World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Research Article)

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Sustainable Agriculture: The Role of Arbuscular Mycorrhizae Fungi in Enhancing Plant Growth, Soil Health and Environmental Sustainability

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World Journal of Advanced Research and Reviews, 2025, 27(03), 1025-1038

Publication history: Received on 25 June 2025; revised on 14 September 2025; accepted on 17 September 2025

Article DOI: https://doi.org/10.30574/wjarr.2025.27.3.2549

Abstract

Arbuscular Mycorrhizal Fungi (AMF) are pivotal in enhancing plant growth, soil health, and agricultural sustainability. Their symbiotic relationship with plant roots allows for improved nutrient uptake, especially in nutrient-deficient soils, while also enhancing water retention and soil structure. As the global agricultural sector faces mounting challenges such as soil degradation, drought, and the over-reliance on chemical fertilizers, AMF offer a sustainable alternative to address these issues. This paper explores the role of AMF in sustainable agriculture, focusing on their contributions to reducing the need for chemical inputs, promoting healthier ecosystems, and improving crop resilience to environmental stressors. Case studies, particularly from Nigeria, highlight AMF's success in improving yields of staple crops such as maize, cassava, and rice, demonstrating their potential for revitalizing degraded soils and supporting organic farming systems. The integration of AMF into farming practices not only supports ecological balance but also enhances long-term food security by fostering a more resilient agricultural landscape.

Keywords: Arbuscular Mycorrhizal Fungi (AMF); Sustainable Agriculture; Soil Health; Crop Resilience; Environmental Stressors; Chemical Fertilizer Reduction

1. Introduction

1.1. Background on the challenges of sustainable agriculture

Sustainable agriculture refers to the practice of producing food, fibre, and other plant products in a manner that is environmentally responsible, economically viable, and socially beneficial(Grumbine, Xu and Ma, 2021). As the global population continues to grow, the demand for food production rises sharply, creating an urgent need for agricultural practices that can meet these demands while preserving the environment.(Gu, Andreev and Dupre, 2021; Boix-Fayos and de Vente, 2023) Traditional farming practices, which often rely heavily on chemical fertilizers, pesticides, and monoculture systems, have led to soil degradation, loss of biodiversity, and environmental pollution(Gallardo, 2024). There is therefore an increasing emphasis on finding innovative solutions that address the challenges of modern agriculture while promoting long-term environmental health.

One promising solution to achieve sustainable agricultural practices is the integration of microorganisms, particularly fungi and bacteria, into agricultural systems.

Microorganisms play a pivotal role in improving soil health, enhancing nutrient availability, and supporting plant growth, all of which are vital to the sustainability of agricultural ecosystems(White *et al.*, 2019; Fierer, Wood and de Mesquita, 2021). Among these microorganisms, Arbuscular mycorrhizal fungi (AMF) have attracted considerable

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attention due to their significant contribution to plant nutrition, soil structure, and environmental sustainability(Fall *et al.*, 2022).

1.2. The Need for Sustainable Agriculture

The growing global population, coupled with increasing urbanization and climate change, has placed immense pressure on agricultural systems to produce more food(Chandio *et al.*, 2020; Beillouin *et al.*, 2022). Traditional farming methods have led to various ecological issues, including soil erosion, reduced soil fertility, and increased dependency on chemical inputs. These practices not only harm the environment but also undermine the long-term productivity of agricultural land. Sustainable agriculture aims to balance food production with environmental conservation, ensuring that agricultural practices can meet the needs of the present without compromising the ability of future generations to meet their own needs(Ashitha and Rakhimol, 2021).

1.3. The Role of Microorganisms in Agriculture

Microorganisms, such as bacteria, fungi, and algae, are key players in maintaining the health and productivity of soils(Ortiz and Sansinenea, 2022). These microorganisms interact with plant roots, aiding in nutrient cycling, disease suppression, and the enhancement of plant growth. For example, nitrogen-fixing bacteria provide essential nitrogen to plants, while mycorrhizal fungi extend the root system to enhance nutrient and water uptake. The inclusion of microorganisms in agricultural practices can reduce the need for chemical inputs, improve soil fertility, and promote the resilience of crops to environmental stressors(Antoszewski, Mierek-Adamska and Dąbrowska, 2022; Aswani, Thomas and Radhakrishnan, 2022).

