

Review

# Arbuscular Mycorrhizae: Under-Tapped Potential Benefits and Perspective on Africa

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**Abstract:** Arbuscular Mycorrhizal Fungi (AMF) is attracting global attention as organic fertilizers and alternatives to chemical fertilizers in crop management practices. Mycorrhizae technology application in Africa is still juvenile compared to other continents in small-to-large scale agriculture and commerce. The sustainable use of AMF technology in resolving bioremediation, bio-restorations and conservation challenges is currently limited by the paucity of their inocula production. Their natural versatility encourages a research trajectory toward their cultivation and exploitation of their potential benefits in improving food, bioeconomic securities and product development. This review focuses on the natural dynamics and potentials of AMF beyond agriculture to biotechnologically oriented product development of industrial, environmental and food relevancies.

**Keywords:** Agriculture, Biotechnology, Arbuscular Mycorrhizae, Symbiosis

## Introduction

Mycorrhiza fungi are significant to the understanding of plants' biogeography, evolution dynamic, plants' distribution pattern, and mostly form symbiosis with the roots of terrestrial plants around the globe. Mycorrhiza is also reported in a few aquatic plants and Bryophytes (Kehri *et al.*, 2018). Plant-fungi interaction is common in rhizospheres and soils across the globe being a part of plants' conquests of land about 500 million years ago (Rimington *et al.*, 2019). In such complex environment, they function in protecting the plant hosts against pathogens including pests, facilitating plants' nutrients uptake and enhancing plants' growth. Additionally, they promote the transfer of valuable resources through their extensive network of hyphae that interconnect plant roots (Horton, 2015). This web of hyphae similarly mitigates the movement of toxic chemicals, pollutants and heavy metals from the soil to the above-ground parts of plants by the phenomenon of bio-filtration (Lekberg and Koide, 2014;

Urcelay *et al.*, 2019). They afford the host plant, resilience, resistance and healthiness by palliating the effect of environmentally stresses (Osemwegie *et al.*, 2013). Mycorrhizae are grouped, based on their mechanism of colonization, into the ectomycorrhizae which do not invade roots cortical cells and endomycorrhizae (orchid, ericoid and glomeromyconan mycorrhizae) which penetrate and invaginate root cells. It is within this major grouping framework that arbuscular-mycorrhizae are represented. The events resulting in the temporal and spatial emergence of different groups of mycorrhizae and mycotrophism in the evolutionary scale is still unclear. Reports in literature on the role of plants, hosts and other ecological factors in the activation of distinct mycorrhiza emergence, differentiation and diversity remained inconsistent (Wilkinson, 2001; Osemwegie *et al.*, 2013; 2017). It is controversial to assume that ectomycorrhizae were modulated by the dynamics of adaptation and environmental variables into endomycorrhizae over time contrary to the position of (Selosse *et al.*, 2009) who hypothesized endophytism as

the basic for symbiotic divergence. This along with the methodologies for exploiting the innate biotechnological potentials of mycorrhizae for public health, food security, environmental and drug discovery challenges has dominated discourse in mycorrhizological conferences around the world (Jacquemyn and Merckx, 2019).

Mycorrhizal fungi are widely and arbitrarily distributed across various non-motile-structure-forming divisions (Glomeromycota, Mucoromycota, Ascomycota, Basidiomycota) of the Kingdom Mycota. They are non-pathogenic fungi and may associate with plants' roots without necessarily drawing any reward from the host despite their innate benevolence under the wood-wide network concept (Sanders, 2003). They are at times engaged in exchange of reciprocal benefits or differential levels of benefit in mutual interactions or mycoheterotrophy (light-limited plants depending on fungal carbon) (Merckx *et al.*, 2009; Jacquemyn and Merckx, 2019). Similarly, AMF varies in symbiotic affinity and while some may require hosts that deliver high-energy photosynthates, some may deliver more nutrients to hosts that far exceed what they got in return. In another instance, the hosts just selectively demand certain types of minerals and vice-versa (Tedersoo and Smith, 2013; Lanfranco *et al.*, 2018). The recent emergence of relevant molecular, genomic approaches coupled with technological growth is expanding the knowledge and understanding potentials of mycorrhizae in the growing bioeconomic market (Sanders, 2003). Quality insight into the community pattern, evolution, physiology, fidelity, affinity of interacting symbionts abounds in literature (van der Heijden *et al.*, 2015).

