2026 Volume: 02 Issue: 04 www.ijrpa.com ISSN 2456-9995 Research Article

International Journal Research Publication Analysis

Page: 01-20

BIOTECHNOLOGICAL ADVANCES IN THE COMMERCIAL PRODUCTION OF ARBUSCULAR MYCORRHIZAL FUNGI: CHALLENGES AND FUTURE PROSPECTS

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Article Received: 26 February 2026
Article Revised: 16 March 2026
Published on: 06 April 2026

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DOI: https://doi-doi.org/101555/ijrpa.1982

ABSTRACT

Arbuscular mycorrhizal fungi (AMF) represent a cornerstone of sustainable agriculture owing to their pivotal role in enhancing plant nutrient acquisition, improving tolerance to abiotic and biotic stresses, and maintaining soil ecological balance. Despite their well-established agronomic benefits, large-scale commercial production of AMF inoculants remains constrained by intrinsic biological limitations, particularly their obligate symbiotic nature, as well as technological and regulatory challenges. Recent advances have significantly improved production efficiency through the development of substrate-based cultivation systems, in vitro root organ culture (ROC), and emerging bioreactor-assisted technologies, enabling enhanced inoculum quality and scalability. Concurrently, innovations in formulation strategies, including carrier optimization and the development of multi-microbial consortia, have contributed to improved shelf life, stability, and field performance. However, challenges related to product standardization, variability in field efficacy, and regulatory inconsistencies continue to limit widespread commercialization. This review critically evaluates recent developments (2024–2025) in AMF production technologies, identifies key constraints, and highlights future opportunities for improving production efficiency, formulation strategies, and application practices. Addressing these challenges will be essential for realizing the full potential of AMF as next-generation biofertilizers in sustainable and climate-resilient agricultural systems.

KEYWORDS: Arbuscular mycorrhizal fungi (AMF); biofertilizers; commercial production; root organ culture; bioreactor systems; inoculum standardization; microbial consortia; sustainable agriculture

1. INTRODUCTION

Arbuscular mycorrhizal fungi (AMF), belonging to the phylum Glomeromycota, are ubiquitous soil microorganisms that establish mutualistic associations with the roots of nearly 80–90% of terrestrial plant species (Smith and Read 2008; Brundrett and Tedersoo 2018). Through this symbiosis, AMF enhance plant nutrient acquisition, particularly phosphorus uptake, while receiving photosynthetically derived carbon from the host plant. In addition to nutrient mobilization, AMF play a critical role in improving plant tolerance to abiotic stresses such as drought, salinity, and heavy metal toxicity, and in providing protection against soil-borne pathogens (Begum et al. 2019; Yang et al. 2021). These multifunctional attributes underscore the ecological and agronomic significance of AMF in sustainable agricultural systems.

Growing environmental concerns associated with excessive use of chemical fertilizers, including soil degradation, nutrient imbalance, and groundwater contamination, have intensified the search for eco-friendly and sustainable alternatives (Tilman et al. 2002; Savci 2012). In this context, AMF-based biofertilizers have emerged as promising tools for enhancing crop productivity, nutrient use efficiency, and soil health while reducing dependency on synthetic inputs (Chen et al. 2018; Berruti et al. 2016). Numerous studies have demonstrated that AMF inoculation can significantly improve plant growth and yield across a wide range of crops and agroecological conditions.

Despite their considerable potential, the large-scale commercial production of AMF remains a major challenge. A key limitation is their obligate biotrophic nature, which requires a living host for growth and reproduction, thereby precluding conventional axenic fermentation methods used for other microbial inoculants (Ijdo et al. 2011; Vosátka et al. 2012). Consequently, AMF production relies on specialized systems such as substrate-based pot cultures, in vitro root organ culture (ROC), and more recently, bioreactor-assisted technologies. While these approaches have advanced significantly, each is associated with limitations related to scalability, cost, contamination risk, and variability in inoculum quality (Declerck et al. 2005; IJdo et al. 2011).