1.4. Introduction to Arbuscular Mycorrhizae Fungi (AMF)

Arbuscular Mycorrhizae Fungi (AMF) are a type of fungi that form symbiotic relationships with the roots of most terrestrial plants(Bhantana *et al.*, 2021). The word “mycorrhiza” is derived from the Greek words "mycos," meaning fungus, and "rhiza," meaning root. In this mutual relationship, AMF extend their hyphal networks into the soil, allowing plants to access nutrients, particularly phosphorus, which is often limited in many soils(Basiru, Ait Si Mhand and Hijri, 2023). In return, plants provide the fungi with carbohydrates derived from photosynthesis(Basyal and Walker, 2023; Gaši *et al.*, 2023). This symbiotic association benefits both organisms, as the fungi enhance nutrient and water uptake for the plant, while the plant supplies organic carbon to the fungi.(Kakouridis *et al.*, 2022a).

1.5. Importance of AMF in Sustainable Agriculture

AMF contributes to sustainable agricultural practices in multiple ways. By improving soil structure and nutrient cycling, they help reduce the reliance on chemical fertilizers and pesticides(Fall *et al.*, 2022; Fayuan *et al.*, 2022). They also support soil biodiversity, enhance plant resilience to stress, and improve overall ecosystem health(Paz *et al.*, 2021). As an integral part of healthy soil ecosystems, AMF contribute to soil aggregation, water retention, and organic matter decomposition, all of which are essential for maintaining soil fertility and preventing erosion(Kakouridis *et al.*, 2022a; Mei *et al.*, 2022).

This article explores the significance of AMF in sustainable agriculture, focusing on their role in enhancing soil health, improving plant growth, and reducing the need for synthetic inputs. It also examines the broader environmental benefits of incorporating AMF into farming systems, such as the promotion of biodiversity, the reduction of agricultural pollution, and the mitigation of climate change impacts.

1.6. Objectives of the Article

The primary objectives of this article are as follows:

- To highlight the importance of AMF in sustainable agriculture.
- To examine the mechanisms through which AMF enhance plant growth and soil health.
- To discuss the role of AMF in reducing the need for chemical fertilizers and pesticides.
- To explore the environmental benefits of AMF application, including the promotion of biodiversity and carbon sequestration.
- To provide evidence of successful AMF application in agricultural systems and discuss its potential for future use.

2. Understanding Arbuscular Mycorrhizae Fungi (AMF)

Arbuscular Mycorrhizae Fungi (AMF) are a group of soil-borne fungi that form symbiotic associations with the roots of most terrestrial plants(Vieira *et al.*, 2025). These fungi play a crucial role in enhancing nutrient acquisition, water uptake, and overall plant health by extending their hyphal networks into the surrounding soil. The fungal hyphae create a larger root surface area, enabling plants to access nutrients, particularly phosphorus, which is often limited in many soils. This mutualistic relationship benefits both organisms: the plant provides the fungi with organic carbon (carbohydrates) produced through photosynthesis, while the fungi enhance the plant's access to essential nutrients and water (Begum, N, *et al* 2020).

2.1. The Mechanism of AMF Symbiosis

AMF form a symbiotic relationship with plant roots by penetrating the root cortex and forming specialized structures called arbuscules, which are the sites of nutrient exchange(Basiru, Ait Si Mhand and Hijri, 2023). The hyphal networks of AMF extend beyond the root system into the surrounding soil, effectively expanding the plant's reach and allowing it to access a larger pool of nutrients(Vieira *et al.*, 2025). In return, the plant provides the fungi with carbohydrates, which are essential for fungal growth and reproduction. This symbiosis allows the plant to thrive in nutrient-poor or degraded soils, where access to minerals such as phosphorus is limited (Fall *et al.*, 2022).

AMF have been found to increase the surface area of plant roots by up to 700 times, thereby facilitating better nutrient absorption, especially phosphorus, nitrogen, and trace minerals that are otherwise inaccessible to plants in the absence of the fungi (Hashem, A, 2020). The mutualistic exchange helps plants become more resilient to various environmental stressors, including drought, salinity, and heavy metal contamination(Fayuan *et al.*, 2022; Ahammed *et al.*, 2023).

2.1.1. Ecological distribution and host specificity

Arbuscular mycorrhizal fungi (AMF) are pervasive in terrestrial ecosystems and form obligatory symbiotic relationships with most land plants(Yang *et al.*, 2012; Wang *et al.*, 2022). Although these associations are not host-specific, they do exhibit a degree of host preference, which, along with limited dispersal, soil-borne life history, and geographic isolation, contributes to their biogeographical patterns. While AMF are cosmopolitan at the genus level, species-level distributions are often restricted and shaped by factors such as habitat filtering and dispersal limitations(Grünfeld *et al.*, 2021; Tsiknia*et al.*, 2021).