While the relevance of mycorrhizae in the management of global ecological stability cannot be underrated, the knowledge of climate change influence and recurrent anthropogenics on their services, interaction with co-existing microbes and possible biotechnological orientation is important (Partel *et al.*, 2017). Also, gaining attention is data providing information on the nature of stimulus or combination of variables underpinning the quantitative trade-offs or biological cross-exchanges and outbidding competitions in mycorrhizal symbioses. This may hypothetically associate the dynamics of mycorrhizal relationship to the hosts' natural ethnomedicinal potentials (Noë and Kiers, 2018). Scientific literatures reported studies on the biochemical processes that underlie the phytometabolomic and ecophysiological dynamics in many plant hosts (Petrovska, 2012). This is further linked to the expression of different bioactivity factors in the hosts. Hoysted *et al.* (2018) observed the need for the characterizations and documentation of diverse physiological and biochemical compounds associated with mycorrhizae. This could hypothetically suggest a correlation between plants phytometabolomic quality, mycorrhizal fungi, and humanity's preference for plants' as veritable biotechnological tool in drug development and therapeutics. It can therefore be assumed that the slow but

long-term consequences of stress exposures from natural and anthropogenic factors may fundamentally activate the mechanism of mycorrhizal formation (Sun *et al.*, 2017; Begum *et al.*, 2019). This mechanism, though not well understood, involves crosstalk by signal molecules like rhizospheric strigolactones and gibberellins or communal influences on relational gene expression (Sadhana, 2014; Padder *et al.*, 2018; Mehmood *et al.*, 2019). Furthermore, understanding how the effect of global change factors, over time, facilitates the mechanism of mycorrhizal formation, host range, trade-off cum signaling dynamics, and their biotechnological amenability.

### Arbuscular Mycorrhizal Fungi

Arbuscular Mycorrhizas (AM) are popular endomycorrhizae that occur globally in over 80% of terrestrial plants (Karliński *et al.*, 2010). The widespread nature of arbuscular mycorrhizal associations has immensely contributed to the successful colonization of land by historic plants and availed them habitat stress tolerance. Arbuscular Mycorrhizal hyphae form distinct balloon-like vesicles or hyphal coils or branching invaginations called arbuscules in root cells (Van der Heijden *et al.*, 2015). AMF belong to the phylum Glomeromycota and demonstrate different levels of plant host specificity or unspecificity (Souza, 2015; Jacquemyn and Merckx, 2019). They are equally resilient with high tolerance capacity for different levels of stress (biotic e.g., pathogens, allelochemicals, pests and anthropogenic disturbances and abiotic factors (salinity, drought, anoxygenic condition, flood, desertification), and biotrophic habit (Silva *et al.*, 2014; Partel *et al.*, 2017). Consequently, they have become attractive biological tool for sustainable agrosystems' activities involving biofertilizers, crops' biosafety and biological control of phytopathogens than other forms of mycorrhizae (Singh *et al.*, 2013). In addition, AMF are reported in *in vitro* soil phytoremediation (phytoextraction and phytostabilization), reclamation, land revegetation, carbon-sequestration, soil aggregate stabilization and natural biofiltration process in numerous soils (Finlay, 2008; Prayudyarningsih *et al.*, 2019). More information is therefore needed on the biochemical phenomena that are responsible for the systematic synthesis of their bioactive principles, and the best as well as cost-effective technologies to harness them for field uses. A few scientific evidences already suggested that the interactive activities of AMF in single or dual (AMF-Rhizobacterium, AMF-Dark Septate Endophytes) mode could trigger the production of selective compounds or the preferential modulation of inherent phytometabolites valuable for biotechnology applications (Mandyam and Jumpponen, 2008; Vosátka *et al.*, 2012; Silva *et al.*, 2014; Pagano and Dhar, 2015). This, according to (Albrechtova *et al.*, 2012), may cause the natural

improvement of food antioxidants, vitamins and minerals contents of plants. Research focus on AMF is slowly shifting to their biotechnological manipulations for different levels of desirable production systems. The consequence of manipulating AMF interaction with plants, parasites, herbivores, pathogens and pests would change mycorrhizological frontiers and revolutionize mycorrhizology. Furthermore, this futuristically has implications for the production inocula using diverse range of *in situ*, *in vivo* and *in vitro* axenic or non-axenic technologies that involved AMF alone or in combination with other plant beneficial microbe(s) (Feldmann and Schneider, 2008; Miransari, 2011).

Although, global emphasis is on developing biotechnologies for the optimal expression of innate bioactive potentials of AMF, harnessing the useful potentials inherent in their biomolecules, metabolic products, and leveraging on them for the alleviation of dimensional challenges is presently premature in Nigerian and many other African countries. The biotechnological applications of AMF are yet to hypothetically find expression as biogenetic resource of preference for bioactive products and drugs development. A few agrosystems such as forest farming, intercropping and organic agriculture in Africa are only vaguely associated with the applications of AMF. Compared to the more popular use of other bioresources (non-nitrogen fixing bacteria, non-mycorrhizal fungi, rhizobium) in the continent of Africa, the knowledge of their economic and no-ecological benefits is still under-explored, and limited by their obscured existence (Shah, 2014; Favre-Godal *et al.*, 2020). The lack of financial, legislative and political encouragements for the large scale production of mycorrhizal inocula and their commercialization is one major bottleneck in the growth of mycorrhizal biotechnology in Africa (Karagiannidis *et al.*, 2010). This has had implications for their applications in mediating desertification of arable land Saharan Africa (Gianinazzi *et al.*, 2010).

This review was undertaken to build on extant information regarding the state of AMF applications in different aspects of national development in Nigeria and other African countries. Attention is on advancing prospects that are inherent in the economic potentials of AMF, their possible utility in biotechnological space, and value addition. This is *vis-a-vis* the growing global interest in expanding bioresources' screening for the accomplishment of sustainable development goals (Basu *et al.*, 2018).