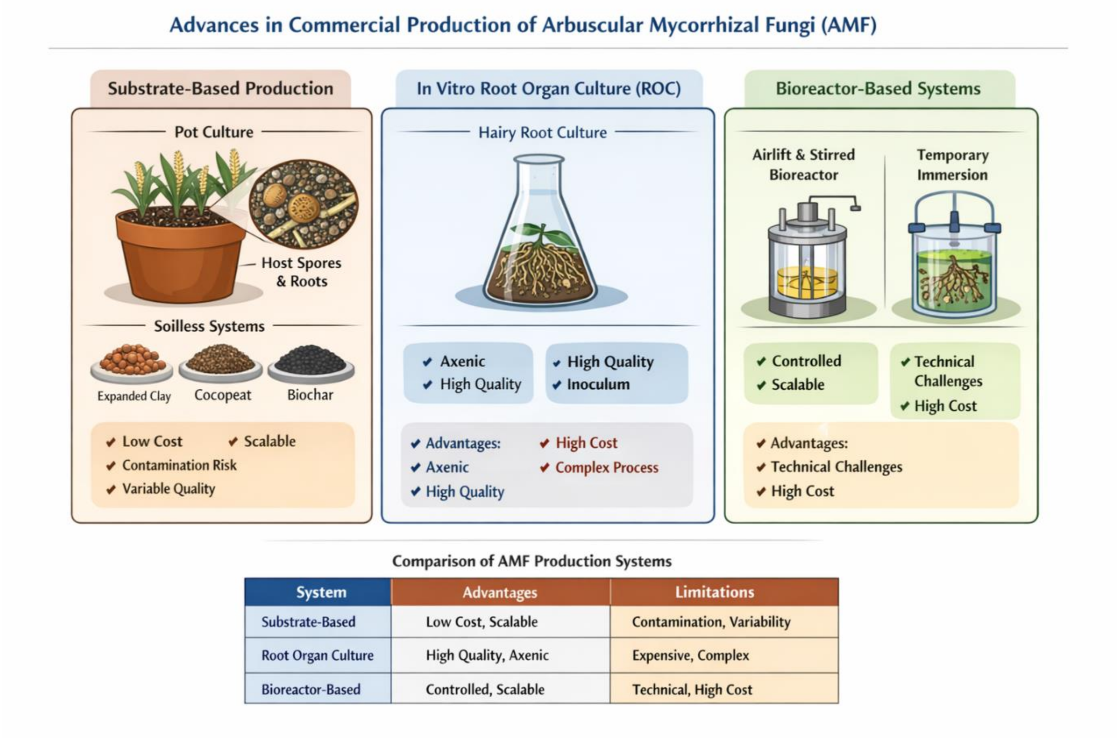
Another major constraint is the inconsistency in field performance of commercial AMF inoculants. Variations in strain compatibility, soil conditions, native microbial communities, and formulation quality often result in unpredictable outcomes under field conditions (Hart et al. 2015; Pellegrino et al. 2015). Additionally, the absence of standardized protocols for production, quality control, and regulatory approval further hinders the commercialization and widespread adoption of AMF-based products.

Recent advances have focused on improving production technologies and formulation strategies to enhance inoculum quality, shelf life, and field efficacy. Developments in carrier materials, multi-strain consortia, and integrated nutrient management approaches have expanded the applicability of AMF across diverse cropping systems (Berruti et al. 2016; Chandran et al. 2021). Nevertheless, significant challenges remain in achieving cost-effective, scalable, and standardized production systems.

This review aims to provide a comprehensive overview of recent advances in the commercial production of AMF, focusing on production systems, formulation technologies, and associated challenges. It further highlights future perspectives for improving production efficiency and ensuring consistent performance of AMF-based biofertilizers in sustainable agriculture.