At broad spatial scales, including global and continental levels, AMF distributions are influenced by host plant range and environmental variables. Regional patterns show distance-decay relationships driven by geographic and ecological heterogeneity, while local and fine-scale distributions are shaped by host identity, habitat, and patchy diversity. Additional influencing factors include climate, soil properties, and anthropogenic disturbances(Grünfeld *et al.*, 2021; Ma *et al.*, 2023).

Research has increasingly highlighted strong host selectivity in AMF, where plant species—including grasses, forbs, and trees—harbour distinct AMF communities. Host factors such as plant age, identity, and evolutionary mechanisms (e.g., preferential carbon allocation and reciprocal reward systems) suggest that plants actively select beneficial AMF. Consequently, the geographical distribution of AMF may be linked to the distribution of their host plants(Lewe, 2023; Philippot *et al.*, 2024)

Two recent global-scale molecular studies have provided important insights. One study, utilizing showed that AMF exhibit both host taxonomic specificity and broader distributions when associated with a greater range of host taxa. Another study found high levels of AMF endemism influenced by geography, soil, and plant community composition. Despite these findings, the mechanisms by which host plants shape global AMF distribution remain unclear.

2.2. The Role of AMF in Plant Growth Enhancement

AMF contribute significantly to plant growth by enhancing the uptake of essential nutrients. Phosphorus, nitrogen, and other vital minerals are often present in limited quantities in soils, especially in low-fertility or degraded environments. AMF extend the plant's root system to access nutrient-rich soil areas that the plant's root alone cannot reach (Soufiani *et al.*, 2023). By doing so, AMF facilitates better nutrient absorption, which is crucial for plant growth, especially in nutrient-poor soils (Kakouridis *et al.*, 2022b).

Research has shown that plants in symbiotic relationships with AMF exhibit several growth advantages, including:

- Increased growth rates: Plants with AMF associations often show accelerated growth, both in terms of root and shoot development(Jing *et al.*, 2022)
- Larger root systems: The fungal hyphae contribute to root proliferation, resulting in more extensive root systems capable of foraging larger areas for nutrients(Ma *et al.*, 2024).
- Enhanced photosynthesis: By increasing nutrient uptake, particularly phosphorus, AMF contribute to improved plant photosynthetic efficiency (Basyal and Walker, 2023)

These growth enhancements translate into healthier and more vigorous plants that are better equipped to compete for resources, survive in nutrient-poor soils, and withstand environmental stresses(Bennett and Groten, 2022).

2.3. AMF and Stress Tolerance

One of the key benefits of AMF symbiosis is the fungi's ability to improve plant resilience to various environmental stressors. This includes:

- Drought resistance: AMF help plants cope with water stress by enhancing root growth and improving water uptake, especially in dry conditions(Das and Sarkar, 2024; Guo *et al.*, 2024a). The extended hyphal network allows plants to access deeper soil layers with more water, thus reducing the impact of drought on plant health (C.-Y. Liu *et al.*, 2024).
- Nutrient-deficient soils: In nutrient-poor soils, especially those lacking phosphorus, AMF is essential in ensuring that plants have access to these critical nutrients. This helps maintain plant growth even in soils with limited nutrient availability(Eze *et al.*, 2024).
- Heavy metal resistance: AMF have been shown to help plants tolerate soils contaminated with heavy metals by sequestering these pollutants in the fungal hyphae, preventing them from entering plant tissues (Fayuan *et al.*, 2022; Crișan, Balestrini and Pagliarani, 2024).

By enhancing nutrient and water uptake, AMF increase plant tolerance to a variety of abiotic stresses, contributing to the resilience of crops in challenging environments. This makes AMF a powerful tool for sustainable agriculture, especially in areas where traditional farming methods struggle due to environmental limitations(C.-Y. Liu *et al.*, 2024).

2.4. Ecological Importance and Evolutionary Role

AMF are found in nearly all terrestrial ecosystems, ranging from tropical forests to temperate grasslands and agricultural systems. They have been integral to the evolution of plants and ecosystems, as the symbiotic relationship between plants and fungi likely played a pivotal role in the colonization of land by plants (Paz *et al.*, 2021). The ability of AMF to enhance nutrient uptake and improve plant health has made them a cornerstone of modern agricultural systems, particularly in sustainable farming practices where minimizing the use of synthetic fertilizers is a key goal(Zhou *et al.*, 2024).

