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The inevitability of arbuscular mycorrhiza for sustainability in organic agriculture—A critical review

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The arbuscular mycorrhizal fungi (AMF) are significant fertility-promoting microbes in soils. They enable soil fertility, soil-health and boost crop productivity. There are generalist and specialist groups among AMF in natural soils. Optimized use of specific AMF concerning crops and soils can improve agricultural sustainability. Thus, AMF is becoming an inevitable biological tool for improving crop productivity and soil health. Especially in the context of chemicalized agriculture undermining the sustainability of food security, safety, and human and ecosystem health, alternative agricultural means have become inevitable. Therefore, AMF has become essential in nature-friendly, organic agriculture. Of such farm fields, natural biological activity is enhanced to sustain soil fertility. Crops show increased innate immunity against pests and diseases in many such systems. Moreover, ecosystems remain healthy, and the soil is teeming with life in such farms. The primary goal of the review was a thorough critical analysis of the literature on AMF in organic agriculture to assess its efficiency as an ecotechnological tool in sustainable agricultural productivity. The novelty is that this is the first comprehensive review of literature on AMF concerning all aspects of organic agriculture. A vital systematic approach to the exhaustive literature collected using regular databases on the theme is followed for synthesizing the review. The review revealed the essentiality of utilizing specific mycorrhizal species, individually or in consortia, in diverse environmental settings to ensure sustainable organic crop production. However, for the exact usage of specific AMF in sustainable organic agriculture, extensive exploration of them in traditional pockets of specific crop cultivations of both chemical and organic fields and wild environments is required. Moreover, intensive experimentations are also necessary to assess them individually, in combinations, and associated with diverse beneficial soil bacteria.

KEYWORDS

agricultural sustainability, AMF, biofertilizer, sustainable agriculture, soil degradation, soil fertility

1. Introduction

Food safety and security for a growing global population have always been crucial challenges for humans (UN Report, 2022). Chemicalized agriculture is not ensuring agricultural sustainability for the future (Ma et al., 2022) because it causes severe environmental challenges and biodiversity erosion (Bremmer et al., 2021; Lambertini, 2021), impacting soil, human, and ecosystem health. It has been causing soil degradation (FAO and ITPS, 2015; Liu J. et al., 2020; Pahalvi et al., 2021), accumulation of toxic metals

(Sahodaran and Ray, 2018), and biocide residues in soils (Silva et al., 2019), affecting its productivity. Continued applications of agrochemicals in the fields cause pest resistance (Phillips, 2020), negatively impacting agricultural production's cost-effectiveness (Durham and Mizik, 2021). Severe water quality deterioration in chemicalized agricultural zones exists (Vera-Herrera et al., 2022). It also contributes to more than 10% of global greenhouse gas emissions (Chai et al., 2019), accelerating global warming. Thus, chemicalized conventional agriculture is challenging food security and safety in the future.

Sustainability in all spheres of human activities, including agriculture, is the focus of the UN's Sustainable Developmental Goals (SDGs) for the world (FAO, 2018; Sridhar et al., 2022). Accordingly, organic farming is emerging as an alternative means of productive and sustainable agriculture (Fitzpatrick et al., 2022; Jaacks et al., 2022). It also enables avoiding environmental impacts and toxicities of chemicalized farming (Amuji, 2022) and improving soil health (Tahat et al., 2020). The scientific world recognizes its potential to meet food security (Morshedi et al., 2017) and food safety (FAO, 2021). Organic agriculture also has the potential to address the crucial challenges of climate change (Cidón et al., 2021) because organic farming can promote excessive sequestration and conservation of carbon in soil systems (Page et al., 2020). Therefore, organic agricultural practice continuously grows globally (IFOAM and FiBL, 2021). Because of the current uprising of a green movement globally and the emergence of new food policies (European Commission Report, 2020) worldwide, the 'green food products' of organic agriculture will be the mainstream food ensuring the health of people (Mie et al., 2017; Ashaolu and Ashaolu, 2020) in the future. Therefore, a paradigm shift is becoming essential for the green organic movement (Runhaar, 2021).

The organic or natural means of soil fertility management include using organic fertilizers and fertility-aiding microbial communities (Yadav et al., 2013; Mohanty et al., 2021; Silveira et al., 2021). The quality and quantity of nutrients released from an organic fertilizer depend on the kind of fertilizers applied (Ye et al., 2020), the physicochemical nature of soils, and the existing biotic community within the same. However, the current low availability and high cost of organic fertilizers limit farmers from supplying sufficient nutrients to crops through organic means (Bergstrand, 2022). Moreover, unfavorable microbial activities in organically enriched soils may cause the leaching of NO_3 into groundwaters (Bibi et al., 2016), denitrification, or acidification of soils (Wang J. et al., 2018), causing loss of soil fertility and environmental degradations. Therefore, achieving success in organic agriculture depends on continuous monitoring of the natural microflora and identification of the exact roles of each of them in maintaining soil health and fertility (Reyes-Sánchez et al., 2022). It also depends on our ability to manage the natural microflora in soils scientifically (FAO, 2022; Mrunalini et al., 2022) and use crop-friendly microbes as biofertilizers, which can be an alternative to chemical fertilizers. A judicious additional supply of desirable microorganisms as a biofertilizer (Yang et al., 2021) has become inevitable for the evolution of organic agriculture as a successful alternative mode of agriculture for the sustainability of human civilization (FAO, 2017). Among the microflora in soils, the AMF is the most significant group of organisms utilizable as biofertilizers (Chen et al., 2018; Fall et al., 2022).

The role of AMF in assisting the sustainability of soil fertility and enhancement of crop productivity is one of the most researched and well-known themes in Agronomy (Giovannini et al., 2020). The AMF form a particular category of organisms supporting plants in satisfying their thirst for water and mineral, especially for plants growing in nutrient-deficient systems (Kobae, 2019; Nanjundappa et al., 2019). The AMF positively supports other soil microbiota (Bhale et al., 2018). AMF are more affluent and influential in organic farm soils than chemicalized farms (Mullath et al., 2019; Barceló et al., 2020; Jiang et al., 2021; Huo et al., 2022). Moreover, chemicalized farms usually do not accommodate all the beneficial AMF, especially the sensitive species (Pontes-da-Silva et al., 2018). They are helpful in the upgradation of soil structure, aiding plants in their water relations, and improving heavy metal tolerance in plants (Zhang et al., 2019; Jadrane et al., 2021; Riaz et al., 2021). They aid plants in developing resistance against diseases through microbial-assisted molecular pathway-triggered immunity (Basu et al., 2018). Thus, the AMF is becoming an integral part of the successful functioning of organic farming and the maintenance of crop fields as a sustainable agroecosystem (Kuila and Ghosh, 2022). However, AMF cannot be effective in soils devoid of one or more nutrients. Some species of AMF, especially in specific environmental conditions, can also have adverse effects on host plants. Sometimes they affect soil seed bank viability (Maighal et al., 2016). Therefore, experimental studies have become inevitable in standardizing AMF involving organic agricultural practices (Ray and Valsalakumar, 2010a,b) in specific soils.

In the above contexts, a systematic, thorough critical review of literature has become essential to explore the current status of AMF as an inevitable component in organic agriculture for further intensification of investigations. Accordingly, the scope of AMF as a successful biofertilizer option for all the sustainable farming models, such as organic farming, eco-farming, and natural farming, which differ in certain aspects and concepts, are considered together in the review. Because all such farming options focus on the sustainability of food production, environmental quality, and improvement in public health (EPRS Report, 2016) by avoiding excessive direct use of chemicals in agriculture, and all such models consider natural means of soil fertility management and pest control (Stoleru and Sellitto, 2016; Rempelos et al., 2021) as the major components of agricultural production management. The significant goals included the identification of the gap and scope in AMF concerning organic agriculture in the existing literature. In addition, the review also focused on identifying the tasks ahead in applying specific AMF or their consortia, along with other biological components, as comprehensive alternatives to the chemicalized provision of nutrients for ensuring sustainable productivity in organic agriculture.

A standard critical approach (Smith et al., 2019; Nazari et al., 2020; Tully and McAskill, 2020) to the available exhaustive literature is followed in the preparation of this review. Specific keywords such as "Organic Farming," "AMF and organic farming," "AMF and soil structure," "AMF and water relations," "AMF and major nutrients," "AMF and micronutrients," "AMF and contaminated soil," "AMF and carbon sequestration," "AMF and agricultural sustainability," "role of AMF in improving disease resistance in the crop," "AMF and adverse effects" and the like are used to identify literature from electronic databases such as Clarivate Web of Sciences, Frontiers, EBSCO, Taylor and Francis, JSTOR, SciFinder, Cambridge University Press, Oxford University Press, Springer and the like for collecting the relevant literature. Since the literature on organic farming is available sufficiently from the 1980s, the literature collection period was fixed as 1989–2022. A similar comprehensive review on the topic (Ryan and Tibbett, 2008) appeared in 2008; however, it discusses the general significance of AMF in agriculture, not emphasizing the need for further research in AMF concerning organic farming. Therefore, the present review is highly imminent and essential.

Overall, the findings reveal that the available literature on AMF in organic farming belongs to various themes such as surveys of AMF in diverse natural and agricultural environments, experimental studies on the role of AMF in various crops under different farming practices, AMF and soil structure in organically managed soils, AMF as an agent of carbon accumulation or carbon cycling in organic farms, AMF as an agent for increasing disease resistance or overcoming stress in crops, AMF as an agent for significant nutrient supply in organic soils, water relations of crops, micronutrient enhancement, heavy metal tolerance, and adverse effects of AMF on organic crops. A critical summary of the details of the findings is discussed below.