2. Advances in Commercial Production of Arbuscular Mycorrhizal Fungi

The commercial production of arbuscular mycorrhizal fungi (AMF) remains inherently complex due to their obligate biotrophic nature, requiring association with a living host for growth and reproduction. This biological constraint has limited the application of conventional fermentation technologies commonly used for other microbial inoculants. Over the past decades, several production systems have been developed to overcome these limitations, each offering distinct advantages and trade-offs in terms of scalability, cost-effectiveness, and inoculum quality (Ijdo et al. 2011; Berruti et al. 2016). Broadly, AMF production systems can be classified into substrate-based methods, in vitro root organ culture (ROC), and bioreactor-assisted technologies (fig 1).



System	Advantages	Limitations
Substrate-Based	Low Cost, Scalable	Contamination, Variability
Root Organ Culture	High Quality, Axenic	Expensive, Complex
Bioreactor-Based	Controlled, Scalable	Technical, High Cost

2.1 Substrate-Based Production Systems

Substrate-based systems remain the most widely adopted approach for large-scale AMF inoculum production. These systems involve the cultivation of host plants in soil or inert substrates such as sand, vermiculite, perlite, or soil–sand mixtures inoculated with AMF propagules (Smith and Read 2008). Their widespread use is primarily attributed to their simplicity, low cost, and adaptability to on-farm production conditions.

2.1.1 Conventional Pot Culture

In conventional pot culture systems, host plants such as maize, sorghum, or clover are grown under controlled or semi-controlled conditions. AMF colonize the plant roots and proliferate in the rhizosphere, producing spores, hyphae, and colonized root fragments that serve as inoculum.

Advantages:

- Simple and cost-effective
- Suitable for large-scale and on-farm production
- Minimal infrastructure requirements

Limitations:

- High risk of microbial contamination
- Significant variability in inoculum quality

- Long production cycles

Despite these limitations, pot culture systems continue to dominate in developing regions due to their economic feasibility and ease of implementation (Vosátka et al. 2012).

2.1.2 Soilless and Substrate-Optimized Systems

Recent advancements have focused on improving substrate-based production through the use of inert or semi-synthetic materials such as expanded clay, cocopeat, and biochar. These substrates enhance aeration, water retention, and ease of spore recovery, thereby improving overall production efficiency (Berruti et al. 2016; Chandran et al. 2021).

Such systems offer:

- Improved uniformity of inoculum
- Reduced contamination risks
- Enhanced spore density and recovery

However, these approaches still depend on host plants and remain sensitive to environmental variability, which can influence production outcomes.

2.2 In Vitro Root Organ Culture (ROC) Systems

Root organ culture (ROC) represents a major technological advancement in AMF production, enabling axenic cultivation under controlled laboratory conditions. This system utilizes transformed “hairy roots” induced by *Agrobacterium rhizogenes*, which can grow independently of the whole plant while maintaining the ability to support AMF colonization (Declerck et al. 2005).

2.2.1 Hairy Root-Based Culture

In ROC systems, excised roots are transformed and maintained in sterile nutrient media, followed by inoculation with AMF spores. Successful colonization leads to the formation of intraradical structures and the production of extraradical mycelium and spores.

Advantages:

- Axenic (contamination-free) production
- High-quality and uniform inoculum
- Excellent reproducibility and standardization

Limitations:

- High operational and infrastructure costs
- Technical complexity
- Limited scalability for bulk production

ROC systems are particularly valuable for research purposes and the production of high-quality inoculum, although their industrial application remains constrained (Ijdo et al. 2011).

2.2.2 Advanced In Vitro Systems (MDP and HAM-P)

Emerging in vitro systems such as Mycorrhizal Donor Plant (MDP) and Half-closed AMF–plant (HAM-P) systems have been developed to enhance colonization efficiency and enable semi-continuous production.

These systems:

- Improve host–fungus interaction efficiency
- Allow sustained inoculum production

However, they remain:

- Labor-intensive
- Space-demanding
- Technologically immature for large-scale commercialization

2.3 Bioreactor-Based Production Systems

Bioreactor-based systems represent the next generation of AMF production technologies, integrating biological and engineering principles to enhance scalability, automation, and process control.