## AMF Utility Perspectives

Human perceptions of the economic relevance of AMF vary across demographic and cultural boundaries. It could be a major determinant of their application trajectory and preference in the biotechnological landscape. Mycorrhizal fungi enhances the capacity of

crops uptake of water and mineral nutrients such as phosphorus, nitrogen, sulfur, copper, magnesium and zinc (Smith *et al.*, 2011; Vosátka *et al.*, 2012). AMF also improves plants nutrition and their ecological competitiveness (Jung *et al.*, 2012). For instance, AMF increases soil phosphorus utilization by contributing to the conversion of organic phosphorus into absorbable ionic forms that are readily mobilized by the plant partner (Lehman and Taheri, 2017; Brito *et al.*, 2019). This ecological capacity has potentially enhanced the economic application of AMF as sustainable biofertilizers (Table 1). Environmental conditions can be tinkered to favor the proliferation of mycorrhizae, the soil augmented with beneficial microorganisms including AMF or enriched with nutrients that promote the population plant-growth beneficial microorganisms.

AMF colonization can prime systemic plants' primary and secondary defense mechanisms, and enhance tolerance to a wide range of above and below-ground extremities by different plant species (Miozzi *et al.*, 2019). Plants' resistance to many soil-borne pathogens is reportedly boosted by Mycorrhizae e.g. delayed the time required by *Ganoderma boninense* to infect and kill oil-palm trees (Tahat *et al.*, 2010). A few of the underlying antipathogenic activities observed in mycorrhizal plants include the production of defense enzymes such as the Phenylalanine Ammonia Lyase (PAL) and Polyphenol Oxidase (PPO). Additionally, it involves the ramping of the total phenol and flavonone (apigenin-pentosylhexoside, lutein-pentosyl-hexoside, caffeic acid, apigenin-dihexoside) contents in the plant hosts (Ntengna *et al.*, 2019). Different accounts of AMF applications in the control of plant diseases in Africa are scanty. This may perceptibly be due to the complexity in the processes leading to the bioprotection host plants against pathogens by AMF (Table 2). AMF protect crops via a range of mechanisms that directly affect the pathogens. These may include competitive inhibition or exclusion, antibiosis, predation, and indirectly through plant-mediated effects (Schouteden *et al.*, 2015; Singh and Giri, 2017; Albuquerque da Silva Campos, 2020). Plant-mediated responses to infections are induced and expressed (endogenously or exogenously) in the form of biochemicals (exudation, volatiles, allelopathic compounds, etc.), anatomical and structural changes to block pathogen colonization. Suffice to say that plants whose roots are colonized by AMF develop systemic resistance and capability to leverage on rhizospheric microbial interactions for defense support (Tahat *et al.*, 2010; Bianciotto *et al.*, 2016). This suggests a strong possibility that the antipathogenic effect of AMF may results from the interaction of two or more mechanisms, one of which could be the modulation of the rhizosphere through the actions of supportive Non-Mycorrhizal Microbes (NMMs) or Plant-Growth-Promoting Microbes (PGPMs).

**Table 1:** Examples of some AMF (Biofertilizer inoculant) and their effect on the crop plant

Crop	Arbuscular Mycorrhizal inoculum	Effect	Reference
Maize ( <i>Zea mays</i> )	<i>Glomus etunicatum</i>	Improved P uptake	Sadhana (2014)
Wheat ( <i>Triticum aestivium</i> L. cv. Henta, Sardari39)	<i>G. deserticola</i> , <i>Glomus etunicatum</i> , <i>Glomus fasciculatum</i> , <i>Glomus mosseae</i> and <i>Gigaspora gergaria</i> ,	Increased P, N and Mg absorption and high proline, phosphatase activities and chlorophyll. It also increased growth and wheat dry weight	Daei <i>et al.</i> (2009; Abdel-Fattah and Asrar 2012; Shahabivand <i>et al.</i> , 2012)
Onion ( <i>Allium cepa</i> L.)	<i>Glomus etunicatum</i> , <i>G. microaggregatum</i> , <i>G. intraradices</i> , <i>G. claroideum</i> , <i>G. mosseae</i> and <i>G. geosporum</i>	Increased in bulb fresh weight	Albrechtova <i>et al.</i> (2012)
Soybean ( <i>Glycine max</i> L.)	<i>Glomus constrictum</i> (Trappe)	Increased plant growth responses, P and N concentrations in shoot and root tissues, acid and alkaline phosphatase activities and total soluble proteins in root tissues	Abdel-Fattah <i>et al.</i> (2014)
Rose of Winter ( <i>Camellia japonica</i> L.)	<i>Funneliformis mosseae</i>	Increased number of flowers.	Berruti <i>et al.</i> (2013)
Cassava ( <i>Manihot esculenta</i> Crantz)	<i>Rhizophagus irregularis</i>	Increased yield	Ceballos <i>et al.</i> (2013)
Green gram ( <i>Vigna radiate</i> L. Wilczek)	<i>G. intraradices</i> and <i>G. mosseae</i>	Increased dry weight of nodules, grain and straw yield, nitrogen, phosphorus and potassium uptake	Bhat <i>et al.</i> (2011)
Lettuce ( <i>Lactuca sativa</i> L.)	<i>Glomus intraradices</i>	Improved growth rates	Aroca <i>et al.</i> (2013)
Sunflower ( <i>Helianthus annus</i> L.)	<i>Glomus mosseae</i> (Pellegrino and Bedini 2014) and <i>Glomus hoi</i>	Production of more dry matter, heavier seeds and greater seed and oil yields	Gholamhoseini <i>et al.</i> (2013)
Chickpea ( <i>Cicer arietinum</i> L.)	<i>Funneliformis mosseae</i> and <i>Rhizophagus irregularis</i>	Increased plant biomass and yield.	Pellegrino and Bedini (2014)
Alfalfa ( <i>Medicago sativa</i> L.)	<i>Funneliformis mosseae</i>	Increased yield	Pellegrino <i>et al.</i> (2012)
Cocoyam ( <i>Colocasia esculenta</i> [Linn.] Schott)	<i>Acaulospora tuberculata</i> and <i>Gigaspora margarita</i>	Increased plant shoot and root dry matter	Ntengna <i>et al.</i> (2019)
Cocoa ( <i>Theobroma cacao</i> L.)	<i>Gigaspora margarita</i> and <i>Glomus mosseae</i>	Increased height, number of leaves, shoot and root matter) and P uptake	Tchameni <i>et al.</i> (2012)