2. The literature on AMF concerning organic farming

In general, there has been a continuous growth of literature on AMF concerning organic farming per year (Figure 1) in the past four decades (the 1980s to 2022). The Microsoft Excel-generated data map (Figure 2) shows the region-wide distribution of literature in the world, which reveals that more than 50% of the total publications are from three countries, China (28.37%), the USA (14.01%), and Italy (9.40%). The entire research data on "AMF in Organic Agriculture" collected from the "Web of Science" reveals that it is spread over 32 sub-disciplines. Among the five hundred and eighty-five research publications collected from over the 32 sub-disciplines in journals/books/websites, 248 relevant research articles are critically analyzed to synthesize the current review. Data analysis reveals that a significant share of research publications, 315 (53.84%) of the total 585 publications, belongs to the sub-discipline, Agriculture. This fact emphasizes the significance of AMF in organic agriculture.

3. Utility of AMF in organic agriculture

Ryan and Tibbett (2008) have thoroughly reviewed the significance of AM fungal benefits in organic agriculture. According to them, AMF improves crop growth and supports them in drought avoidance and disease control. They also contribute to long-term ecosystem sustainability by improving and maintaining soil structure, plant community structure, and diversity. Although AMF root colonization in crops is higher in organic farms than in conventional fields, the benefits may vary depending on crops, soils, geographic locations, and seasons. However, they cannot be substituted for fertilizer inputs. Moreover, the authors observe that the AMF flora in conventional chemicalized farm soils can sometimes be "weedy," less beneficial, or not beneficial to crops. Therefore, the application of AMF in organic agriculture of specific crops, soils, and cultivation practices must be optimized for desirable results. However, researchers have also reported that although AMF in natural soils improves the quality of vegetables, inoculation with non-native mycorrhizal fungi can suppress native AMF in crops and negatively impacts the quality of vegetables (Mukherjee et al., 2020), even in organic agriculture. The same authors also observed that organic farming consistently improves disease tolerance in crops but cannot explain the role of AMF in the same.

Avoiding chemical fertilizers in fields can significantly improve the microbial diversity in soils, including that of AMF. However, the nature and amount of organic matter added to soils decide the abundance and diversity of microbes, including mycorrhiza in soils (Ma et al., 2018, 2022; Naorema et al., 2021). According to Liu L. et al. (2020), decreased availability of readily available phosphorus increases AMF activity in crop fields. Accordingly, while organic fertilizers with less readily available phosphorus trigger the abundance and diversity of AMF in soils, chemical fertilizers with more readily available phosphorus decrease the soil's AMF flora. A comparison of organic and conventional farming suggests that, in the long run, organic farming increases the species diversity of AMF (Kazeeroni and Al-Sadi, 2016; Gazdag et al., 2019) in such fields. In a review of the influence of organic farming systems on soil biodiversity, Leksono (2017) explains that organic agricultural activities cause an increase in AMF spore density and species richness in soils. In general, while organic farming contributes to an increase in the diversity of AMF, intensive soil management practices of conventional agriculture considerably diminish them (Manoharan et al., 2017).

In general, researchers view that AMF enhances NPK uptake by plants (Nadiah et al., 2020; Chandrasekaran, 2022; Shen K. et al., 2022; Shen M. et al., 2022). Thus, AMF assist plants in improving their biomass. AMF also help specific plants in their synthesis of particular metabolites (Trisilawati et al., 2019). Accordingly, AMF are well-known to have a direct positive influence on plant physiology or plant biochemical pathways. Igiehon and Babalola (2017), in their review on the role of biofertilizers in sustainable agriculture, emphasize the significance of AMF in improving the resistance of crops to diseases and tolerance to abiotic environmental stresses. Suja et al. (2017) also show that organically grown plants can ensure stable yield and product quality in crops such as Taro while keeping soil quality intact.

In general, the literature on the utility of AMF in organic agriculture is tremendous. Therefore, the exhaustive literature (46 articles) on various aspects of AMF in organic agriculture is systematically given in Table 1 below for a bird's eye view. The table reveals that the research on AMF in organic farming includes field surveys and field or other experimental studies. It is clear from the table that existing studies endorse AMF as an inevitable component of organic agriculture. It also reveals the significant gap between rigorous experimentations with crop-specific, climate, and soil-specific AMF application trials in the organic farming of diverse crops. Accordingly, exploration

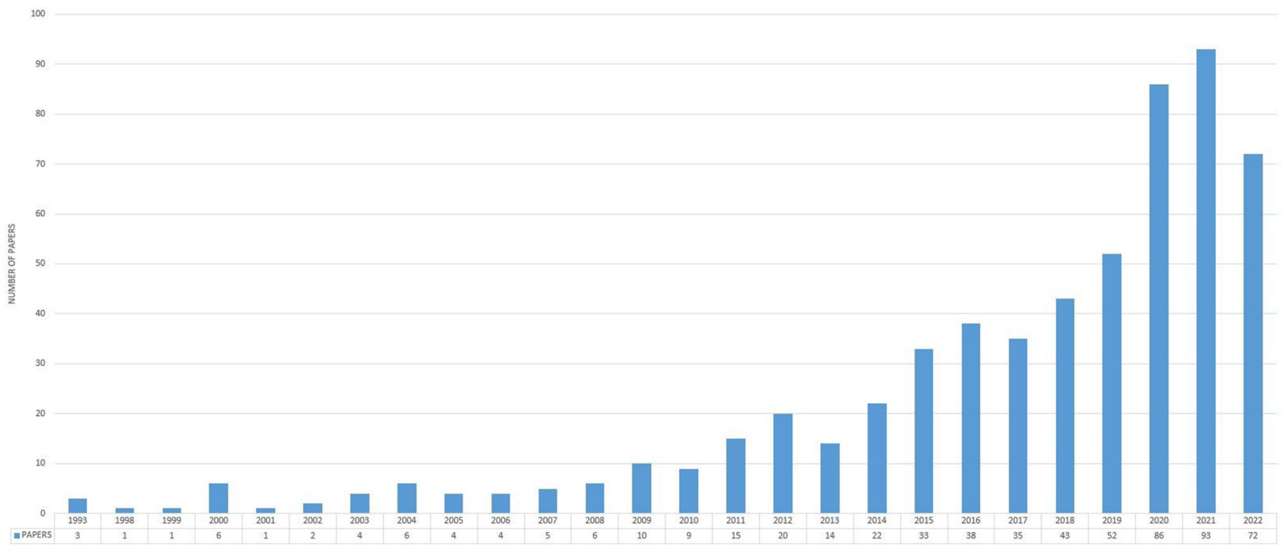

FIGURE 1
Year-wise growth of Literature on AMF concerning organic farming (1993–2022).

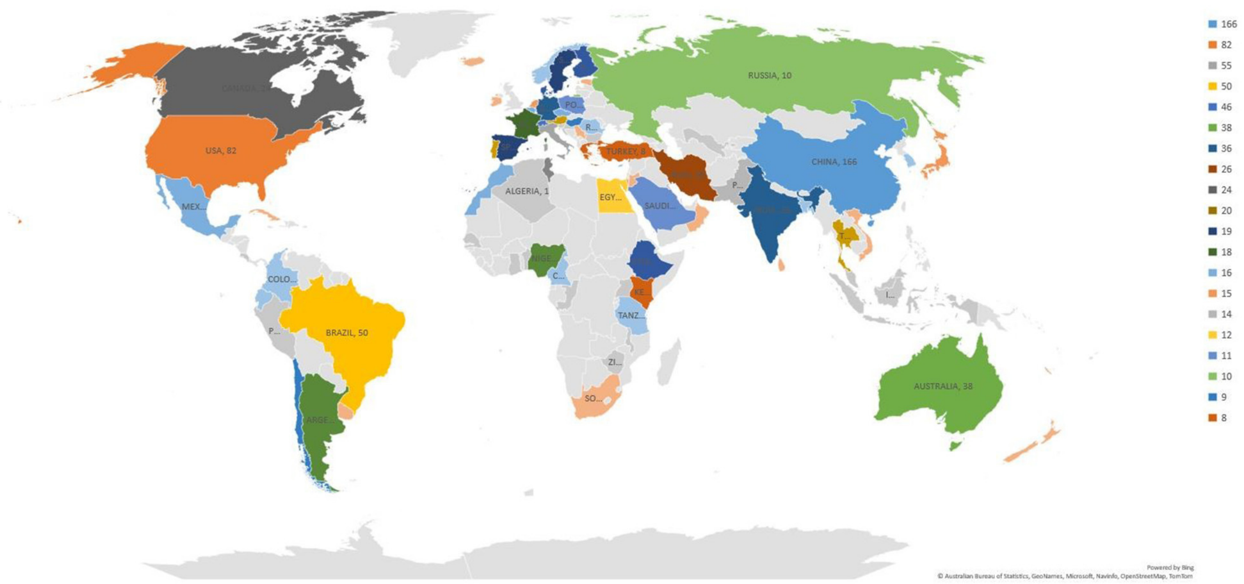

FIGURE 2
Country-wise distribution of available literature on AMF and organic agriculture.

of the natural AM flora of specific crop fields in traditional crop belts, both chemicalized and organic, is also essential (Valsalakumar et al., 2007) for identifying the beneficial and weedy AMF for each crop. Then only experimental trials of judicious utilization of AMF in organic agricultural management can be decided.

4. AMF and soil structure

Soil structure is a "master quality" of soil (Ray, 1993; Ray et al., 1993), one of the most significant parameters of soil health. It is the outcome of the sum of biological activities in the soil of any natural environment (Rillig et al., 2017). A good structure with a high percentage of water-stable soil aggregates is a unique marker of organically managed natural fields. Biologically highly organized, structured soils are especially visible in organically enriched and non-chemicalized agricultural fields where the diversity of AMF is also relatively high (Marinho et al., 2019). The AMF directly contributes to good soil structural quality and maintenance in natural soils. Among the diverse factors contributing to soil structure formation, glomalin secretion from extraradical hyphae of AMF is a significant component (Muneer et al., 2020), which helps in soil binding.

Glomalin-related soil proteins (GRSP) are a range of glycoproteins released into soils by the hyphae and spore

TABLE 1 Summary of reports on the benefits of organic agriculture, especially the beneficial roles of AMF, as appeared in the literature—a critical analysis.