AMF also contributes to soil biodiversity by supporting a wide range of organisms in the soil ecosystem. The fungi enhance the microbial community structure, which, in turn, promotes soil health and biological activity(Basyal and Walker, 2023). The incorporation of AMF into agricultural systems can therefore contribute to overall ecosystem health, promoting biodiversity and soil fertility.

3. AMF and Soil Health

Arbuscular Mycorrhizae Fungi (AMF) play a vital role in enhancing soil health, which is fundamental to achieving sustainable agriculture. Their intricate hyphal networks bind soil particles together, fostering the formation of soil aggregates. This aggregation improves the soil structure, increases porosity, and enhances water infiltration, all of which are critical factors for healthy soil. As a result, soils with AMF inoculation are less prone to erosion and compaction, ensuring long-term soil stability(Sarwade, Gaisamudre and Gaikwad, 2024; Zhang *et al.*, 2024) .

3.1. Improved Soil Structure and Stability

The physical structure of soil determines its capacity to retain water, nutrients, and support plant roots. AMF contributes to the formation of soil aggregates by producing hyphal networks that bind soil particles. This leads to improved soil porosity and water retention, which reduces the likelihood of erosion caused by wind or water. The presence of AMF helps to mitigate soil compaction, which can hinder root growth and water infiltration, especially in heavy clay soils (Aminzadeh, Dorostkar and Asghari, 2025).

In soils enriched with AMF, the increased aggregation leads to improved soil aeration and drainage, creating an environment that supports root expansion and enhances nutrient uptake. This change in soil structure can be particularly beneficial in soils that are prone to erosion or have been degraded by intensive agricultural practices (Bhupenchandra *et al.*, 2024).

3.2. Enhancement of Microbial Diversity

AMF not only improves the physical properties of soil but also fosters a more diverse and dynamic microbial community. The mycorrhizal networks function as "highways" for various soil microorganisms, including bacteria and other fungi, facilitating their movement and interactions within the soil. This increased microbial activity enhances nutrient cycling, particularly nitrogen and carbon, leading to improved soil fertility. The diversity of microorganisms in the soil has been linked to greater ecological stability, as diverse microbial communities are more resilient to environmental changes and stress(Calderon and Dangi, 2024).

AMF contribute to the health of the entire soil ecosystem by supporting a balanced microbial network that improves organic matter decomposition, nutrient cycling, and the breakdown of pollutants (Sarwade, Gaisamudre and Gaikwad, 2024).

3.3. Resilience to Environmental Stressors

AMF playsa crucial role in enhancing the resilience of plants to various environmental stressors, making them a valuable tool for sustainable agriculture. Among the most significant challenges faced by modern agriculture are drought, soil degradation, and extreme weather conditions. AMF provides a natural solution to these challenges by improving plants' ability to withstand environmental stress, ensuring crop productivity even in adverse conditions(Guo *et al.*, 2024a; Hornstein and Sederoff, 2024).

3.4. Drought Tolerance

Drought stress is becoming increasingly common as climate change leads to more frequent and prolonged periods of dry conditions. AMF helps plants tolerate drought by improving their water absorption capabilities. The extensive hyphal networks of AMF extend into deeper soil layers, allowing plants to access water that would otherwise be unavailable to their roots(Das and Sarkar, 2024; Guo *et al.*, 2024b). This ability to tap into deeper soil moisture allows plants to maintain hydration during periods of insufficient rainfall, reducing the negative impact of drought on crop yields(Tang *et al.*, 2024)

3.5. Soil Degradation and Nutrient Deficiency

Soil degradation is another major challenge that affects agricultural productivity. Degraded soils often have low nutrient content and poor water retention, making it difficult for plants to thrive. AMF helps restore the health of degraded soils by improving nutrient availability, enhancing soil aggregation, and increasing water retention. By improving soil structure and nutrient cycling, AMF make it possible for crops to grow in soils that would otherwise be too poor or compacted to support healthy plant growth.