**Table 2:** Documented effects of AMF on pathogens of some common economic plants in Africa

Crop	Arbuscular Mycorrhizal Fungi sp	Effects of AM on pathogen-infected crop	Target pathogen	References
Potato	<i>Rhizophagus irregularis</i>	Milder symptoms and significant stimulation of shoot growth and resistance	Root-rot ( <i>Rhizoctonia solani</i> ), Late Blight Dis. ( <i>Phytophthora infestans</i> )	Thiem <i>et al.</i> (2014); Velivelli <i>et al.</i> , 2015; Alaux <i>et al.</i> , 2018)
Tomato	<i>Funneliformis mosseae</i> , <i>Rhizophagus irregularis</i> , <i>Glomus mosseae</i>	Decreased effect of pathogens and improves host resistance	<i>Fusarium</i> wilt ( <i>Fusarium oxysporum</i> ), root-knot nematodes, Bacteria wilt ( <i>Ralstonia solanacearum</i> )	Fritz <i>et al.</i> (2006; Tahat <i>et al.</i> , 2010; Maffei <i>et al.</i> , 2014; Bidellaoui <i>et al.</i> , 2019; Prakash and Sharma, 2017)
Barley Cotton, Banana	<i>Glomus mosseae</i>	Reduced infestation, induce bioprotection	Take-all dis. ( <i>Gaeumannomyces graminis</i> ), <i>Fusarium</i> wilt ( <i>Fusarium oxysporum</i> ), Verticillium induced wilt ( <i>Verticillium oxysporum</i> )	Khaosaad <i>et al.</i> (2007; Norouzi <i>et al.</i> , 2009; Castellanos-Morales <i>et al.</i> , 2011; Castillo <i>et al.</i> , 2019)
Cocoyam	<i>Acaulospora tuberculata</i> and <i>Gigaspora margarita</i>	Reduce disease incidence and improve host defence system	Soft root rot dis. ( <i>Pythium myriotylum</i> ), Black pod dis. ( <i>Phytophthora megakarya</i> )	Claude <i>et al.</i> (2019; Ntengna <i>et al.</i> , 2019; Tchameni <i>et al.</i> , 2012)
Common bean plant ( <i>haseolus vulgaris</i> L.)	<i>Glomus mosseae</i> , <i>Glomus intraradices</i> , <i>Glomus clarum</i> , <i>Gigaspora gigantea</i> and <i>Gigaspora margarita</i>	Reduced the percentage of disease severity and incidence	Damping-off ( <i>Pythium debryanum</i> ), root-rot ( <i>Rhizoctonia solani</i> )	Al-Askar and Rashad (2010; Hathout <i>et al.</i> , 2010; Nasir Hussein <i>et al.</i> , 2018)

While it is assumed that the antipathogenic mechanisms of AMF cannot be mutually exclusive, they may conceivably be complementary, cross-signaling or overlapping with other non-microbial rhizospheric organisms (nematodes and microarthropods) and abiotic factors for optimal effects (Cameron *et al.*, 2013; Dos Santos and Maranhão, 2018). Besides the aforementioned, Strigolactones (SL) and eight other phytohormones that include Abscisic