Exact location	The kind of investigation	Soils/plants/crop	Variables measured	Major findings	References
A. Field survey/ field study for AMF in organic agricultural soils vs. conventional fields					
Urupema, Santa Catherina, Brazil	Field survey of AMF in organically managed orchards, conventional orchards, and grasslands	*Malus domestica*	Bradford-reactive soil protein, AMF richness, Mycorrhizal inoculum potential, Hyphal length, and AMF spore abundance	The AMF activity is higher in organic orchards than in grasslands concerning all the studied variables, whereas the conventional orchards did not maintain the AMF activity	Purin et al., 2006
North Carolina, USA	Field survey examining the impact of different farming practices on soil properties, including microbial species and their effect on Plant pathogen *Sclerotium rolfsii*	Soil samples of different farms	Soil physicochemical and biological parameters such as selected microbial species and different kinds of nematodes, and the total microbial biomass	Organic farming improves all the soil properties compared to other farming practices	Liu et al., 2007
Kyeongi, Korea	Field survey of red pepper cultivating organic farms and other differently managed agricultural systems to assess the effect of organic farming on AMF in soil	*Capsicum annum*	The mycorrhizal inoculum potential, root colonization, spore density and community analysis of AMF using molecular technique	AMF activity is higher in organic farming than in the other systems. But no significant difference in mycorrhizal root colonization over the different systems	Lee et al., 2008
Zeeland and Flevoland, Netherland	Field survey of onion farms under organic and conventional agricultural management practices	*Allium cepa*	AMF colonization rate, molecular diversity analysis	Organic farming enhances AMF diversity in soils and root colonization in crops	Galván et al., 2009
Netherlands	Field survey of agricultural fields, organic and conventional (chemicalised) arable fields cultivated with Maize and Potato throughout the country and five semi-natural grasslands	*Zea mays* and *Solanum tuberosum*	Soil chemical parameters, average root length, DNA extraction studies of AMF community in the field using the T-RFs followed by Principal component analysis	No significant differences between organic and conventional fields for any of the variables; previous crops and phosphate availability are predictors of differentiation among the AMF assemblages; AMF diversity is higher under organic farming, and AMF richness increases significantly over time	Verbruggen et al., 2010
Pavia, Italy	Field study of rice following crop rotations to evaluate the biodiversity of AMF in the rhizosphere of the crops concerning agricultural practices such as conventional and organic means	*Oryza sativa*	Physico-chemical characters of soil, root colonization of AMF; AMF diversity analysis by DNA extraction and PCR methods	No root colonization is found in conventional farms, whereas 0 to 34 % colonization in organic farms; AMF colonization in rice roots disappears after flooding; AMF species in rice belong to Paraglomorales/Archeosporales; the conventional system depresses AMF infection in rice; organic farming promotes AMF diversity in rice fields	Lumini et al., 2011
Ratchathani and Sisaket provinces, Thailand	Survey of AMF in organically grown Chili fields, *in vivo* culture of spores and pot experiment on the effect of ten species of the selected AMF on Chili	*Capsicum frutescens*	Soil nutrient assessment (NPK), Plant growth parameters such as shoot height, stem diameter, root and shoot fresh weight, number of fruits and flowers per plant, % of root colonization and spore density	Fourteen species of AMF are isolated from the Chilly organic fields. Experiments revealed that *Acaulospora appendicula* (HR0201), *A. denticulata* (RA2106), and *G. clarum* (RA0305) are the best chili growth promoters, insensitive to P status, increase growth, flowering and fruiting in Chili	Boonlue et al., 2012

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TABLE 1 (Continued)

Exact location	The kind of investigation	Soils/ plants/crop	Variables measured	Major findings	References
Montepaldi Long Term Experiment site, University of Florence, Central Italy	Field study of AMF activity in four plots of organic and conventional Maise fields	AMF in the Maize field and mycorrhizal inoculum potential (MIP) of the Maize field	Soil physicochemical properties, root colonization of Maize roots, mycorrhizal inoculum potential	No significant differences in soil physicochemical characters among the three systems in the site; MIP and Glomalin-related soil proteins are significantly higher in organic methods; AMF activity is progressively higher in organic systems than in conventional systems	Bedini et al., 2013
South-western Ontario, Canada	A comparative field study to explore variations in AMF communities of organically managed and conventionally managed forage fields	Perennial forages (*Medicago sativa* and *Phleum pratense*)	Soil DNA extraction, molecular estimation of AMF species richness and community structure in diverse fields	Soil AMF communities are different among organically and conventionally managed forage fields. *Funneliformis mosseae* is common in conventional farm soils, whereas *Claroideoglomus. claroideum* is an abundant species of AMF in organically managed fields	Schneider et al., 2015
South Flanders, Belgium	A comparative study of the AMF communities in conventionally and organically managed apple orchards across a region	Apple trees (Jonagold cultivar grafted on M9 rootstocks)	Soil chemical parameters, AMF diversity and community composition using 454-pyrosequencing of small-subunit rRNA gene amplicons	AMF richness is significantly higher in organic orchards than in conventional orchards; Plant available P is firmly inversely correlated with AMF richness	van Geel et al., 2015
Flanders, the Northern part of Belgium and the Southern part of the Netherlands	Field survey of organically and conventionally managed Vineyards to study the advantage of organic farming	*Vitis vinifera* grafted on SO4 rootstocks	The soil chemical parameters, AMF diversity using DNA extraction followed by pyrosequencing	No difference in AMF diversity between organically and conventionally managed vineyards; plant-available P and soil pH are the variables significantly related to AMF diversity. High soil P jeopardize the potential role of AMF in soil. No effect of Cu concentration in soil on AMF diversity	van Geel et al., 2017
Washington and Oregon, USA	A comparative field study of AMF diversity in organic and fungicide fumigated and non-fumigated conventional fields	*Allium cepa*	Soil physicochemical characters, AMF community, root colonization	AMF richness and diversity are more extraordinary in organic than conventional fields. Fumigation does not alter AMF community structure but reduces AMF diversity. Dominant AMF taxa are found in moderate P levels in organic and traditional onion crops	Knerr et al., 2018
Sao Francisco river basin, Brazil	Field survey of AMF community structure concerning native flora in different fields followed by greenhouse experiment	AMF concerning the native flora of Forest, grasslands and cultivation fields of *Zea mays, Saccharum officinale*	Soil physicochemical properties, AMF diversity and spore count and root colonization	Soil management practices of cultivated areas decrease the diversity of AM fungi in cultivated fields more than in natural forests. Adding AMF spores of known species into crop fields is better than leaving the field to acquire the AMF of poor quality naturally	Azevedo Correa, 2019
North West and South-West regions, Switzerland	A field study to test the impact of different farming techniques such as conventional and organic farming on root fungal community structure in 60 wheat fields	*Triticum aestivum*	DNA sequencing of AMF diversity indices, fungal root network for each farming system and diversity of keystone species	The diversity and overall taxonomic composition of AMF do not vary over conventional, no-till and organic systems, but the farming system significantly affects the root fungal community structure of organic	Banerjee et al., 2019

(Continued)

TABLE 1 (Continued)

Exact location	The kind of investigation	Soils/ plants/crop	Variables measured	Major findings	References
Juchowo, Northern Poland	A field study examines the effect of tillage on soil properties and soil enzymatic activity in organically and conventionally managed soils	Soil study	Soil chemical property, soil enzyme activity, easily extractable glomalin-related protein content (EEGRSP), pH, total organic carbon (TOC), total nitrogen (TN), dissolved organic carbon (DOC), and dissolved nitrogen (DON)	Reduced tillage causes organic soils to significantly improve all the measured parameters, including EE-GRSP, than conventional farm soils with normal tillage. Soil enzyme activity in organic soil with reduced tillage is superior to traditional farm soils	Kobierski et al., 2020
The central valley of California, USA	Field survey of AMF associations with roots of Almond concerning orchard management practices and soil properties	*Prunus dulcis*	AMF root colonization in *Prunus dulcis* orchards of 1.5 to 20 years old, both organic and conventional; soil properties such as total N and C, exchangeable soil K, P, Ca, Mg, Na	Cover crops of resident vegetation and soil P concentrations are the most significant factors affecting high root colonization in Almond	Vasilikiotis et al., 2020
Switzerland	Filed survey of organic, conventional with tillage and conventional without tillage practices for assessing the influence of pesticide residues on soil microbial community, including AMF	*Triticum aestivum* and vegetables	Soil physicochemical analysis, mycorrhizal colonization, microbial biomass and basal respiration	Negative correlations exist between AMF in roots and pesticide content in the soil, and pesticide is a crucial driver of AMF abundance in the field	Riedo et al., 2021
Dordogne, Correze and Lot, South Western France	Field survey to compare the effects of cover crops and soil microbial populations on AM fungal colonization in walnut plantations grown organically and conventionally	Walnut and Faba bean	Physicochemical soil properties, fungal colonization, arbuscular abundance, the mycorrhizal intensity with and without the introduction of cover crops	Soil microbial communities and cover crops can explain the natural mycorrhisation of walnut trees. The cover crops have different influences on walnut plantations according to farming systems	Thioye et al., 2022
B. Field experiment for AMF influence/ performance in crops/fields					
Pantnagar, Uttarakhand, India	A field experiment to examine the impact of organic farming on the microbial community, including AMF in the rhizosphere	*Hibiscus esculentus* L, *Pisum sativum* L., *Vigna unguiculata*	The activity of culturable and non-culturable residing bacterial populations in the soil, as well as the movement of added *Pseudomonas fluorescens* and AMF in soil, and soil enzyme activity	Differentiation in the community structure of microbial population in different plots corresponds to the difference in inoculants, whereas uninoculated stories show uniform distribution; AMF inoculants cause changes in root exudation pattern and changes in inhabiting rhizosphere bacterial community	Srivastava et al., 2007
Bologna, Italy	An experimental study to assess the effect of a consortium of AMF and other plant growth-promoting microbes in tomato farming with and without compost	A particular cultivar of Tomato by the name "*Riogrnde*"	Yield and quality of vegetable	The soil probiotics increase the growth of tomatoes as well as mycorrhizal root colonization at medium amendments of the compost	Baruffa, 2008
Chiba, Japan	Experimental plant growth in the presence of rhizobia and AMF individually or in combination with and without organic or chemical fertilizers	*Phaseolus vulgaris*	Plant shoot dry weight, root nodulation, AMF colonization	Dual inoculation with AMF and rhizobia is more effective in increasing the productivity of legumes but better under organically managed soils than the chemically managed soils	Aryal et al., 2003

