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Role of Arbuscular Mycorrhizal Fungi (AMF) in Enhancing Phosphorus Uptake and Sustainable Crop Production

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***Abstract*—Phosphorus (P) is an essential macronutrient, yet its availability in soils is often limited due to fixation in insoluble forms. Arbuscular Mycorrhizal Fungi (AMF) form symbiotic associations with plant roots, extending hyphal networks that mobilize inaccessible phosphorus, enhance nutrient uptake, and improve plant growth. This review synthesizes recent literature (2023–2025) on AMF mechanisms, multi-crop benefits, environmental factors affecting their efficiency, and emerging strategies such as multi-strain inoculants and precision agriculture integration. Data from groundnut, wheat, soybean, and maize demonstrate the crucial role of AMF in sustainable, climate-resilient crop production.**

***Index Terms*—Arbuscular mycorrhizal fungi, phosphorus, biofertilizers, groundnut, wheat, soybean, maize, sustainable agriculture, precision farming**

I. INTRODUCTION

Phosphorus is the second most vital macronutrient for plants, involved in energy transfer (ATP), nucleic acid synthesis, membrane formation, and signalling (Pan et al., 2023). Although abundant in soils, only 1–3% of total P is available due to fixation as Ca–P, Fe–P, or Al–P complexes. Excessive chemical fertilizer application is inefficient, with only 15–25% utilized by crops, leading to environmental issues such as eutrophication and soil degradation (García-Berumen et al., 2025).

AMF enhance plant phosphorus acquisition by extending hyphal networks beyond root depletion zones, solubilizing inorganic and organic P, and stimulating rhizosphere microbial communities that further improve nutrient turnover (Wang et al., 2023; Sun et al., 2025). Additionally, AMF improve soil structure, water uptake, and resilience to abiotic stresses, making them integral to sustainable agriculture.

II. MECHANISMS OF PHOSPHORUS UPTAKE BY AMF

2.1 Hyphal Network Expansion

AMF hyphae penetrate beyond the root zone, accessing P unavailable to roots. Hyphal extension increases surface area for absorption and improves P mobility from soil micropores (Peng et al., 2025).

2.2 Enzymatic Mineralization

AMF secrete phosphatases and acid phosphatases to mineralize organic P compounds such as phytates, converting them into bioavailable orthophosphate forms (Sun et al., 2025).

2.3 Rhizosphere Interactions

AMF modify root exudation patterns and recruit beneficial P-solubilizing bacteria, enhancing nutrient availability (Wang et al., 2023). AMF also regulate plant P transporter genes (e.g., Pht1 family), improving uptake under low P or saline stress conditions (Peng et al., 2025).

2.4 Environmental Factors

Soil pH (5.5–7.5), temperature (25–30°C), organic matter, and moisture strongly influence AMF colonization and efficiency (Sun et al., 2025; Wang et al., 2023).

Table 1: Mechanisms of Phosphorus Mobilization by AMF

Process	Description	Outcome
Hyphal Network Expansion	Hyphae extend beyond roots to inaccessible P zones	Increased P acquisition
Enzymatic Mineralization	Phosphatases convert organic P to inorganic forms	Increased bioavailable P
Rhizosphere Recruitment	Stimulate P-solubilizing bacteria	Enhanced nutrient cycling
Gene Regulation	Upregulation of plant P transporters	Improved P uptake efficiency

III. AGRICULTURAL SIGNIFICANCE OF AMF

3.1 Crop Yield Enhancement

AMF inoculation improves root architecture, nutrient uptake, biomass, and yield across crops (Sun et al., 2025). Multi-crop meta-analysis:

Crop	Yield Increase (%)	P Uptake Increase (%)	Reference
Groundnut	10–25	20–35	Das Mohapatra et al., 2024
Wheat	15–30	25–40	Sun et al., 2025
Soybean	20–35	30–45	Peng et al., 2025
Maize	12–28	18–38	Wang et al., 2023

3.2 Soil Health Improvement

AMF enhance soil microbial activity, aggregate formation, and carbon sequestration through glomalin production, contributing to long-term soil fertility (Zhu et al., 2024).

3.3 Reduction in Chemical Fertilizer Dependence

AMF inoculation can reduce P fertilizer use by 20–30% without compromising crop yield (García-Berumen et al., 2025).

IV. MULTI-STRAIN AND COMBINED BIOFERTILIZERS

Combining AMF with phosphate-solubilizing bacteria or multi-strain AMF inoculants increases P uptake consistency and yield stability under varying soil conditions (Shahzad et al., 2025). Functional synergy includes:

- Acidification of rhizosphere
- Mineralization of organic P
- Enhanced root colonization

Table 2: Multi-Strain AMF vs Single-Strain

Inoculum Type	P Uptake (mg/kg soil)	Relative Increase
Single-strain AMF	210–250	Baseline
Multi-strain consortium	420–480	+100–120%

V. INTEGRATION WITH PRECISION AGRICULTURE

Precision agriculture enables site-specific AMF inoculation using soil sensors, GIS mapping, and drones, optimizing inoculum placement for maximum P uptake and minimal fertilizer use (García-Berumen et al., 2025).

VI. LIMITATIONS

- Environmental extremes (pH, moisture, salinity) reduce AMF activity
- Competition with indigenous microbes may limit colonization
- Shelf-life and inoculum formulation challenges (Hnini et al., 2025)

VII. FUTURE PROSPECTS

- Synthetic Microbial Consortia – Combine AMF with PGPR and P-solubilizers
- AI & Precision Agriculture – Predict optimal inoculation strategies
- Advanced Carriers – Nanoparticles, biochar, alginate to improve survival and field efficacy

VIII. CONCLUSION

AMF are key to sustainable agriculture, enhancing phosphorus use efficiency, crop productivity, soil health, and stress resilience. Multi-strain inoculants, precision agriculture, and AI integration offer promising avenues to scale up AMF-based biofertilization for global food security.

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