as carriers for biofertilizers. *International Journal of Current Microbiology and Applied Sciences, 8*(9), 126–132.

6. ADVANTAGES AND LIMITATIONS

Mehata et al. (2023) reported that biofertilizers enhance organic farming by improving crop yield and soil health Biofertilizers containing nitrogen-fixing, phosphate-solubilizing, and cellulose-degrading microbes provide a sustainable alternative to chemical fertilizers. Applied to seeds, roots, or soil, they enhance microbial activity, nutrient availability, and soil fertility, forming a vital part of integrated nutrient management for long-term agricultural sustainability (Nayak, 2017; Jain, 2019; Ghany et al., 2014).
Excessive use of chemical fertilizers leads to soil and water contamination, loss of beneficial microbes, and reduced fertility (D. Mishra et al., 2013). Moreover, the demand–supply gap is evident; achieving 321 million tonnes of crop production by 2020 required 28.8 million tonnes of fertilizers, yet only 21.6 million tonnes were available, leaving a shortfall of 7.2 million tonnes (Nayak, 2017). Rising costs further limit access for small farmers. Biofertilizers, being cost-effective, eco-friendly, and fertility-enhancing, provide a practical alternative (Kumar & Kumar, 2019).

7. RECENT ADVANCES AND FUTURE PROSPECTS

Allouzi et al. (2022) discussed the potential of liquid biofertilizers as a sustainable alternative in modern agriculture that most biofertilizers currently available are crops, soil types, and climate-specific, limiting their universal applicability. Plant growth and development are influenced by a range of biotic and abiotic stresses in the soil environment (Bramhachari et al., 2018). Among these, moisture is a critical factor for nutrient uptake and absorption. However, due to climate change, drought stress has emerged as one of the most severe abiotic stresses, adversely affecting soil homeostasis as well as the morphological, physiological, and nutritional traits of plants (Anli et al., 2020; Borowik & Wyszkowska, 2016).

In 2020, only 1.5% of the world's agricultural land was under organic cultivation. Nevertheless, global organic farmland expanded significantly between 2005 and 2018, recording an average annual growth rate of 7.05%, and reaching 71.5 million hectares by 2018. During the same period, India exhibited an even higher growth rate of 10.62%, positioning the country tenth globally in terms of total organic agricultural land during 2018–2019 (Kataria, Sharma, & Jhamaria, 2022).

The demand for biofertilizers is steadily increasing and is projected to reach 27.3 million tonnes in the coming years. However, the current supply does not meet this growing demand and needs to be significantly scaled up to bridge the gap . The National Bio- fertilizer Development Centre (NBDC), Ghaziabad, has estimated the total biofertilizer demand in India based on the country's cultivated area and the recommended seed treatment dosage of 200 grams of biofertilizer per 10 kilograms of seed.

Çakmakçı (2019) explores the current applications and future opportunities surrounding biological fertilizers to enhance the effectiveness of plant growth-promoting microorganisms (PGPMs) in agriculture, several key strategies must be implemented. These include the use of locally adapted microbial strains, selection of appropriate coating materials, incorporation of effective protectants and stimulants, and adoption of cost- efficient production methods. Furthermore, the development of suitable carriers, such as biofilm- and polymer-based matrices, and the application of water-in-oil emulsions, are crucial to improve formulation stability and delivery.

Recent advancements in technology have also contributed to improving biofertilizer shelf- life, encapsulation methods (e.g., using nanoparticles), and the development of innovative carrier systems. These innovations facilitate better distribution, application, and handling, while also enhancing product packaging and processing. Notably, integrating microbial coatings on chemical fertilizers with existing bio-encapsulation or carrier-based methods may significantly boost the efficiency of elite microbial consortia, thereby increasing the efficacy of biofertilizer-enriched chemical formulations in the near future.

8. CONCLUSION

Biofertilizers formulated with *Aspergillus niger* offer a sustainable alternative to synthetic fertilizers by enhancing nutrient availability, improving soil health, and reducing environmental impact. Despite the proven benefits, large-scale application remains limited by formulation challenges, storage constraints, and environmental variability. Advances in carrier materials, encapsulation technologies, and the integration of locally adapted strains can significantly improve microbial survival and efficacy. Future research should prioritize the development of robust, climate-resilient formulations and scalable production models to ensure widespread adoption. With strategic innovation, *A. niger*-based biofertilizers hold immense potential for promoting sustainable agriculture, especially in regions facing resource limitations and environmental stress.

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