Acid (ABA), Auxins (AUX), Brassinosteroids (BR), Cytokinins (CK), Gibberellins (GA), Ethylene (ET), Jasmonate (JA) and Salicylic Acid (SA) are also reported by (Bedini *et al.*, 2018) in AMF actions in mediating plant infections. These hormones may act independently, differently or interplay (co-act) to trigger plant host defenses or crosstalk via signal transduction to influence the functional roles of AMF effecting host's

healthiness. The kinetics and interaction of several forms (phytohormones, exudates, volatiles, other metabolites) of mediating molecules has become an important biological model for the investigation of asymbiotic (without roots present), pre-symbiotic (with roots present but no colonization) and post-symbiotic (colonization of roots) inhibitory or inductive behaviors of fungi in the rhizosphere (Abdel-Ghany *et al.*, 2014; Liu *et al.*, 2019). These hormones were also implicated in plants' affinity for symbiosis, responses to microclimate changes, and mutually benefitting interactions with other non-mycorrhizal organisms in their community (Savary *et al.*, 2020). Despite this, they are implicated in the processes of plant-specific and non-plant specific mycorrhization, multifunctionality, hyphal branching and plant diversity dynamics. Proteins involved in plant defense responses caused the production of hydroxyproline-rich glycoproteins, phenolics peroxidases, chitinase, B-1-3 glucanases-callose deposition and PR-pathogenesis related proteins (Tahat *et al.*, 2010). It is therefore logical to suggest that the individual and collective roles of phytohormones in mycorrhization, AMF-plant crosstalk and herbivory is still rudimentary and inconsistent.

Recently, the applications of AMF, particularly in agroecosystems in Nigeria and some African countries, is gaining attention. Popular practice of farm land preparation has always involved the dumping of organic biodegradable wastes, composts and slurries on arable spaces to stabilize soil aggregates and facilitate humification. The need by humanity to control pedogenesis and renewable sustainability of the plant-soil system cannot be downplayed in the global drive for food security and safety (Smith and Read, 2008; Lanfranco *et al.*, 2018; Begum *et al.*, 2019). The perennating AMF hyphae are reported by (Hamel and Strullu, 2006) to aggregate and confer structural stability to the soil through their role in soil organic matter management. Another hypothetical mechanism for the effective performance of AMF as biofertilizer is underscored by their superior ability to sequester mineral nutrients from far and wide. Their hyphae reach well beyond the rhizospheric phosphorous depletion zone to nutrient-rich zones to absorb minerals required by the hosts (Smith *et al.*, 2011; Sun *et al.*, 2017). Furthermore, fungal hyphae, apart from interconnecting different spatial plants species, are much thinner than the roots and can therefore perennates smaller pores for beneficial resources (Allen, 2011). This behavior has helped in enhancing the expression of plant inorganic Phosphorus (Pi), NH<sub>4</sub>, K, Zn, Cu, Fe, Ca and S ions' transporters in the AMF-plant system (Giovannetti *et al.*, 2014; Breuillin-Sessoms *et al.*, 2015; Walder *et al.*, 2015). It has been reported that plants possess a symbiotic nutrient uptake pathway (Smith *et al.*, 2011). According to (Igiehon and Babalola, 2017), AMF improve mineral nutrients uptake via transporters that are coded for

different genes. AM interaction stimulates plant genes to express inorganic nutrient transporter proteins which are yet to be adequately characterized in terms of location, expression pattern and transport dynamics (Sasaki *et al.*, 2016). Improved plant nutrition by AMF compensates for yield loss due to exopathogenic causes (Singh *et al.*, 2019). Studies have also shown that there exists physical competition between endomycorrhizal fungi and other rhizosphere microorganisms for space and nutrients in the root architecture. It is therefore possible that AMF's competitive advantage in resource derivations had a suppressive effect on other rhizospheric microbes or pathogens (Jung *et al.*, 2012; Singh *et al.*, 2019; De Corato, 2020).

Reports are rife on the capacity of AMF to increase sugar content, essential elements (Zn, Mg, etc.), antioxidants and beneficial mineral elements in the plant symbionts (Qin *et al.*, 2020). While personal interactions with some local indigenous farmers in south-west Nigeria showed vague awareness of these capabilities, the application of AMF in improving crops quality is more widely reported in some developed nations of the world (Gianinazzi *et al.*, 2010; Albrechtova *et al.*, 2012). Understanding AMF use in agroecosystems can be facilitated by the discovery of mycorrhizal supportive signaling chemical like strigolactones (García-Garrido *et al.*, 2009; Vosátka *et al.*, 2012; Shtark *et al.*, 2018; Rochange *et al.*, 2019). Similarly, (Sharma *et al.*, 2007) reported that phosphorus-induced changes caused by AMF in root exudation could inhibit pathogen spore germination. This AMF function confers plant host with resilience to environmental adversities (Gosling *et al.*, 2006). Mycorrhizal colonization of crops infected with viruses produced a higher level of Jasmonate (JA) which plays a key role in creating an environment unfavorable for viral infection (Miozzi *et al.*, 2019). Roots colonized by AMF are usually more branched and the diameter of the adventitious roots is larger than those of non-mycorrhizal plants (Shtark *et al.*, 2018).