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TABLE 1 (Continued)

Exact location	The kind of investigation	Soils/ plants/crop	Variables measured	Major findings	References
Tuscany, Italy	A field experiment to assess the effect of organic and conventional soil management practices on soil quality in Mediterranean soils cultivated with different crops on rotation	*Beta vulgaris*, *Triticum aestivum*, *Helianthusannus*, *Vicia faba*, *Triticum durum*, *Zea mays*, *Trifolium pratense*	Soil physicochemical, biochemical and biological parameters, metabolic quotient, AMF spore count, root colonization microarthropod community	A significant increase in C was observed in the organic system over the conventional method. However, the biological soil quality index is higher in traditional fields than in organic fields; the 5-year assessment is insufficient to identify the influence of the organic model of crop management in fields	Mazzoncini et al., 2010
Petrolina, Brazil	Field experimental study to test the effect of organic and chemicalised practices on microbial population in seedless grape fields	The seedless grape cultivar "Festival seedless/LAC 766 rootstock"	AMF spore number per gram of soil, most probable number of propagules, AM species richness, root colonization, Bradford-related soil protein (EE-BRSP), microbial biomass carbon (C-MB), microbial respiration, and soil FDA activity	The highest sporulation and three times root colonization are present in the organic system; organic cultivation is not increasing EE-BRSP. AMF sp such as *Acaulospora excavata* is found only in organic systems	de Oliveira Freitas et al., 2011
Taperoa Municipality, Paraiba state Brazil	An experimental study comparing the effects of different combinations of organic (goat manure) and green waste (Glyricidia) on AMF community in inter-cropping systems of three crops	Maise (*Zea mays)*, Cowpea (*Vigna unguiculata)*, Cotton (*Gossypium hirsutum*)	Spore density, diversity, glomalin-related proteins (GRSP), and root colonization	Application of goat manure favor AMF activity and diversity in the rhizosphere of Maise and cowpea compared to the control. Goat manure and Glyricidia favor glomalin production and spore in the rhizosphere of cotton	Sousa et al., 2011
Israel	Experiments to test plant biomass variation concerning different spp of AMF applications and other organic amendments	*Allium schoenoprasum*	Spore germination assay, root colonization, and biomass production	Yield in organic farming of Allium using AMF technology depends on a careful selection of the organic manure composition and specific species of AMF	Üstüner et al., 2009
University of Wyoming Sustainable Agriculture Research and Extension Center, Lingley, Wyoming	Experiment to see if microbial substrate quality and use induce changes in soil microbiota parameters, including microbial biomass and community structure, in response to alternate management systems	*Medicago sativa, Dactylis glomerata, Bromis riparius* and *Avena sativa*	Soil Physicochemical parameters, Phospholipid fatty acid (PLFA), Fatty acid methyl ester (FAME)	The organic management of the crops resulted in a higher soil organic content and microbial biomass. The bacterial, fungal, and protozoan abundance increased from 2 to 36 folds, marked by the PLFA increase. This led to the belief that crop rotations, tillage management, soil amendments, and legumes did play a considerable role in the increase in soil microbial properties	Ghimire et al., 2018
Sissle valley, Canton Aargau, Switzerland	A long-term field experiment to test the role of soil tillage (reduced and conventional tillage) and type of fertilizers (farmyard manure and slurry or slurry only) on AMF communities in the organically managed farm	Sunflower, Wheat, Maize, Spelt	Soil chemical characteristics; AMF spore densities in the field, AMF species richness in the field soil (top-soil and sub-soil) and AMF diversity	Increasing land use intensity reduces spore density and changes in AMF community composition. Several AMF species can be specialists for specific soil types or management practices. It is essential to explore the role of AMF communities and individual AMF sp on plant growth and health	Säle et al., 2015
Swiss research Agroscope, Changins	A field experiment to evaluate the long-term influence of fertilization practices (farmyard manure + crop residue and conventional mineral fertilizer) on soil physicochemical properties, microbial communities and crop yields	Wheat-Maise-Wheat rotation followed by Sugarbeet and then by Rapeseed	Soil physicochemical parameters, soil microbial biomass and microbial community structure	Organic amendments significantly increase soil organic matter content more than conventional chemical fertilizers. The organic amendments raised crop yields, especially compared to traditional chemical fertilization	Blanchet et al., 2016

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TABLE 1 (Continued)

Exact location	The kind of investigation	Soils/ plants/crop	Variables measured	Major findings	References
Agricultural Research Station, Heilongjiang Academy of Agricultural Sciences, Harbin city, Heilongjiang province, China	Field experimental study to assess different combinations of NPK and organic manure to test the impact of chemical fertilizers on AMF	*Zea mays*	DNA extract from Rhizosphere samples of each experimental setup to estimate AMF using 18S rRNA gene amplification and Illumina sequencing	Significant increase in AMF diversity in organic manured fields; Organic matter in soils is a critical factor for AMF in soils. N and P were the other factors influencing AMF in soils	Zhu et al., 2016
Chulalongkorn University study area, Keang Koi District, Saraburi Province, Thailand	A field experiment to test the effect of *Funneliformismossae*in a crop (seedlings with and without 50 spores per plant) in an organic pot medium	*Lactuca sativa*	Leaf number, fresh weight of leaves, photosynthesis and chlorophyll-a content, root colonization (%), soil and plant nutrient content and antioxidant enzyme assay of inoculated plant	AMF inoculation increases the yield of the crop; specificity in interrelations between *F. mosseae* and butterhead-lettuce grows the quality and quantity of the crop in an organically cultivated medium	Charoonnart et al., 2016
Scheyern Research Farm, Germany	A field experimental study to test organic and integrated systems with plow tillage and minimum tillage on soil microbial community, including AMF	Rotation of four crops of Potato-Mustard, Winter Wheat-Maize, and Winter Wheat in integrated plots whereas seven crops in organic plots	Microbial community structure, Microbial biomass, phospholipid fatty acid profile (PLFA), and glomalin content	Organic farming and minimum tillage positively influence microbial biomass and microbial community, including AMF; saprotrophic fungi are more sensitive to tillage. A combination of organic farming and minimum tillage is an effective cropping system	Sun et al., 2016
Experimental field of Shimane University, Matsue, Japan	A field experiment to test AMF and Gliocladium fungi application in wood and bamboo waste as a productive system for *Capsicum annuum*	*Capsicum annum*	Shoot length, stem diameter, Soil and plant mineral content ($NO3^-$, K^+, and Ca^{++}, the root colonization rate	The combination of AMF and GF in bamboo and wood waste is a beneficial, sustainable, and productive system for the *Capsicum annuum*	Islam and Katoh, 2017
Calakmul Biosphere Reserve, Campeche, Mexico	A field experiment to test the impact of chemical fertilizers, vermicompost, vermicompost leachates, and no fertilization on AMF diversity in soils	*Physalis ixocarpa*	Soil physicochemical parameters, AMF root colonization, AMF diversity, crop yield, root and shoot biomass, fruit production	Vermicompost and leachates can promote AMF diversity in soils, leading to increased crop growth and production comparable to chemical fertilization in the crop	Cruz-Koizumi et al., 2018
Therwil, Switzerland	A field experiment to test artificially introduced draft on soil water content, microorganisms, and crops under conventional and biodynamic (BioDyn) farming systems	*Triticum aestivum*	Soil physicochemical characters, basal soil respiration, alpha and beta diversity of bacterial and fungal communities, indicator species, crop growth, yield and weed cover, AMF diversity, and abundance	The organic farming (BioDyn) system enhances soil water storage capacity. However, the interaction between farming systems and drought on microbial communities should be investigated further under more substantial, extended, and repeated droughts	Kundel et al., 2020
Saskatchewan, Canada	Field experimental study to test the effect of the AMF and *Penicillium bilaiae,* individually and in combination in different soils	*Triticum aestivum, Lens culinaris, Linum usitatissimum*	Root-colonization rate and soil physicochemical characteristics	Applying AMF or *P. bilaiae* does not consistently improve P uptake in soils. The initial AMF activity of the soil does not determine the response of the crop to inoculation with the AMF	Knight, 2020
Maremma Regional Park, Grosseto, Italy	An experimental study in the presence or absence of an AMF (*Rhizophagus irregularis*) to test its effect on micronutrient uptake in twelve different bread wheat genotypes	*Triticum aestivum*	Root colonization, plant height and yield, micronutrient uptake and protein content of different Wheat cultivars	Wheat micronutrient content can be promoted by combined reliance on efficient genotype and AMF field inoculation	Pellegrino et al., 2020

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TABLE 1 (Continued)