The ability of AMF to restore soil health makes them invaluable in areas affected by land degradation. Through their symbiotic relationship with plants, AMF contribute to long-term soil restoration, which in turn ensures sustainable agricultural production in challenging environments(Sarwade, Gaisamudre and Gaikwad, 2024)

3.6. Reduction in Chemical Inputs

One of the core objectives of sustainable agriculture is to reduce reliance on chemical fertilizers and pesticides. Conventional farming practices often depend heavily on synthetic fertilizers and pesticides, which can lead to soil degradation, biodiversity loss, and water pollution. AMF provides a natural alternative by improving nutrient uptake and plant health, reducing the need for chemical inputs(Qian *et al.*, 2024; Yuan *et al.*, 2025)

AMF enhances the efficiency of nutrient uptake in plants, especially phosphorus, nitrogen, and trace minerals. This enables plants to grow more efficiently with reduced dependence on synthetic fertilizers. Phosphorus, a key nutrient that is often in limited supply in soils, is one of the nutrients that AMF help plants acquire more effectively. By improving the plant's access to phosphorus, AMF enable farmers to reduce the amount of chemical fertilizers required to maintain crop growth(Soufiani*et al.*, 2023; Bello, Saidu and Uzoma, 2024)

In addition to phosphorus, AMF also improve the uptake of other nutrients, such as nitrogen and potassium, further reducing the need for chemical inputs. This not only helps decrease farming costs but also reduces the environmental impact of fertilizer runoff, which is a major cause of water pollution in agricultural regions(Liu *et al.*, 2021).

3.7. Pest and Disease Resistance

AMF can also help reduce the need for chemical pesticides. Plants with AMF associations are generally more robust and resilient, which makes them less susceptible to pests and diseases. The increased vigor and health of plants resulting from AMF symbiosis strengthen their natural defenses, making them more capable of resisting attacks from insects and pathogens (Pu *et al.*, 2022, 2022; Yağmur *et al.*, 2024).

Furthermore, the improved soil health promoted by AMF inoculation creates an environment less conducive to the growth of harmful soil pathogens. A diverse microbial community, supported by AMF, helps suppress the growth of pathogenic organisms that could otherwise damage crops(Fayuan*et al.*, 2022). As a result, farmers can reduce or eliminate the use of chemical pesticides, contributing to more sustainable farming practices and improving the long-term health of the soil ecosystem.

4. Environmental Implications of AMF in Agriculture

Arbuscular mycorrhizal fungi (AMF), obligate symbionts within the *Glomeromycota* phylum, play a central role in plant-soil interactions and broader agroecological processes. Their symbiotic relationship with over 80% of terrestrial plant species, including key staple crops such as maize, wheat, and rice, underscores their functional importance in agriculture. Beyond facilitating phosphorus uptake, AMF uses considerable influence on soil health, nutrient cycling, and environmental sustainability, making them critical agents in the transition toward more ecologically resilient agricultural systems(R. Liu *et al.*, 2024; Chaudhary, Poudyal and Kaundal, 2025a).

4.1. Improved Nutrient Efficiency and Reduced Environmental Externalities

4.1.1. Contributions to Climate Change Mitigation

AMF also plays a role in climate change mitigation through its effects on carbon (C) cycling and sequestration. The carbon transferred from host plants to AMF supports the formation of stable soil organic matter, particularly through the deposition of glomalinaarecalcitrant compound that contributes to long-term soil carbon storage. In this way, AMF contribute to the development of soils as carbon sinks, complementing aboveground biomass-based mitigation strategies(Loo *et al.*, 2022; Tang *et al.*, 2023)

4.1.2. Promotion of Agroecosystem Biodiversity and Resilience

The presence of diverse AMF communities has been linked to increased crop resilience under abiotic stress conditions, including drought, salinity, and heavy metal contamination. AMF help buffer these stresses by improving water and nutrient uptake and by modulating plant hormonal responses. Additionally, by mediating competitive interactions among plants, AMF can enhance plant diversity in intercropping or polyculture systems, supporting ecological stability and reducing pest and disease pressure(Chiasson, Gumiere and Gumiere, 2024)

The integration of AMF into agricultural systems offers numerous environmental benefits. By reducing the need for chemical fertilizers and pesticides, AMF contribute to the reduction of agricultural pollution, which has been a major concern in conventional farming systems. AMF also plays a role in mitigating the effects of climate change by enhancing carbon sequestration. The improved soil structure and microbial diversity promoted by AMF enhance the soil's ability to store carbon, thereby helping to offset greenhouse gas emissions(Chaudhary, Poudyal and Kaundal, 2025b).

Additionally, the use of AMF supports biodiversity conservation. Healthy soils rich in mycorrhizal networks support a wide range of plant species, which, in turn, support diverse animal and insect populations. This contributes to the preservation of ecosystems and the promotion of biodiversity in agricultural landscapes(Nie *et al.*, 2024).