## State and Prospect of AMF

In the Nigerian and African context, arbuscular mycorrhizal fungi remains underutilized biotechnologically compared to their numerous applications as reported from many other developed nations. Why it is interesting that different reviews and empirical reports exist on the inherent economic potentials of AMF, these potentials are yet to be fully harnessed for the benefits of many Africans. Consequently, the biotechnological applications of AMF are strongly undermined by information and technology access coupled with profound illiteracy. Current views and opinions about the field and large-scale applications of AMF in industries remained equivocal. The apparent global apathy for the consistent applications of

chemically synthesized products such as drugs, antibiotics, agro-allied inputs and industrial raw materials is a major stimulant to the paradigm that presently encourages mass research on naturally occurring biogenetic resources. This increasing bioresources' screenings is predicated on a search for affordable, cost-effective but equally potent bio-equivalents to substitute, complement and compete with chemosynthetic products dominating the global market space. Centuries of human reliance on synthetic products has generated concerns that are based on many factors related questions about their safety, and safe application in food, environment and drugs. Sedimentary residues of some of these chemical products which may not be easily biodegraded or metabolized have been reported to compromise animal, human and environmental health with implication for life-expectancy and global climate challenge (Nicolopoulou-Stamati *et al.*, 2016). This has caused an unprecedented rise in the exploitation of bacteria, algae, fungi, plants and animals, through the use of advanced biotechnological methods, for the development of valuable bioproducts or bioalternatives (Vassilev *et al.*, 2005; Song *et al.*, 2020). It is recently that screening attention was given to AMF in product development despite their over 400 million years of existence. The delay in their applications for economic gains may be linked to any or a combination of the following: (i) Their obscured nature in the ecosystems; (ii) difficulty in their in vitro and large scale cultivation, (iii) ignorance of their economic and commercial potentials; (iv) poor knowledge of their non-ecological values for possible bioeconomic improvement; (v) relatively poor knowledge of their diversity and presence compared to the global estimated data for other biogenetic resources. While AMF are incontrovertibly perceived as unsustainable in bioeconomic terms, the socio-political frame-work relating to fund, patents and legislations, poor access to appropriate information, and technologies may contextually be accountable for their current utility state in Nigeria and other African nations.

The African continent is endowed with a broad range of vegetation zones and has close to 60% (600 million hectares) of potential global cultivable land that could feed over 239 million people, if properly used, with nearly 50% of this population located in Nigeria. It has been reported by the FAO that though Africa has the potential to be the world food basin, it lacks the necessary orientation to meet the continent's growing food demands and abolish hunger. This situation could be attributed to various factors that are both political and cultural. Other conceivable reasons may be traceable to Nigeria's relatively slow disposition to the use of technology, artificial intelligence and biotechnological approaches for economic gains. While food safety concern is a global phenomenon, focus is on biological fertilizers, organic antibiotics, probiotics, biocontrol

agents and systemic irrigation strategies. In this wise, arbuscular mycorrhizae has naturally assisted cropping and holds more untapped potentials that can help crop manage soil water, nutrients (phosphate, nitrate and carbon) and diseases (Aseel *et al.*, 2019). Contrary to reports, arbuscular mycorrhizal is more effectively evident in nutrient and/or water deficient soils and are now more recently being biotechnological re-engineered through research in many developed nations for values applicable to improving crop yield in inert, saline and even nutrient-rich soils (Noë and Kiers, 2018). The manipulation of AMF with associated nitrogen-fixing or other non-symbiotic microbes in the improvement of plant growth and crop quality is currently receiving attention by many scientists. Also, AMF is slowly becoming a conceivable strategy in altering soil community structure and ontogenesis (Sanders, 2003; Padder *et al.*, 2018). This may turn out to be a healthy innovation for the prospect of agriculture in the arid regions of the African continent. Consistent but strategic prospecting of mycorrhizal technologies and biotechnologies for resolving the food security challenges in Africa is fundamental to micropropagation, plant disease protection, afforestation, food safety, crop yield, soil preparation and management, nutrients mobilization and bioavailability of moisture.

Similarly, AMF may have potential implications for re-vegetating waste, polluted and desertified lands for the expansion arable lands in Africa. Savary *et al.* (2020) report that AMF as well as other fungi are responsible for the accumulation and sequestration of toxic ions (Cu, Zn, Ni, Cd, Pb), and transfer of essential mineral elements to the host (Khan *et al.*, 2000; Mathur *et al.*, 2007; Abdel-Razek *et al.*, 2009). Chen *et al.* (2018; Park *et al.*, 2016) also implied that the effective ability of AMF in soil bioremediation and management of soil mineral elements are enhanced by the phenomenon of protocollaboration across host plant species. Although, the definition of the term is more generally related to plant roots interconnectivity for improved survival, it could apply to the complex substance networking by AMF hyphal perennation and anastomosis (Leake *et al.*, 2004; Wipf *et al.*, 2019). Suffices to say that mycorrhizal mycelium interconnects host plants in different communities, and freely conduct growth as well as protective materials between the different species. This interconnectivity is fundamental for the plants' functional resilience (Jakobsen and Hammer, 2015). It also afforded AMF the uncommon capacity to selectively bio-extract toxic contaminants, redistribute nutrients based on inter-specific preference and needs, or deploy some of these mobilized substances purposely for host defenses against pathogens and pests (Merckx *et al.*, 2009; Lanfranco *et al.*, 2018). Based on this unique characteristic, they are presumed to be the foremost biofertilizers all around the world. Many African farmers