2.3.1 Liquid-Assisted Root Culture Systems

These systems combine ROC techniques with liquid media, providing improved nutrient availability and controlled growth conditions. They facilitate enhanced fungal proliferation and enable better manipulation of environmental parameters.

Advantages:

- Controlled nutrient and environmental conditions
- Improved fungal growth dynamics

Limitations:

- Oxygen transfer limitations
- Sensitivity of roots and hyphae to shear stress

2.3.2 Airlift and Stirred Bioreactors

Airlift bioreactors are particularly suitable for AMF production due to their low shear stress and efficient gas exchange. These systems support delicate root–fungus interactions while enabling process automation and monitoring.

Key benefits include:

- Enhanced reproducibility
- Improved scalability
- Real-time process control

However, challenges remain in optimizing:

- Hydrodynamic conditions
- Root anchorage and stability
- Efficient fungal colonization

(Berruti et al. 2016).

2.3.3 Temporary Immersion Systems (TIS)

Temporary immersion systems (TIS) provide intermittent exposure of roots to liquid media, improving oxygenation and nutrient uptake while minimizing waterlogging and contamination risks.

These systems:

- Enhance biomass and spore production
- Improve aeration and metabolic efficiency
- Reduce contamination compared to static systems

TIS holds considerable promise for scaling up AMF production, although further optimization is required.

2.4 Comparative Evaluation of Production Systems

Production System	**Advantages**	**Limitations**
Substrate-based systems	Low cost, scalable, simple	Contamination risk, variability
Root organ culture	High-quality, axenic,	Expensive, technically

(ROC)	reproducible	demanding
Bioreactor systems	Controlled, scalable, automated	High cost, technical challenges

Quantitative Comparison of AMF Production Systems

Parameter	**Substrate-Based**	**ROC**	**Bioreactor**	**Remarks**
Spore yield	50–500 spores g^{-1}	1000–5000/plate	2–10× ROC	Varies with system
Production time	8–16 weeks	4–8 weeks	3–6 weeks	Faster in controlled systems
Contamination risk	High	Very low	Low	Axenic in ROC
Scalability	High	Moderate	High (emerging)	Industrial potential
Cost	Low	High	Very high	Tech dependent

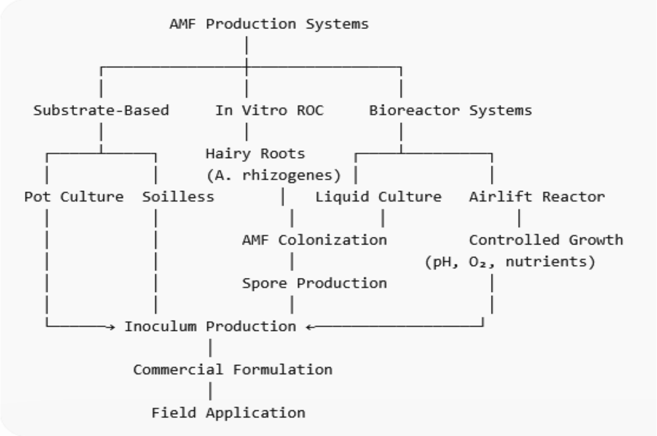
2.5 Key Challenges in Production Systems

Despite significant progress, several constraints continue to limit the efficiency and scalability of AMF production systems:

- The obligate symbiotic nature of AMF restricts independent growth and limits fermentation-based approaches
- Scalability challenges persist in controlled systems such as ROC and bioreactors
- Inoculum quality remains inconsistent in substrate-based production systems
- High capital and operational costs hinder adoption of advanced technologies

Addressing these challenges will be critical for developing reliable, standardized, and economically viable production systems capable of supporting the large-scale commercialization of AMF inoculants.