5. Case Studies and Practical Applications

The practical applications of Arbuscular Mycorrhizal Fungi (AMF) in agriculture are becoming increasingly recognized as essential tools for sustainable farming practices. Numerous case studies highlight the ability of AMF to improve crop yields, increase plant resilience, and restore degraded soils, making them indispensable in the fight for food security and environmental sustainability. Below, we explore case studies from various regions, particularly in Nigeria, to illustrate the effectiveness of AMF in different agricultural contexts.

5.1. Case Study 1: AMF in Maize and Wheat Cultivation in Nigeria

In several parts of Nigeria, particularly in regions suffering from nutrient-poor soils and drought, AMF inoculants have been tested to enhance the growth of maize and wheat. A research study conducted in the north-central region of Nigeria demonstrated that inoculating maize with AMF led to an increase in crop yield by 20–30% compared to untreated fields. This was particularly evident during dry seasons, where maize plants inoculated with AMF showed better drought tolerance, as the fungi helped extend the root system and improve water uptake.

Table 1 Summary of AMF Effects on Crop Types in Nigeria

Crop Type	Region	AMF Benefits	Yield Increase
Maize	North-central Nigeria	Drought resilience, phosphorus uptake	20–30%
Cassava	Southern Nigeria	Enhanced root biomass	25%
Rice	Anambra State	Improved root structure, nutrient uptake	18%

Source :Adebowale et al., 2023

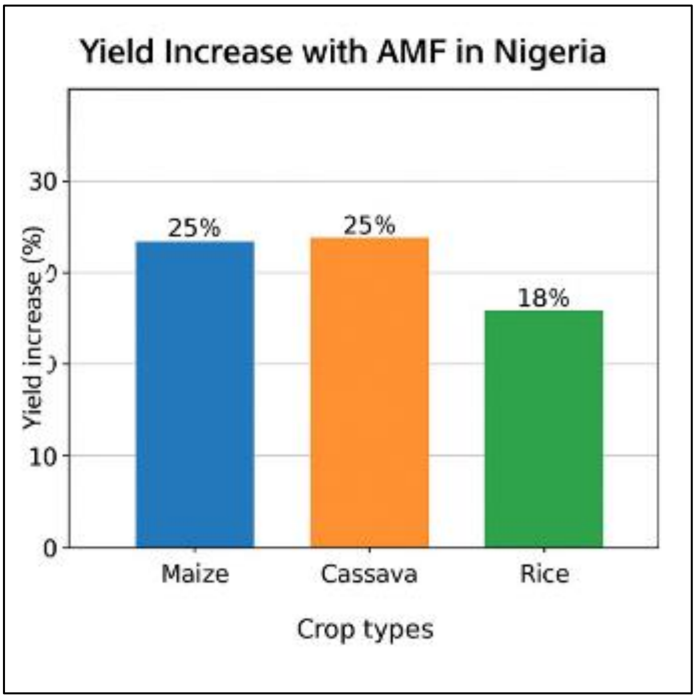

Figure 1 Yield increase with AMF in Nigeria

Yield increase (%) observed in maize, cassava, and rice due to AMF application in various regions of Nigeria.Data derived from field studies conducted between 2018 and 2023 (Adebowale et al., 2023).

In wheat farming in the same region, the application of AMF also resulted in a notable improvement in phosphorus and nitrogen uptake, which are typically limited in the soil. This led to healthier wheat plants with enhanced vigor, reduced fertilizer use, and an overall increase in yield. The success of AMF in these crops in Nigeria suggests that these fungi can be a sustainable alternative to chemical fertilizers, providing significant economic benefits to farmers in dry and nutrient-deprived areas (Olorunfemi et al., 2020).

5.2. Case Study 2: AMF in Cassava Production in Southern Nigeria

Cassava is a staple crop in Southern Nigeria, but soil degradation has become a significant issue affecting its yield. A study conducted in Edo State found that inoculating cassava plants with AMF significantly enhanced their root growth, biomass production, and nutrient uptake. The study showed that cassava plants grown with AMF symbiosis had larger roots, which are vital for both food and income generation.

The application of AMF in cassava cultivation led to a 25% increase in root yield and a notable reduction in the need for synthetic fertilizers. Farmers reported a healthier crop, reduced root rot, and less vulnerability to drought stress, making AMF a valuable tool for improving cassava production in degraded soils. This case study underscores the potential of AMF to restore soil fertility and improve crop resilience in Nigeria’s agriculturally important regions (Adebowale et al., 2023).

5.3. Case Study 3: AMF for Soil Remediation in Degraded Lands in Nigeria

Soil degradation is a significant challenge in many parts of Nigeria, especially in areas where intensive farming practices have depleted the soil’s natural fertility. In a project conducted in the Lagos region, AMF were used in soil remediation efforts to restore degraded farmland. The introduction of AMF into the soil not only helped to restore microbial diversity but also improved soil aggregation, water retention, and nutrient cycling.