now employ practices consistent with harnessing the natural soil control potential to mitigate the use and effect of chemical fertilizers on crops' health and safety. Nutrient enrichment by potential mycorrhizal inocula and mycorrhizal-growth enhancing agrosystem practices are additional possibilities for the eradication of hunger. Presently, many oil-polluted land reclamation initiatives in Africa and south-south of Nigeria now relied mostly on fallow, deep mechanical plowing and phytoremediation approaches even though (Park *et al.*, 2016) noted that intense pollution could overwhelm their remediation potential. While many laboratory studies in Nigeria are still focusing on exploring the potential of AMF as bioremediant of polluted soils, little success has been recorded on the field applicability of such results for field scale challenges (Chibuikwe, 2013). More investigations are therefore required to fully quantify their impact on the ecosystem and plant community, influences on soil microbiomes and commercial cultivation.

Metabolomic-based paradigm is attractive to the global bioeconomic quests for safe environmental and health compatible bioactive compounds of biological origins (Smith *et al.*, 2010; Jacquemyn and Merckc, 2019). Organic products development is largely from plants, bacteria, algae and non-mycorrhizal fungi with attention seldom given to mycorrhizae. This may possibly suggests that their limited applications are disproportionate to their diversity and preponderance (Karagiannidis *et al.*, 2010). Furthermore, their existence and complex chemotactic signaling currency also affected their tractable use in prospecting bioactive materials for non-agricultural applications. They may also qualify as potential bioindicators of soil suitability for farming (Hamel and Strullu, 2006; Raudaskoski and Kothe, 2015). The late attraction to the chemosystematic values of AMF compared to other biogenetic resources is still debatable. Maciá-Vicente *et al.* (2018) attributed the vast majority of documented bioactive compounds from plant sources to transgenic genes generated by cross-linked effects from ecophysiological adaptability of AMF. This effect resulted in diverse phytometabolomics modulation and reconfiguration to value-adding products as reported by (Singh *et al.*, 2013; Silva *et al.*, 2014; Maciá-Vicente *et al.*, 2018) on the improvement of valuable biomolecules in above-ground plant parts. Although mycorrhizal fungi are least explored in bioprospecting, their non-mycorrhizal forming counterparts are routinely screened biotechnologically based on their ability to produce natural products that are configured for wide range applications. This chemosystematic potential which may also be significant for mitigating herbivory is logically assumed to be replicated also in the mycorrhizal fungi possibly because of their shared lineage with plants (Savary *et al.*, 2020). Their exploitation can invariably suffice as a buffer to

the pressure of over-exploitation of the non-mycorrhizal forming fungi and plants across the global (Miransari, 2011; Hoysted *et al.*, 2018). Over-exploitation of these natural bioresources disrupts conservation initiatives, contributes to growing environmental concerns (climate change, global warming, disease outbreaks, desertification, forest depletions, etc.), and ecosystem imbalance. Therefore, to magnify preference for the biotechnological applications of AMF indigenous to Africa in prospecting functionally diverse bioactive products, more biochemical, genetic and transcriptomic studies may be required to screen the veracity of their chemosystematic potentials. This is aside the urgent need to properly identify and document mycorrhizal species indigenous to Nigeria and Africa.

In many large scale farming operations in Nigeria, the use of biological control agents in crop disease management is strongly overshadowed by the reliance of farm owners on different commercial chemical biocides (pesticides, herbicides, fungicides, bactericides, etc.). While this dependence may be linked to the spontaneous actions of the chemicals, its long-term use and exposure to crops as well as the environment are not without dire health, food safety and environmental consequences (Olowe *et al.*, 2018). The perceptive hazards associated with this practice, even in food preservation, did not discourage their use possibly due to lack of access to cheaper, easy-to-use, more effective bioequivalents. Consequently, a stronger solution through effective extension service network and routine screening of bioresources is required to propagate safer alternatives bio-products with equivalent biocidal and biopreservative activity respectively (Adetunji *et al.*, 2018; 2019). Mycorrhizal fungi have antipathogenic traits that are either genetic or acquired by induced transduction mechanism (Lanfranco *et al.*, 2018). Similarly, Tahat *et al.* (2010) reported that AMF in many plants systematically reduces the surface area of infection and stimulate hypersensitive responses to prevent penetration of the pathogens or release toxic exudations. AMF over several millennia have evolved the capacity to outcompete different pathogens (Mehmood *et al.*, 2019). The aforementioned therefore suggest the need for more *in situ* trials of mycorrhizal fungi and other beneficial microbes' populations in selected agrosystem practices. Equally noteworthy is the recent emerging interest and research effort toward their commercialization for wider availability as biofertilizers. In the Nigerian agricultural context, the traditional knowledge of land preparations, and the choice of agrosystem practice already mirrored consideration for the criticality of plant beneficial microbes in crop production even though the potentials are yet to be fully exploited.