Flow diagram for AMF Production Pathways



3. Advances in Formulation Technologies and Shelf Life of AMF Inoculants

The commercial success of arbuscular mycorrhizal fungi (AMF) as biofertilizers is strongly dependent on the development of effective formulation strategies that ensure high propagule viability, ease of handling and application, and extended shelf life. Unlike free-living microorganisms, AMF propagules—including spores, hyphae, and colonized root fragments—are highly sensitive to environmental conditions, making formulation and storage critical determinants of product performance and market acceptance (Berruti et al. 2016).

3.1 Types of AMF Formulations

3.1.1 Solid Carrier-Based Formulations

Solid carrier-based formulations remain the most widely utilized commercial products. These formulations involve blending AMF propagules with carriers such as peat, vermiculite, perlite, clay, or biochar, which serve as protective matrices.

These carriers provide:

- Physical protection to propagules
- Moisture retention capacity
- Nutrient buffering properties

Recent studies have demonstrated that **biochar- and clay-based carriers** can significantly enhance spore survival and stability during storage (Kumutha et al. 2023).

Limitations:

- Bulky nature leading to higher transportation costs
- Susceptibility to contamination
- Gradual decline in propagule viability over time

3.1.2 Liquid Formulations

Liquid formulations represent an emerging and increasingly attractive alternative due to their operational advantages.

Key features include:

- Ease of application via seed treatment or fertigation
- Uniform distribution in soil systems
- Lower risk of contamination during application

Typically, these formulations contain suspended spores or colonized root fragments, along with stabilizers and protective additives. However, maintaining long-term viability in liquid systems remains challenging due to continuous metabolic activity and oxygen limitations (Kumutha et al. 2023).

3.1.3 Encapsulated and Gel-Based Formulations

Encapsulation technologies, such as alginate bead entrapment and polymer-based matrices, have gained considerable attention for improving AMF stability and delivery efficiency.

Advantages include:

- Protection from desiccation and environmental stress
- Controlled and sustained release of propagules
- Enhanced shelf life and field persistence

Encapsulation also enables targeted delivery of AMF inoculum to the rhizosphere, thereby improving colonization efficiency.

3.1.4 Seed-Coating and Granular Formulations

Seed coating with AMF inoculum is an innovative approach that allows direct placement of propagules in close proximity to emerging roots.

Benefits include:

- Reduced inoculum requirement
- Improved early root colonization
- Simplified application process

Evidence suggests that seed-coat formulations can enhance propagule survival during storage and improve field performance compared to conventional carrier-based systems (Kumutha et al. 2023).

3.1.5 Multi-Microbial Consortia

Recent advances have focused on developing composite formulations combining AMF with beneficial microorganisms such as plant growth-promoting rhizobacteria (PGPR) and phosphate-solubilizing bacteria.

These consortia:

- Enhance nutrient mobilization and uptake
- Improve plant growth and stress tolerance
- Increase overall biofertilizer efficacy

However, maintaining compatibility, stability, and functional synergy among multiple microbial partners remains a significant formulation challenge (Kumutha et al. 2023).

3.2 Factors Affecting Shelf Life of AMF Inoculants

3.2.1 Storage Temperature and Moisture

Temperature and moisture are the most critical factors influencing AMF survival during storage.

- Low temperatures can induce dormancy, thereby prolonging shelf life
- Elevated temperatures accelerate metabolic degradation and reduce viability

Recent findings indicate that controlled low-temperature storage conditions significantly enhance AMF longevity and infectivity (Koziol et al. 2025).

3.2.2 Carrier Material and Formulation Type

The physicochemical properties of carriers—including porosity, water-holding capacity, and nutrient composition—directly influence propagule survival.

For example:

- Vermiculite-based formulations can maintain high infectivity for several months under optimal conditions
- Powder-based carriers such as talc, clay, and biochar improve long-term stability (Kumutha et al. 2023)

3.2.3 Storage Duration

Shelf life is inherently limited by the gradual decline in propagule viability and infectivity over time. Nevertheless, recent studies indicate that AMF inoculum can retain functional efficiency under controlled storage conditions, although colonization potential may decrease with prolonged storage (Falcão et al. 2025).