After inoculating the land with AMF, the soil showed improved physical structure, with better water infiltration and reduced erosion (Folorunso, O. (2023). Within two years, the land’s productivity increased, and the yield of maize and vegetable crops improved by 30%, even without additional chemical fertilizers. This case study demonstrates how AMF can be instrumental in rehabilitating degraded lands, turning once-unproductive areas into viable agricultural zones (Ibrahim et al., 2019).

5.4. Case Study 4: AMF in Organic Farming Systems in Nigeria

Organic farming, which emphasizes sustainable agricultural practices without the use of synthetic chemicals, has gained popularity in Nigeria, particularly in regions with environmentally-conscious farmers. In a case study conducted in Oyo State, farmers adopted AMF as part of their organic farming practices to reduce dependence on chemical fertilizers and pesticides.

The use of AMF in organic farming systems was shown to enhance soil health, increase nutrient uptake, and reduce pest and disease prevalence. In crops such as tomatoes, peppers, and leafy greens, the presence of AMF not only reduced the need for chemical fertilizers but also improved the plant's resistance to pests, which are common challenges in organic systems. The results were promising, with crop yields increasing by 15-20%, providing farmers with a more sustainable and cost-effective approach to farming (Ogunyemi et al., 2021).

5.5. Case Study 5: AMF in Rice Cultivation in Nigeria

Rice farming is a key agricultural activity in Nigeria, especially in the Middle-Belt and Southeastern regions. A recent study in Anambra State explored the impact of AMF on rice growth and soil health. The research showed that AMF inoculated rice plants demonstrated a significant improvement in root development and nutrient acquisition. The fungi extended the rice plant's root system, allowing it to access phosphorus and nitrogen more effectively, which are often limiting factors in rice cultivation.

The study also noted that AMF-inoculated rice plants exhibited better resistance to water stress and disease. These benefits translated into an average 18% increase in rice yield, with a reduction in the need for chemical fertilizers. This study highlights the potential of AMF to increase rice productivity in Nigeria, especially in areas affected by low soil fertility and water scarcity (Opara-Nadi et al., 2020).

6. Conclusion and Implications for Sustainable Agriculture in Nigeria

The case studies presented above demonstrate the remarkable potential of AMF in enhancing agricultural productivity, improving soil health, and promoting sustainable farming practices in Nigeria. From maize and wheat in northern Nigeria to cassava and rice in the southern regions, the application of AMF has been shown to increase crop yields, improve drought tolerance, and restore soil fertility in degraded areas. These case studies not only validate the importance of AMF in addressing the challenges of modern agriculture but also highlight their potential role in transforming Nigerian agriculture into a more sustainable and resilient system.

Farmers in Nigeria are increasingly recognizing the value of AMF as a natural, cost-effective solution to many of the problems they face. By reducing dependence on chemical fertilizers and pesticides, AMF can contribute to the restoration of soil health, enhance crop yields, and provide economic benefits, especially for smallholder farmers in both rural and semi-urban areas. As the agricultural sector continues to face pressures from climate change, land degradation, and population growth, the role of AMF in promoting sustainable agricultural practices will only grow more critical.

7. Policy Implications and Challenges in Implementation

7.1. Integrating AMF into Agricultural Policy

Despite their ecological importance, AMF remains underrepresented in agricultural policies and extension services. Current subsidy structures often incentivise synthetic fertilizer use, overshadowing the benefits of biologically mediated nutrient acquisition. A paradigm shift is needed, one that incorporates soil microbiome health as a pillar of sustainable land management. Policy instruments can include:

- Incentives for microbial inoculant use, especially in low-input or organic systems.
- Funding for long-term soil health monitoring, including microbial indicators
- Training programs for extension agents and farmers to build awareness of AMF benefits and practical integration methods.

Incorporating AMF into broader soil health legislation, such as regenerative agriculture standards or climate-smart farming initiatives, would not only enhance environmental stewardship but also align with international commitments like the UN Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger) and SDG 13 (Climate Action).

7.2. Practical and Scientific Barriers

Widespread application of AMF in agriculture faces several challenges. One key limitation is host specificity and context dependence. AMF effectiveness varies according to plant species, soil conditions, and existing microbial communities. Moreover, the commercial AMF inoculant industry lacks standardization, with inconsistent strain quality and performance across environments.