Mycorrhiza propagation can be a source of foreign revenue and the key to bioeconomic growth in many

African countries. While the level of reported experimental studies on the application of mycorrhizal fungi, especially in successful product development, is low, (Berruti *et al.*, 2013) investigated their *in vitro* role in plant stress modulation using a growth chamber, greenhouses, and field models. Their experiment involved the use of mono-species or multiple-species inoculants under varied physical conditions. Information on the role of enzymes secretion in AMF mediatory response to soil contamination, enzyme composition and their relevance to chemotaxonomy, host affinity and distribution are scarce. Estrada *et al.* (2013; Hashem *et al.*, 2018) implicated enzyme actions in modulating host plant tolerance to ionic and hormonal imbalances, oxidative, osmotic and salinity stresses respectively. Additionally, the applications of multiple mycorrhizal (Bi *et al.*, 2018) might express combined enzyme dynamics that could enhance photosystem II, stomatal conductance, membrane electrolytes' leakages, and increased in the production of superoxide dismutase and catalases (Qin *et al.*, 2019). This observation confirms the role mycorrhizal fungi in improving crop yields and affirms the presence of diverse inherent potentials that could be valuable to humanity but still uncovered.

While this review noted the current rudimentary state of AMF prospecting for multidimensional applications in Nigeria and Africa, it acknowledges them as promising bioresources in the future of biotechnological advancement. Maximizing their potential uses through technology transfer and research innovations that target indigenous challenges is becoming interesting and requiring more economic scale studies (Vijayakumar and Saravanan, 2015). AMF have unique but inspiring functionalities and promising potentials that remained under-utilized in a variety of industrial processes involving the production of bioplastics, biopackages, antimicrobials, biofortification, tonics, biosurfactants, nutritional and vitamin supplements. Furthermore, little is known about their application in the production of beverages (fruit and alcoholic), pharmaceuticals, organic chemicals, agrochemicals, cosmetics and bioenergy products in the African continent. Several studies have identified the presence of infective AMF propagules and mycorrhizal associations in some contaminated (heavy metals, petroleum hydrocarbon) lands without clear quantification of the underlying mechanisms (Nicolopoulou-Stamati *et al.*, 2016). Similarly, references on their application in indigent petroleum, metallurgy, petrochemical and the mining processes are few (Asmelash *et al.*, 2016; Park *et al.*, 2016; Garcés-Ruiz *et al.*, 2017; Wang, 2017). Recognizing the potentials that abound in the diversity of AMF and perfecting their inocula commercialization are basic to their application in afforestation processes,

bioeconomic, food security and safety initiatives in many sub-saharan countries. This consciousness is rapidly evolving and expanding beyond agronomy to other value addition interests in biofortification, biopreservation, entomopathological and food processing biotechnologies. Also, their innovative applications for design and ornamentation purposes are incontrovertibly undermined by lack of critical understanding of AMF mycelial functionalities, impacts, technical and experiential qualities. One could assume that the AMF mycelium is potentially valuable, as other fungal mycelia, for use as non-toxic, biodegradable and sustainable materials to interlock other substances in the production of bioplastics and food packages (Molina and Horton, 2015; Karana *et al.*, 2018). Giving more attention to AMF explorations may open up novel possibilities for their innovative application in the creation of exotic material or product concepts of bioeconomic significance (Bâ *et al.*, 2012). Raising AMF to an appreciable level of commercial relevance and preference among the list of bioeconomically dependent genetic resources is still far-fetched.

## Conclusion

The environmental, biotechnological and socio-economic potentials of AMF and other mycorrhizae are underexplored for bioeconomic development in many developing nations of the world. Africa, apart from being tagged the "mother continent" from an archeological perspective, is ranked as one of the most biological diverse continents in today's world throughout her 30.3 million Km<sup>2</sup> spread, yet one of the least dependent on biological resources for economic advancement. This simply suggests that the diversity of African biogenetic resources are undercounted, understudied, poorly documented, underexploited for economic and biotechnological benefits. It is further assumed that the large biodiversities in Africa, their value-adding potentials and ecological services are equivocal. AMF applications are mostly associated with agroecosystem practices rather than in food, environmental and industrial systems in Africa. In Nigeria, the availability of well-researched, documented and verse alternative biogenetic resources is a throw-put to the consideration of AMF in biotechnology systems. Therefore awareness of the diverse bioeconomic possibilities of AMF could shift African scientists toward their exploration. This might help reduce the generic ecosystem consequences that are directly or indirectly linked to overexploitation of other common bioresources. Similarly, the world is constantly in need of stable products and biomaterials with multiple bioactivities, zero-toxicity or side-effects



and wide versatility to replace the chemically synthesized equivalents. It is therefore not farfetched to expand the spectrum of choice to further strengthen products development and food security strategies. AMF in association with other fungi may hold the key to the world's next wonder product or novel drug discovery.

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## Author's Contributions

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**Charles Oluwaseun Adetunji:** Conceptualization, drafting and reviewing the MS.

**Abbot Okotie Oghenekaro:** Contributed to the development of part of the subtitles on the MS.

**Elizabeth Temitope Alori:** Drafting of the subtitle Arbuscular Mycorrhizal Fungi.

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## Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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