Exact location	The kind of investigation	Soils/ plants/crop	Variables measured	Major findings	References
Rodale institute experimental farm, Kutztown, Pennsylvania, USA	Experiment to test the quality of vegetables under organic and conventional farming practices with and without AMF treatment	*Glycine max, Solanum lycopersicum, Capsicum annum, Dacus carota*	Prevalence of Plant diseases, Nutritional quality of vegetables (Vitamin C, antioxidants, mineral nutrients), and crop-yield	Stress management is an effective strategy for enhancing crops' antioxidants, vitamins, and other phytonutrients; environmental factors decide the nutritional quality and antioxidant responses, and crops in organically enhanced soil show better nutritional quality and antioxidant reactions under stress. The most significant advantage of organic farming in crops is tolerance to water and resistance to diseases.	Mukherjee et al., 2020
Global change experiment facility, Central Germany	Field experimental study to assess the role of climate and agricultural practices in conventional vs. organic farming	*Triticum aestivum*	Soil physicochemical properties, AMF community structure, and wheat nutrient concentrations	AMF communities appear sensitive to climate change. In general, AMF richness correlates with nutrient richness in Wheat; in both kinds of soil management, AMF is inevitable to the sustainability of agroecosystems	Wahdan et al., 2021
Therwil, Switzerland	A field experiment to explore the interactive effects of long-term agricultural management and extreme weather events on AMF communities in Winter Wheat fields under organic and conventional management practices	*Triticum aestivum*	Soil physicochemical properties, vegetation data, neutral lipid fatty acid (NLFA) for estimating AMF biomass, and DNA sequencing for AMF community structure	Experimental short-term extreme weather does not affect AMF communities in soil, but some taxa act as indicators	Kozjek et al., 2021
Ostrobothnia, Western Finland	Field experimental study to assess the effect of different nitrogen sources and fertilization intensities on nitrogen leaching and crop yields	*Hordeum vulgare, Secale cereale, Avena sativa, Vicia sativa, Phleum pratense, Trifolium pratense, Festuca pratensis*	Soil physicochemical properties and biological properties such as basal respiration, microbial biomass, AMF community composition	Basal respiration, microbial biomass, and fungal and bacterial richness are high in organic systems with less tillage	Peltoniemi et al., 2021
C. Greenhouse/pot experiments to assess the beneficial role of AMF					
Berlin, Germany	Greenhouse experiment to test the effect of AMF on antioxidant content in Tomato under ecological and conventional cultivation methods	Foliar and brown-rot-tolerant variety of Tomato known as *Vitella* F1	Lycopene, β-carotene and total phenols and also the shoot and fresh root weight	AMF inoculated tomato plants under ecological cultivation methods have higher antioxidant content than increased performance	Ulrichs et al., 2008
Illinois, USA	Greenhouse experiment to test the effect of AMF inoculation in strawberries in organic soils and its impact on resistance to herbivorous insect, *Philanenus spumarius*	Bare-root Strawberry variety "Ozark Beauty"	Root colonization, AMF spore density, plant survival rate, flowering, runner production, root, and shoot biomass	Although inoculation in organic soils improves the growth performance of the crop, it does not affect the plant's response to herbivory	Borowicz, 2009
South of Vonda, West of Delisle, Vanscoy and Vonda, Canada	Randomized block experiments in organic fields and growth-chamber experiments to test the effect of seeding rate on AMF colonization and whether colonization rate and level affect P uptake in Lentil and field pea	Field Pea ("CDC Mozart") and Lentil ("CDC Sovereign")	Crop density using quadrat method, physicochemical soil characters, plant biomass, seed weight, P in plants, per cent root colonization by AMF	Root colonization in field-grown plants increased with seeding rates; the lowest plant density showed the highest P uptake per plant, whereas total P uptake per pot increased with increasing plant density	Baird et al., 2010

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TABLE 1 (Continued)

Exact location	The kind of investigation	Soils/ plants/crop	Variables measured	Major findings	References
Massachusetts, USA	Greenhouse experiment to test the effects of AMF from conventional fields, organic farms and commercial inoculum in *Cucumis* on plant traits specific to herbivory and pollination dynamics	*Cucumis sativus*	Soil physicochemical characters, length and width of leaves, above-ground biomass, mineral and cucurbitacin content of leaves, flower number and size, nectar production, floral volatiles, AMF colonization	Applying AMF from organic soils can significantly improve P content in leaves in Cucumis. Still, the increase in nutrient uptake is not translated into plant growth or an increase in flower number. AMF from conventional farms can increase the cucurbitacin content of plant roots	Barber et al., 2013
Estonian Crop Research Institute, Jogeva, Estonia	An experimental greenhouse study to test the effect ofAMF originating from organic and conventional systems on six different Wheat cultivars	*Triticum aestivum*	Soil chemical analysis, plant height, the grain, shoot and root weights, root colonization and DNA sequencing to identify the AMF	AMF inoculum from organic fields influences plant growth more than the same from conventional fields. The different Cultivars harbored different varieties of AMF. Root colonization from organic fields is lesser in the crops than in traditional fields. Overall, the Ecology of AMF in the field is essential to explore the full potential of the same in crops	de Leon et al., 2020
Tharaka Nithi County, Kenya	Greenhouse experiment to test the effect of dual inoculation of Bradyrhizobia and AMF on nutrient uptake under organic and conventional soil systems	*Glycine max*	Soil physical characters, AMF root colonization, nodulation, shoot dry weight, shoot nutrient content	Organic farming and dual inoculation with AMF and bradyrhizobia are significant in enhancing biological soil fertility and a critical step toward sustainable production of healthy foods and managing environmental quality	Gitonga et al., 2021

walls of AMF. It is one of the most extensively studied and thoroughly reviewed topics in AMF concerning soil structure. The hydrophobic and thermo-stable glomalin is released into the soil on AMF spores and degradation of hyphae. In a review of 25 years of research on the role of GRSP in soils, Irving et al. (2021) conclude that it cements and protects soil organic matter and particles as a water-repellent surface material, thus promoting soil aggregation (Figure 3). It is not only GRSP; soil organic matter and organic carbon, in general, also act as a general cementing material to contribute to soil aggregation (Yang et al., 2017). AMF enhances soil aggregate stability by regulating root exudation in plants (Lu et al., 2019).

In a review of the role of glomalin as a potential soil conditioner, Zou et al. (2016) explain the two fractions of GRSP as easily extractable (EE-GRSP) and difficultly extractable (DE-GRSP) kinds. According to them, the total GRSP, the sum of the two fractions, contributes to soil aggregation and influences soil-water relationships. Experiments have shown that the AM-induced production of GRSP and specific soil enzymes are valuable indicators of soil fertility. However, the quantity of such compounds in soils varies with phosphorus levels in soils (Wu et al., 2015).

A review of the significance of glomalin in soil reveals that it influences the permeability of soil surfaces due to their hydrophobicity leading to lesser water loss and better soil moisture conservation (Holátko et al., 2021). In general, AMF enables plants to overcome water stress through enhanced contribution to water-stable soil aggregation (Zhang et al., 2016). An experimental greenhouse study reveals that different AMF influence soil aggregation (Barbosa et al., 2019). However, in two locally adapted tree seedlings, pot experiments with three other AMF species such as *Funneliformis mosseae*, *Glomus versiforme*, and *Rhizophagus intraradices,* show their general influence, especially in causing a significant increase in EE-GRSP and soil aggregation (Zhang et al., 2019). Thus, AMF helps the ecological restoration of many mining-affected sites by contributing to the rise in soil macro aggregates, pore sizes, and an enhanced adhesion of metals in the roots (Zhang et al., 2021).

Singh et al. (2020) observe that it is crucial to keep GRSP production high in soils due to its significance in maintaining soil structural quality in a review. Interaction between plant, soil, and AMF determines the GRSP content in cultivated fields. Therefore, the strategy to improve soil structural quality requires the application of suitable AMF and crops with high root exudates that promote better AMF growth in soils. Accordingly, organic agriculture using appropriate AMF is highly relevant in the reclamation of barren soils, primarily industrially and chemicalized agriculturally degraded soils, to ensure food security and safety for a sustainable human future on the earth. Moreover, experimentation on specific AMF-involved improvement in soil structure has also become highly significant.

5. AMF and carbon sequestration

The role of AMF in carbon sequestration in field soils, especially in Maize-cultivated coal-field soils, is an experimentally proven

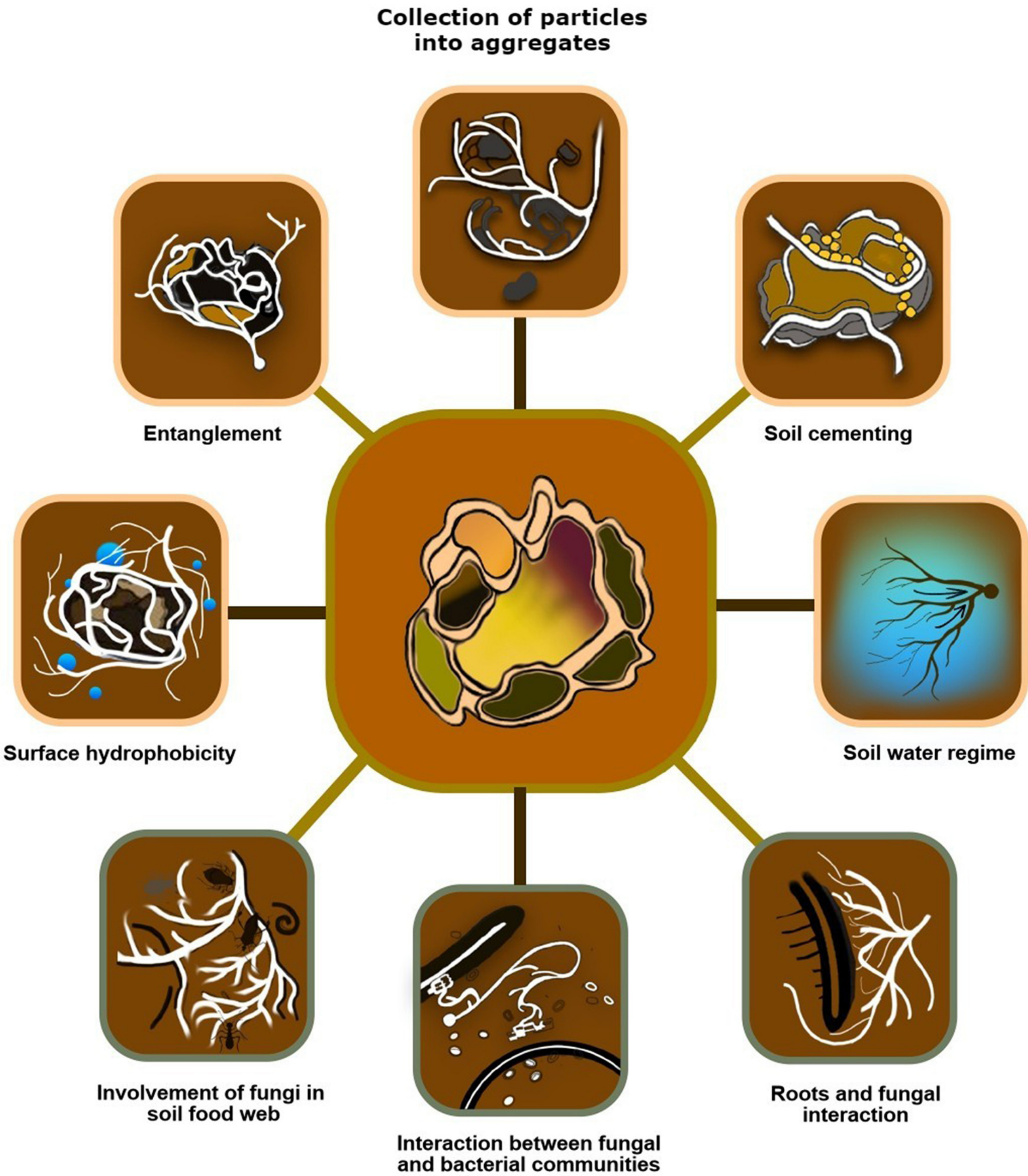

FIGURE 3
Roles of AMF in soil health.