3.2.4 Oxygen Availability and Metabolic Activity

In liquid formulations, oxygen availability is a critical factor affecting propagule viability. Excessive metabolic activity during storage can:

- Deplete energy reserves
- Reduce germination potential
- Accelerate viability loss

3.2.5 Contamination and Microbial Interactions

Contamination by unwanted microorganisms poses a significant risk to AMF inoculum quality. Competing microbes may:

- Reduce propagule viability
- Alter nutrient availability
- Compromise formulation stability

Although axenic systems such as ROC-derived inoculum minimize contamination risks, they increase production costs and complexity.

3.3 Strategies to Improve Shelf Life

Recent advancements in formulation science have focused on extending the shelf life and functional stability of AMF inoculants through:

- Use of advanced carrier materials (e.g., biochar, polymer matrices)
- Encapsulation and controlled-release technologies
- Optimization of moisture content and drying protocols
- Low-temperature and controlled-atmosphere storage
- Incorporation of stabilizers and protective additives

These strategies aim to maintain high propagule viability, infectivity, and field performance over extended storage periods.

3.4 Challenges in Formulation Development

Despite notable progress, several challenges continue to limit the effectiveness of AMF formulations:

- Lack of standardized formulation protocols
- Significant variability in product quality across manufacturers
- Reduced shelf life under tropical and subtropical conditions
- Difficulties in maintaining viability during transportation and storage

These limitations directly impact product reliability, farmer confidence, and large-scale adoption.

3.5 Future Perspectives

Future research efforts should focus on:

- Development of next-generation carrier materials with enhanced protective properties
- Advanced encapsulation and targeted delivery systems
- Standardization of quality control and shelf-life assessment protocols
- Integration of formulation strategies with production technologies

Improving formulation stability and shelf life will be essential for ensuring the commercial viability and global adoption of AMF-based biofertilizers in sustainable agriculture.

4. Challenges and Constraints in Commercial Production of AMF

Despite substantial advances in production technologies and formulation strategies, the large-scale commercialization of arbuscular mycorrhizal fungi (AMF) remains constrained by a complex interplay of biological, technological, ecological, and regulatory factors. These limitations not only hinder production efficiency but also compromise product consistency, reliability, and field performance, thereby restricting widespread adoption in modern agricultural systems.

4.1 Biological Constraints: Obligate Symbiosis and Host Dependency

A fundamental limitation in AMF production arises from their obligate biotrophic nature, which necessitates a living host plant for growth and reproduction. Unlike free-living microorganisms, AMF cannot be cultured independently in synthetic media, thereby precluding the use of conventional fermentation technologies (Ijdo et al. 2011; Declerck et al. 2005).

This biological dependency results in:

- Prolonged production cycles
- Limited scalability of production systems
- Increased operational and production costs

Furthermore, variability in host specificity and plant–fungus compatibility complicates the selection of optimal host systems for efficient inoculum production, particularly at industrial scales.

4.2 Variability in Field Performance

Inconsistent field performance remains one of the most critical barriers to the successful commercialization of AMF inoculants. While controlled experimental conditions frequently demonstrate significant agronomic benefits, these outcomes are often not reproducible under heterogeneous field environments (Hart et al. 2015; Pellegrino et al. 2015).

Key factors contributing to this variability include:
- Soil physicochemical properties
- Indigenous AMF and microbial communities
- Climatic and environmental conditions
- Crop genotype and agronomic practices

In many cases, introduced AMF strains fail to establish or effectively compete with native populations, resulting in limited or inconsistent plant growth responses.

4.3 Inoculum Quality and Lack of Standardization

The absence of universally accepted standards for AMF inoculum quality represents a major bottleneck in commercialization. Commercial products often exhibit substantial variability in:
- Spore density
- Viability and infectivity
- Purity and contamination levels

Evidence indicates that some commercial inoculants contain low propagule counts or non-viable spores, leading to suboptimal field performance (Berruti et al. 2016). Additionally, inconsistencies in production protocols, carrier materials, and storage conditions further exacerbate variability in product quality and reliability.