From a technical veiw, mass production of viable and diverse AMF strains remains complex, often requiring symbiotic plant cultures and sterile conditions. Additionally, in high-input conventional systems, pre-existing soil disturbances and agrochemicals can suppress native AMF populations, diminishing inoculation success.

Overcoming these barriers demands interdisciplinary collaboration among microbiologists, agronomists, policymakers, and practitioners. Investment in region-specific AMF consortia, coupled with field-based validation, will be critical for effective scaling.

8. Conclusion

Arbuscular Mycorrhizal Fungi (AMF) represent a revolutionary innovation in the field of sustainable agriculture. Their symbiotic relationship with plant roots plays a crucial role in enhancing plant growth, improving soil health, and increasing resilience to environmental stressors such as drought, soil degradation, and nutrient deficiencies. AMF are particularly valuable in promoting sustainable farming systems by reducing the reliance on chemical fertilizers and pesticides. This leads to healthier ecosystems, better soil structure, and improved biodiversity, all of which contribute to long-term agricultural sustainability.

By improving the efficiency of nutrient uptake, enhancing water absorption, and bolstering plant immunity, AMF offer a natural solution to the challenges facing modern agriculture. These fungi not only help increase food production but also assist in maintaining environmental integrity, making them a powerful tool for promoting eco-friendly farming practices.

As research into the application of AMF continues to expand, the potential of these fungi to transform agricultural practices is becoming clearer. Their integration into farming systems represents a significant step forward in meeting the food security needs of the global population while minimizing environmental degradation. The use of AMF, therefore, aligns with the broader goals of sustainable development, offering an effective and natural method for addressing some of agriculture’s most pressing challenges.

Recommendations

Promote AMF Awareness and Education To fully capitalize on the potential of AMF, it is essential to increase awareness and education among farmers, agricultural extension agents, and policymakers. Training programs should be established to educate farmers about the benefits of AMF inoculation and its application in different crops. Practical workshops and demonstration plots can help show farmers the tangible benefits of AMF in enhancing crop yields and soil health.

Incorporate AMF into National Agricultural Policies Governments should include the use of AMF in national agricultural policies and frameworks that aim to achieve sustainable farming practices. Financial incentives and subsidies could be offered to farmers adopting AMF inoculation, particularly in areas where soil degradation and nutrient depletion are prevalent.

Promote AMF Research and Development Further research is needed to explore the full range of AMF species and their potential applications in various agro-ecological zones. Research institutions and universities should prioritize studies on AMF's role in increasing crop resilience, improving soil quality, and reducing the use of chemical inputs. Collaborative research between universities, agricultural organizations, and the private sector can accelerate the development of AMF-based products and solutions tailored to specific regional needs.

Encourage Private Sector Involvement The private sector, particularly agricultural input suppliers, should be encouraged to develop and market AMF inoculants. Commercial production of AMF-based biofertilizers and biocontrol agents can help provide farmers with affordable, high-quality products. Partnerships between government bodies, research institutions, and the private sector can facilitate the widespread adoption of AMF products in commercial farming systems.

Promote AMF Use in Organic Farming Given their effectiveness in enhancing soil fertility and reducing dependence on synthetic fertilizers, AMF should be actively promoted in organic farming systems. Organic certification bodies can include AMF inoculation as part of their guidelines to enhance sustainability and improve the quality of organic products.

Expand AMF Application in Soil Remediation AMF's role in soil restoration should be further explored, especially in areas with severely degraded soils. Large-scale soil remediation projects, such as the reclamation of mining sites, over-farmed lands, and desertified areas, could benefit from the introduction of AMF inoculants. Public-private partnerships can help scale such efforts, leading to the revival of unproductive land.

Monitor and Evaluate AMF Impact Long-term studies and evaluations should be conducted to assess the effectiveness of AMF in improving soil health and crop productivity. These studies should focus on both the direct benefits to farmers and the broader environmental impacts of AMF adoption. By monitoring changes in soil quality, water retention, biodiversity, and crop yields, policymakers and agricultural experts can better understand the full benefits of AMF and fine-tune their application.

8.1. Final Thoughts

The integration of AMF into agricultural practices offers a promising path toward more sustainable and resilient farming systems. As the global population continues to grow, the need for sustainable agricultural solutions becomes even more pressing. AMF provide an effective, natural alternative to conventional farming methods, offering not only a way to increase food production but also a means to protect and restore our planet's precious soil resources. By embracing AMF, we are taking a significant step toward achieving food security and sustainability, ensuring that future generations inherit a healthier planet.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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