fact (Wang et al., 2016). The activity of AMF in regulating the delivery and flux of C by variably influencing C sequestration and decomposition, especially by leaving a more significant amount of recalcitrant residual mass of chitinous cell wall, is already thoroughly reviewed (Parihar et al., 2020). According to Agnihotri et al. (2022), GRSP released into the soil by the AMF can prolong the mean residence time of C in soils, which also enables the formation of water-stable soil aggregates that prevent soil degradation, enhance organic matter stabilization, and the like. Plant carbon input into the soil through the shoot, root, and mycorrhizal pathways by C3 and C4 grasses is an experimentally proven fact (Huang et al., 2021). Experimental studies reveal that AMF significantly increases rhizo-carbon stabilization in soil macroaggregates (Jeewani et al., 2021). Zhang et al. (2016) also emphasize the importance of AMF in soil carbon stabilization and sequestration in semiarid steppe ecosystems, especially in the wet seasons. Thus, there is sufficient evidence in the literature to emphasize that AMF is inevitable to C accumulation and C-cycling in cultivated fields, especially in organic farms. However, the role of AMF and involvement in optimum C maintenance in agricultural fields remain open questions for further experimental investigations.

6. AMF and disease resistance in crops

The AMF can support plants in getting easy access to nutrients, even from nutrient-deficient or otherwise environmentally stressed soils (Fard et al., 2020). Naturally, plants with proper AMF associations in the root grow healthier than those without such symbionts in their roots (Dobo, 2022). Thus, even in stressful environments, AMF enables plants to develop better disease resistance. Diagne et al. (2020) state that AM fungi are crucial in building disease resistance and overcoming crop biotic and abiotic stress. An increase in disease resistance is one of the significant positive roles of AMF symbiosis to the plant partner, either by aiding in the uptake of nutrients or helping plants compete for nutrients, thereby enhancing photosynthetic productivity and even antibiosis.

In field experiments, it has been shown that AMF species such as *Glomus hoi, Clariodeoglomus clareoideum,* and *Glomus mossae* can provide various defensive benefits to host populations against fungal pathogens such as Powdery mildew (Eck et al., 2022). Similarly, *Glomus sp.* has been shown to improve resistance to damping-off disease in Cucumber plants caused by *Rhizoctonia solani* (Aljawasim et al., 2020). Pre-inoculation of *F. mosseae* can enhance resistance to early blight in Tomato (Song et al., 2015). Root colonization by AMF systematically increases defense-related enzymes and genes in the leaves of tomatoes upon the pathogen challenge. The AMF *Rhizophagus irregularis* has also been shown to enhance plant resistance against the fungal pathogen *Fusarium oxysporum* in Tomato plants (Wang et al., 2022). Molecular studies have revealed that AMF proteins such as ATL 31 and SYP 121, and Callose synthase PMR4 are higher in AMF colonized plants, which play a vital role in the priming of Callose accumulation and acting as an induced resistance mechanism in different plant species against fungal plant pathogens such as *Botrytis cinerea* (Sanmartín et al., 2021).

An experimental study has shown that among the environmental factors, light intensities have a significant influence on mycorrhizal association as well as mycorrhizal-induced disease resistance in plants (De La Hoz et al., 2021). However, when different varieties of Rice are inoculated with AMF, such as *Funneliformis mosseae* or *Rhizophagus irregularis*, the plant response to productivity and resistance to blast disease vary between different rice cultivars (Campo et al., 2020), which indicates the need for case by the case study of AMF utilization for disease resistance in Rice.

Mycorrhizae have been shown to add effective disease resistance to avirulent and virulent bacterial and fungal pathogens in tomatoes (Fujita et al., 2022). Moreover, the activation of both Salicylic acid and Jasmonic acid-mediated signaling pathways are enhanced in the primed plant by AMF colonization in the crops. In a review, Kadam et al. (2020) establish that mycorrhizal-induced disease resistance results from a synergistic involvement of AMF-enhanced physiological, phytohormonal and metabolic changes in plants.

Hohmann and Messmer (2017), in a review, have explored the plant genotype-related mycorrhizal responsiveness in crops. They have emphasized the need for an organic breeding program and novel breeding tools, which are essential to use plant-microbe interactions during crop selection efficiently. Similarly, Khrieba and Publishers (2019), in a review of the role of AMF in plant nutrition and protection from pathogens, concludes that AMF root colonization is well-known to improve plant resistance and tolerance to biotic stresses. According to the author, the mechanism underlying the processes are three-fold: (1) providing a physical barrier to pathogens, (2) competing with the pathogen, and (3) producing secondary metabolites, aggressive chemicals and toxins, and the like. The amount and the type of root exudates secreted by the plants also affect the mycorrhizal establishment.

Overall, a critical review of the existing literature establishes that AMF significantly improves crop disease resistance. Therefore, AMF are inevitable to the emergence of sustainable organic agriculture. However, detailed research concerning AMF and disease resistance in specific crops and soils under every climatic zone of organic and chemicalized cultivation regimes against specific pathogens has become essential for enabling the application of AMF as an alternative to toxic chemicalized disease control agents in the successful conduct of organic agriculture.

7. AMF and the macro-nutrients

The importance of AMF for sustainable nutrient availability in organic farming is a well-reviewed topic (Ebbisa, 2022). Mycorrhizal assistance, especially AMF, is essential for sustainable soil availability of nutrients and water to crops in ecological and organic farming (Ortaş, 2018). The success of organic agriculture in the future depends on how intelligently we use highly mycorrhizal host crops in rotations (Njeru, 2018). Moreover, the use of exotic and indigenous mycorrhizae has a decisive role in determining the future of modern agriculture (Bhantana, 2021). According to Ortas and Rafique (2017), the AMF has the unique capacity to extract NPK beyond the rhizosphere of plants and to release the same into host plants using many expressions of plant transporters. However, the amount of nutrient allocation between the host and the AMF symbiont is a fundamental factor facilitating the exchange and allocation process, which should be further explored. The AMF addition augments the capacity of Wheat to have sufficient nutrients from phosphorus-low soils and thus, enhances the crop's yield (Ortas and Bykova, 2018). In general, AM fungi are crucial in increasing the growth and yield of many crops by reducing the need for hazardous pesticides and industrial chemical fertilizers in agriculture (Diagne et al., 2020).

The AMF can aid in organic farming, even in poorly developed soils. The synergistic application of an extensive range of plant growth-promoting bacteria, AM fungi, and the like has become a common practice to enhance nutrient uptake (Ray and Valsalakumar, 2010a) in crops. Even in poor calcareous soils, AMF causes an improvement in the uptake of immobile mineral nutrients present in low concentrations (Lombardo et al., 2020, 2021). A combination of green compost and mycorrhiza improves the uptake of N, P, K, and Ca by Alfalfa crops in overexploited poor Mediterranean soils (Ben-Laouane et al., 2021). Specific studies on different compost systems in organic farming on two species of AMF reveal that AMF activity, especially that of *Funneliformis mosseae,* is not affected by the other compost systems

(Akpinar et al., 2019). According to these authors, AMF species such as *Funneliformis mosseae* is better than *Claroideoglomus etunicatum* in the significant nutrient uptake in *Allium porum* L. In low-input cropping systems of Sesame crops, soil characteristics profoundly influence the composition and species richness of AMF in the fields (Harikumar, 2015). However, further intensive and extensive research on AMF application in diverse environmental settings using different crop varieties is essential in standardizing specific AMF as suitable biofertilizers in organic agriculture. The correlation between AM fungal root colonization and an increase in root density of crops still needs to be adequately correlated under optimal nutrient conditions (Cockerton et al., 2020).

Some of the recent experimental studies reveal some controversial findings also. For example, an experimental field comparison of organic and conventional farming methods shows that compared to traditional farming, organic farming causes more variability in nutrients, antioxidants, and vitamin C contents in diverse crops, and especially, the AMF inoculation results in a reduction in the vitamin C, antioxidants and phytonutrients in vegetables (Mukherjee et al., 2020). According to these authors, there can be potential antagonistic and synergistic interactions between the native and introduced AMF species, which require a period of stabilization. Therefore, long-term studies with more vegetables are essential to establish the exact beneficial role of specific species of AMF in the organic farming of vegetables. In the absence of chemical fertilizers in organic soils, better availability of mineral nutrients, including nitrogen, can be ensured by applying suitable AMF inoculation. In general, the review emphasizes the need for more investigations on soil and crop-specific applications of AMF in specific soil environments under organic farming practices for using the same as an agent for augmenting primary nutrient supply to crops.

8. AMF concerning water relations in soils

The AM fungi generally play a positive role in plant water relations, especially in stressed soil environments, which is also a reviewed topic (Tyagi et al., 2018). According to the authors, although there is significant progress in understanding the role of AMF in helping drought tolerance, 'omic' data is essential to elucidate the actual mechanisms of AMF-assisted drought tolerance in plants. Experimental studies reveal that AM fungal association can increase net photosynthetic rate in water deficit conditions, which can be related to higher water availability for transpiration (Quiroga et al., 2019). The authors suggest that AMF can enhance the water permeability of root cells to overcome the water deficit.