4.4 Technological and Scale-Up Limitations

Although advanced production systems such as root organ culture (ROC) and bioreactor-based technologies offer improved control and inoculum quality, their large-scale implementation remains challenging.

Major constraints include:
- High capital investment and operational costs
- Technical complexity and specialized expertise requirements
- Sensitivity of AMF and host roots to environmental fluctuations

In bioreactor systems, specific challenges include:

- Optimization of oxygen transfer and nutrient delivery
- Minimization of shear stress on delicate fungal structures
- Maintenance of stable root–fungus symbiosis

Consequently, the transition from laboratory-scale systems to industrial-scale production remains a significant hurdle (Ijdo et al. 2011).

4.5 Shelf Life and Storage Constraints

AMF propagules are highly sensitive to environmental conditions, resulting in limited shelf life of commercial formulations. Critical factors influencing storage stability include temperature, moisture content, and oxygen availability, all of which directly affect:

- Spore viability
- Germination potential
- Infectivity

Under tropical and subtropical conditions, rapid decline in propagule viability is commonly observed, posing significant challenges for storage, transportation, and distribution (Kumutha et al. 2023).

4.6 Ecological and Environmental Constraints

The introduction of non-native AMF strains into agricultural ecosystems raises important ecological concerns. These include:

- Potential displacement of indigenous AMF communities
- Alterations in soil microbial diversity and function
- Unpredictable ecological interactions

Moreover, the effectiveness of AMF inoculation is highly context-dependent, influenced by soil type, cropping systems, and environmental conditions (Brundrett and Tedersoo 2018). This ecological variability complicates the development of universally effective AMF products.

4.7 Regulatory and Certification Challenges

The regulatory landscape for AMF-based biofertilizers remains fragmented and inconsistent across different regions. Key challenges include:

- Absence of standardized quality benchmarks

- Inadequate certification and quality assurance systems
- Weak enforcement of regulatory frameworks

These gaps have contributed to the proliferation of substandard and counterfeit products, undermining farmer confidence and limiting market growth (Kumutha et al. 2023).

4.8 Economic and Market Constraints

Economic considerations play a critical role in the adoption of AMF technologies. The commercialization of AMF inoculants is constrained by:

- High production costs, particularly for advanced systems such as ROC and bioreactors
- Limited awareness and technical knowledge among farmers
- Uncertainty regarding cost–benefit outcomes

As a result, farmers often remain hesitant to adopt AMF-based products, especially when immediate economic returns are not evident.

4.9 Knowledge Gaps and Research Limitations

Despite extensive research efforts, several critical knowledge gaps persist:

- Limited understanding of AMF–plant–soil interactions under field conditions
- Lack of predictive frameworks for assessing inoculation success
- Insufficient long-term, multi-location field studies

Addressing these gaps is essential for improving the predictability, consistency, and effectiveness of AMF-based technologies.

4.10 Critical Perspective

The challenges outlined above underscore a fundamental paradox in AMF commercialization: although the ecological and agronomic potential of AMF is well established, its translation into reliable, scalable, and economically viable agricultural solutions remains incomplete.

Overcoming these constraints will require:

- Integration of multidisciplinary approaches encompassing microbiology, agronomy, and bioprocess engineering
- Development of standardized production, formulation, and quality control protocols
- Strengthening of regulatory frameworks and certification systems
- Enhanced farmer awareness, extension services, and field validation programs

A coordinated effort among researchers, industry stakeholders, and policymakers will be essential to bridge the gap between scientific potential and practical application, thereby enabling the successful commercialization of AMF-based biofertilizers.

5. Future Perspectives and Conclusions

5.1 Future Perspectives

The commercial utilization of arbuscular mycorrhizal fungi (AMF) is at a critical juncture, where advances in biological understanding and technological innovation offer unprecedented opportunities for transforming AMF into reliable and widely adopted biofertilizers. However, realizing this potential requires addressing existing bottlenecks through integrated and forward-looking approaches.