Field experimental studies reveal that farming practices, especially organic farming, decide the kind of AMF community composition rather than its diversity in crop fields (Kozjek et al., 2021). They reveal that the AMF community can cope with short-term droughts in the field. However, according to Wahdan et al. (2021), the interaction between farming practice and climate decides AMF community composition in the fields. The crops can resist drought using a corresponding change in the AMF community structure in soils, especially in organically managed fields. However, long-term field experiments reveal that experimental drought promotes AMF abundance up to three times higher in organically cultivated fields under biodynamic fertilization than in conventionally managed farms (Kundel et al., 2020). The authors endorse the significance of AMF-assisted biodynamic organic farming for better resistance of crops to overcome the scarcity of water in the soil.

In vegetable crops, AMF supplementation enables overcoming water stress, especially in organic systems. Vegetable crops in a water-stressed organic field environment contain more antioxidants than those under conventional field systems (Mukherjee et al., 2020). The reduced tillage practice followed in organic farming is beneficial in improving the water relations of crops in organic fields (Kobierski et al., 2020). The enhanced water retentions under a continuous crop cover in organically managed soils conserve soil moisture better than in conventionally managed systems, which adds stability to the soil microbiome (Peltoniemi et al., 2021). The authors view that the absence of chemical fertilizers in such an organic system promotes the maintenance of a high diversity of AMF.

The AMF, along with other microbes in an organic environment, form a unique biotic community that contributes to the high quantity of microbial residues such as GRSP in soil, which improves soil aggregate stability to a considerable extent that ultimately can improve the general water regime of the soils (Sun et al., 2016). The AMF-inoculated soils usually have higher soil water potential (Zou et al., 2014). The GRSP secreted into soils by the AMF acts as a drought tolerance mediator that helps produce leaf abscisic acid, indole-acetic acid, and methyl jasmonate, stress mediators (Chi et al., 2018) in plants. The AM inoculation in organic fields enables plants to absorb water and other nutrients from the soil solution through their widespread extraradical hyphae, allowing plants to avoid drought stress (Posta and Hong Duc, 2020). In general, sufficient evidence is available in the literature on the importance of AMF as an inevitable component in organic farming to ensure sustainable management of optimum water utilization of crops in the field. However, intensive experimental studies are essential in optimizing water availability to specific crops in specific soils concerning specific AMF.

9. AMF and micronutrient availability

Mycorrhizal assistance in improving micronutrient uptake in crops is a reviewed topic. The AMF is significant to several plants' absorption of diverse micronutrients (Upadhayay et al., 2019). Nursery inoculation of tomato seedlings with specific AMF can enhance the absorption of nutrients, including the micronutrients such as Mn and Fe, in the crop under salt stress (Balliu et al., 2015). Thus, it enables the crops to overcome stress. According to Coccina et al. (2019), AMF can significantly aid the biofortification of Zinc in barley and Wheat. The authors suggest that AMF assists plants in absorbing micronutrients, even from soils low in the quantity of such micronutrients. Thus, they enable an improvement in the quality of organic foods. In general, experimental studies reveal that mycorrhiza-inoculation can improve yield in Wheat, even in P-deficient soils, by helping the plant to have sufficient P and other micronutrients such as Zinc (Zn), manganese (Mn), copper (Cu), and iron (Fe) from soils (Ortas and Bykova, 2018). The Zinc iron permease protein (ZIP) transporters help acquire Zinc by AM fungi and assist crops in getting sufficient nutrients from soils (Ruytinx et al., 2020). According to the authors, such fungi regulate the expression of some zinc transporters and genes involved in primary metabolism that supply zinc to host plants. The metal transporters are generally located in the extraradical mycelium, especially in *Glomus intraradius* (Wang, 2017; Wang et al., 2017). In addition to supporting nutrient access from nutrient-deficient soils, the AMF also helps absorb mineral nutrients from an inaccessible organic substrate, mineral particles, and rock surfaces (Teotia et al., 2017). Experimental evidence suggests that specific species of AMF support crops such as grapes in absorbing micronutrients like Zn from soil (Aslanpour et al., 2019).

Overall, a critical analysis of the available literature on the role of AMF in the absorption of micronutrients by plants reiterates that by employing suitable mycorrhiza species for specific crops and soils, micronutrient availability in the organic field can be assured. Thus, applying suitable AMF in organic fields can enhance the productivity and quality of organic produce. However, there is a high scope for experimenting with specific AMF in specific soils concerning the accumulation of particular micronutrients in diverse crops under different climate regimes. Such experiments can optimize environmental conditions for applying specific AMF as an alternative to micronutrient deficiency in organic farming.

10. Heavy metal tolerance and AMF

AMF-induced heavy metal tolerance in organic crops is a highly researched topic, already being reviewed from different perspectives (Begum et al., 2019; Gong and Tian, 2019; Dhalaria et al., 2020; Riaz et al., 2021). Although some heavy metals such as Fe or Cr are helpful to plants in traces, most of the heavy metals in soils act as severe abiotic stress that causes the formation of reactive oxygen species in the cells (Jalmi et al., 2018). According to these authors, plants respond to heavy metals through specific stress-related protein molecules to tackle metal toxicities. Some heavy metals are naturally present in all soils, but toxic heavy metals accumulate in soils through anthropogenic means such as chemicalized agriculture (Sahodaran and Ray, 2018). Chemical fertilizers are notorious for heavy metal contaminants such as Cd, Cr, Ni, Pb, and the like (Alengebawy et al., 2021). Continuous use of such contaminated chemical fertilizers in the field can lead to a gradual accumulation of metals in the soil over years of usage (Adhikari et al., 2021). In general, toxic heavy metals affect soil health by directly influencing the microbial flora of the soil and soil structure (Chu, 2018; Jarosławiecka and Piotrowska-Seget, 2022).

Heavy metals, on absorption into plant cells, modify the biochemical, metabolic, and physical pathways demonstrating reduced growth accompanied by yield and productivity (Srivastava et al., 2017). Therefore, organic agriculture that avoids harmful chemical fertilizers can be an excellent alternative farming method to overcome the crisis of heavy metal accumulation in the fields. Such a benefit of organic farming is reflected in organically grown vegetables, which have significantly lower concentrations of heavy metals than those raised by chemicalized means (Głodowska and Krawczyk, 2017). Janeeshma and Puthur (2020) reveal that the AM-mediated phytoremediation of heavy metals in soils is a well-established theme. The authors conclude that the AMF association enhances plants' primary metal tolerance mechanisms because AMF either directly absorb metals onto the hyphal wall or, through GRSP secretions, binds the heavy metals with the soil and makes them non-available to plants, thus improving plant tolerance to heavy metals in soils.

Riaz et al. (2021) have reviewed AMF-induced heavy metal tolerance in plants. According to them, enzymatic and non-enzymatic mechanisms are active in the heavy metal tolerance in plants. The AMF triggers antioxidant enzymatic protective systems in the host plants on soil exposure to heavy metals. Abdelhameed and Metwally (2019) explain how AMF protects *Trigonella* sp. against Cd stress, especially by lowering the damaging effects on plant development through enhanced activation of antioxidant enzymes. Thus, the fungus diminishes the detrimental influences of Cd on plant physiology. Gong and Tian (2019) explain in a review the mechanism of AMF action in alleviating heavy metal impact. They reveal the direct contributions of AMF in enhancing metal tolerance by immobilizing heavy metals through direct binding to the cell wall or chelation of the metals in soils by hyphal secretions of glycoproteins. However, according to them, the indirect contributions of AMF in metal tolerance in plants include diverse processes such as inducing the expression of regulatory genes to resist metal stress, regulation, and expression of antioxidant enzymes and the like.

Begum et al. (2019), in a review, explain the role of AMF in plants growing in stressful environments. According to the authors, AMF can be helpful for plants in effectively combatting diverse environmental stresses such as salinity, drought, nutrient stress, alkali stress, cold stress, and extreme temperatures. The authors believe future research should focus on identifying genes and gene products controlling the AMF-mediated growth regulation of plants in stressful environments. Dhalaria et al. (2020), in a review, explain how the AMF acts as a potential agent to avoid metal tolerance in soils. According to them, the AMF is the most promising and effective strategy to overcome heavy metal stress in plants. In certain species of AMF, even the spores accumulate heavy metals such as lead (Salazar et al., 2018) and reduce their availability in soils for plants to absorb.

The AMF also reduces the heavy metal impact in plants such as soybean through a dilution effect on the crop, ensuring the prevention of metal intake (Spagnoletti and Lavado, 2015) or a hyphal exploration of unstressed parts of the soil to avoid metal accumulation in plants (Garg et al., 2017) as a means of avoidance of metals in soils. The study of an orphaned mining site revealed that many *Glomeromycota* communities survive in these areas and at extreme metal toxicity levels (Sánchez-Castro et al., 2017). Thus, AMF is a handy tool for cultivating crops in heavy metal-contaminated soils, primarily if maintained organically with a high diversity of AMF in soils. However, the AMF cannot degrade the heavy metals in soils. It can only help plants prevent the availability of such metals, and the metal would remain in the system. Moreover, there is evidence in the literature regarding AMF assistance in accumulating heavy metals in plants (Gavrilescu, 2021; Ai et al., 2022; Chen et al., 2022; Szada-Borzyszkowska et al., 2022).

Therefore, intensive experimental studies are required to identify and standardize the use of metal-stress-alleviating species of AMF concerning specific crops and soils to overcome plant metal stress in heavy metal-contaminated fields.

11. Adverse effects of AMF in organic agriculture

In general, AMF determines plant community structure, while plant community determines the kind of AMF in a vegetation system (Horn et al., 2017). However, according to the authors, the AMF community in a field or natural system also has independency, which is the outcome of interactions among them in the soil. Previously, researchers (van der Heijden et al., 1998; Lin et al., 2015) viewed interactions in the plant characteristics, including plant functional groups and life histories, as significant predictors of AMF in a plant community. According to them, mycorrhizal dependency determines which plant species dominates vegetation. Moreover, plant-plant interactions in a community are also influenced or decided by the mycorrhizal species in the system (Hoeksema, 2005). In such a situation, unlike monocropping systems, adding a non-native AMF into the soil can have unpredictable outcomes in the community structure, especially in a usual multi-cropping organic farming system.

Experimental studies reveal that in farm fields, in the presence of suitable AMF species, AMF-dependent crops are positively influenced (Kim et al., 2017). In contrast, not all weeds are negatively affected by AMF (Veiga et al., 2011) or vice versa. However, if favorable to weeds, such differential influential roles of AMF on crops and weeds can sometimes negatively affect weed management in agricultural systems, mainly when properly monitored generalized AMF biofertilizers are applied to diverse crop fields.

The harmful effect of AMF on specific species, such as Eucalyptus seedlings, especially those growing in soils deficient in certain minerals such as iron (Janos et al., 2013), is known. The positive influences of AMF on the growth and competence of invasive species such as *Rudbeckia lacinata* and *Solidago gigantea* in the natural environment are also well-known (Majewska et al., 2017). Such findings point out that in natural vegetation or cultivated fields, the addition of a new AMF species can have a significant differential influence on species diversity, crop performance, and enhancement in the competitive capacity of invasive species, depending on the specific AMF community in a soil or plant species occupying the area. Thus, introducing an alien species of AMF, even as a biofertilizer, can also harm the community structure of the natural ecosystem, such as an aggressive weed outbreak. Therefore, specific AMF application needs to be judiciously practiced with exact information on their influence on all the species in a natural community or crops and weeds in agricultural systems. Especially in global climate change, the plant-soil biotic interactions can lead to specific unexpected dimensions in crop response to soil factors from ecologically ignorant AMF management in soils (Sendek et al., 2019). Notably, adding an AMF species in organic farming can create community imbalances in agriculture or adjacent natural ecosystems. Currently, organic farms, in general, are multi-cropping systems (Carof et al., 2022; Fernández et al., 2022; Trinchera et al., 2022) that use a high diversity of natural crops and other flora together in the sustainable management of soil fertility and crop productivity.

AMF application can also have adverse impacts on nutrient uptake in plants. Plants in organic farms rich in AM fungi in soils may compete for nitrogen acquisition, and such a contest can reduce the grain yield of maize, especially in N-limiting soils (Wang X. X. et al., 2018). The mycorrhizal dependence of plant species is its constitutive property, and different plant species may react differently to the same mycorrhizal fungus species (Heklau et al., 2021). Plants are regarded as facultatively or obligately mycotrophic. Moreover, the presence of AMF in some plants decreases their tolerance to adaptive traits, such as tolerance to herbivory (Garrido et al., 2010). The above critical review of the literature on the negative influence of AMF on organic agricultural management thus, reveals that while the AMF can be beneficial to organic farming, sometimes the same will have adverse effects on the organic cultivation of specific crops and the stability of natural ecosystems. Therefore, particular studies involving specific plant-fungus species-related experimental works, along with field surveys of AMF in cultivated fields and natural ecosystems, are essential to a better understanding the correct ecological management of AMF in organic farming systems.

12. The future perspectives of AMF concerning organic agriculture

Although chemicalized agriculture affects food security, safety, and sustainability through its negative impact on soil systems (Ouyang and Norton, 2020; Vågsholm et al., 2020; Bisht and Chauhan, 2021), organic farming as a definite alternative to sustainability has not yet been sufficiently rationalized. Experiments reveal that chemical fertilizer usage can be avoided or reduced to a certain extent if specific AMF is used for specific crops in particular soil systems (Begum et al., 2019; Trejo et al., 2021; Dobo, 2022; Kuila and Ghosh, 2022). The future perspective of organic farming as a sustainable agricultural model emphasizes a learned accommodation of the natural microbial biodiversity components, including AMF, in a naturally favorable organic soil environment for ensuring self-sustenance of soil fertility (Tscharntke et al., 2021; Sietz and Neudert, 2022; Uwamungu et al., 2022). Therefore, organic farming as prospective agriculture to rejuvenate the lost natural vigor of our land resources and biodiversity needs further standardization.

Rational and judicious application of crop and soil-specific AMF species is inevitable as biofertilizers in developing future sustainable organic agricultural (Trisilawati et al., 2019) production systems. However, the successful adaptation of mycorrhizal aid in plant growth and ecosystem services requires proper monitoring, knowledge about the effects of agricultural amendments, organizing database tools, good plant breeding, and myco-engineering of the associated microbiota (Rillig et al., 2016; Silva-Flores et al., 2022). In this context, a herculean research task is ahead in utilizing AMF as an ecotechnological tool for agricultural sustainability through organic farming.

The future research prospects include specific surveys of natural mycorrhizal associates of diverse crops in different climatic and soil zones (Pellegrino et al., 2015; Nidheesh et al., 2018) of the world. Along with the traditional spore-based taxonomic methods (Prayudyaningsih et al., 2019), molecular metagenomic approaches to identify the species (Eun Kang et al., 2020; Alrajhei et al., 2022) have become inevitable to fulfill this task in the future.

An extensive and intensive survey of natural mycorrhizal flora needs to be followed by intensive experimental trials at laboratory and field scales (Sahodaran et al., 2019; El Hilali et al., 2022; Ouledali et al., 2022; Wang et al., 2023) to standardize specific strains in specific soils over definite seasons in diverse climatic zones. It is essential to identify specific AMF for particular crops under climate change conditions (Jerbi et al., 2020; Kozjek et al., 2021), primarily to ensure proper application of the same in sustainable organic cultivation systems. In developing AMF as a crop-specific biofertilizer, multiple mycorrhizal combinations that are genetically distant are required (Chen et al., 2017; Crossay et al., 2019), especially for supporting specific crops in specific soil environments and climatic zones.

Identifying the genes and transcription factors of both AMF and host plants that enable the AMF to react to diverse environmental stresses has become an essential task for researchers in this field for the future (Zou et al., 2020; Sun et al., 2022). Such investigations would enable the development of mycorrhizal partnerships with a maximum positive effect on host plants (Guo et al., 2021; Grünfeld et al., 2022). Further studies for identifying generalist and specific species of AMF suitable for diverse organic crop systems concerning different climate and soil systems have become essential. Moreover, an adequate understanding of their crop-supportive processes is inevitable in utilizing mycorrhiza as a definite agent of sustaining soil fertility in organic agricultural systems (Juntahum et al., 2022; Kuila and Ghosh, 2022).

13. Conclusion

The current critical analysis of literature on AMF concerning organic agriculture reveals that there has been a continuous growth in research on the same over the last four decades (1980–2022). Still, more than 50% come from three countries, China, the USA, and Italy. It emphasizes the need for more global research efforts in this regard. However, the existing literature on the application of AMF in organic farming reveals that the AMF has the potential to emerge in organic farming as a successful alternative to chemicalized agriculture for the sustainability of food security and safety in the future. Specific analysis of literature under the different heads reveals the following particular points of view in this regard.

1. Although AMF root colonization is higher in organic crops than in chemicalized farms, the existing research does not recommend AMF as a substitute for chemical fertilizer inputs.
2. The AMF flora in a chemicalized farm can be weedy, whereas their presence in natural organic soils benefits crops in many ways.
3. The exact diversity of AMF flora concerning most crops and natural soils is yet to be explored.
4. Intensive soil management practices of chemicalized agriculture destroy natural AMF flora in soils.
5. The successful application of AMF in organic farms as a crop-beneficial input needs optimization of the application concerning cultivation practices, which demand intensive experimental studies on AMF concerning specific varieties of diverse crops, diversity of soil factors, climate, and other species of plants in the field.
6. AMF application in organic farms enables improvement in soil structure through direct physical binding of soil particles, stimulation of root exudation, and secretion of glomalin-related soil proteins as soil cementing components.
7. The GRSP and soil enzymes can be valuable indicators of soil fertility.
8. Specific AMF applications in barren soils can enable its reclamation.
9. The AMF significantly contributes to carbon sequestration and carbon stabilization in soils.
10. AMF application can improve the quality of plant food through an enhancement in their useful biochemical components, including secondary metabolites.
11. AMF application in organic farming can considerably improve disease resistance in crops.
12. AMF in organic farms improves disease resistance by providing a physical barrier to root pathogens, acting as a competitor, or stimulating the plants to produce defensive secondary metabolites against pests.
13. AMF in organic soils, in conjunction with other PGPRs, can assist plants in accumulating sufficient macro and micronutrients, especially in nutrient-deficient soils.
14. AMF enables plants to thrive in water-deficit soils by promoting increased water accumulation potentials of the host plants.
15. The AMF secreted GRSP act as a mediator for drought tolerance in plants.
16. The AMF in organic soils enable the plants to overcome heavy metal stress by making the metals non-available to plants, either by directly binding the metals on their cell walls or storing them in their spores or indirectly by binding them to soil particle through GRSP.
17. Non-judicious application of the generalist AMF species into fields sometimes becomes more favorable to weeds than the crops.

Overall, the literature analysis reveals that the AMF has yet to become an economically successful alternative to chemical fertilizers in organic farming, which is possible only through the proper acquisition of knowledge on the rational application of specific AMF concerning soils, climate, crops, varieties, and cultivars through further field surveys and experiments. Such rigorous field studies and experimentations with crop-specific and climate and soil-specific species of AMF concerning specific crops under various organic regimes alone can generate sufficient information to transform organic farming into a rational alternate agricultural process to ensure sustainability. Generally, it has become imperative to standardize AMF as a biofertilizer in mono and multi-cropping agricultural organic farming. Therefore, globally focused research on AMF concerning organic agriculture as a precise rational agricultural means has become essential for global food security and safety for the future.

Author contributions

NG collected the literature per the plan and directions of JR. NG and JR analyzed the literature. NG prepared the first draft. JR critically analyzed and revised the same and both finalized the content and format. Both authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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