One of the foremost priorities is the development of standardized, scalable, and cost-effective production systems. While substrate-based methods will continue to play a role in low-cost production, there is an increasing need to refine in vitro and bioreactor-based systems to achieve industrial scalability. Advances in bioprocess engineering, including improved reactor design, optimized aeration systems, and controlled nutrient delivery, are expected to enhance production efficiency and consistency.

Equally important is the establishment of robust quality control and certification frameworks. The lack of standardized benchmarks for inoculum quality remains a major barrier to commercialization. Future efforts should focus on defining minimum thresholds for spore density, viability, infectivity, and purity, supported by validated analytical protocols. Harmonization of regulatory guidelines at national and international levels will be essential to ensure product reliability and facilitate global market expansion.

The development of next-generation formulation technologies represents another key area of advancement. Innovations in carrier materials, encapsulation techniques, and controlled-release systems are expected to improve shelf life, stability, and field performance of AMF inoculants. Integration of AMF with compatible microbial consortia, including plant growth-promoting rhizobacteria, offers additional opportunities for enhancing functional efficacy and broadening the spectrum of agronomic benefits.

A critical research priority lies in improving the predictability and consistency of field performance. This will require a deeper understanding of AMF–plant–soil interactions across diverse agroecological conditions. Long-term, multi-location field trials should be prioritized to evaluate the effectiveness of different AMF strains and formulations under real-world conditions. Additionally, the identification of context-specific inoculation strategies tailored to crop type, soil characteristics, and climatic conditions will enhance adoption and impact.

The integration of AMF into climate-resilient and sustainable agricultural systems is another promising avenue. AMF have the potential to contribute to carbon sequestration, improve soil structure, and enhance nutrient use efficiency, thereby supporting climate-smart agriculture. Their role in reducing dependency on chemical fertilizers aligns with global sustainability goals and environmental conservation strategies.

Furthermore, capacity building and farmer awareness will be critical for successful commercialization. Extension services, demonstration trials, and knowledge dissemination programs are needed to educate farmers about the benefits, application methods, and expected outcomes of AMF inoculation. Strengthening linkages between researchers, industry stakeholders, and policymakers will facilitate the translation of scientific advances into practical applications.

5.2 CONCLUSIONS

Arbuscular mycorrhizal fungi represent a cornerstone of sustainable agriculture, offering significant potential to enhance crop productivity, improve soil health, and reduce reliance on chemical inputs. Over the past decades, considerable progress has been made in developing production technologies, formulation strategies, and application methods for AMF inoculants. However, their large-scale commercialization continues to be constrained by biological limitations, technological challenges, variability in field performance, and regulatory inconsistencies.

This review highlights that while substrate-based production systems remain widely used, advanced approaches such as root organ culture and bioreactor-assisted technologies hold promise for improving inoculum quality and standardization. Similarly, innovations in formulation technologies are enhancing shelf life and delivery efficiency, although further refinement is needed to ensure long-term stability under diverse environmental conditions.

A critical barrier to widespread adoption is the inconsistency in field performance, which underscores the need for improved understanding of ecological interactions and context-specific application strategies. Addressing these challenges will require coordinated efforts in research, technology development, policy formulation, and stakeholder engagement.

In conclusion, the future success of AMF-based biofertilizers will depend on the ability to integrate advances in production, formulation, and field application with robust quality control systems and supportive regulatory frameworks. By overcoming current constraints and leveraging emerging opportunities, AMF have the potential to play a transformative role in advancing sustainable, resilient, and environmentally responsible agricultural systems.

ACKNOWLEDGEMENTS

The authors express their sincere gratitude to the Head, Department of Biological Sciences, Rani Durgawati University, Jabalpur, Madhya Pradesh, for providing the necessary facilities and support to carry out this work. Financial assistance received from the Council of Scientific and Industrial Research (CSIR), Government of India, is gratefully acknowledged.

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