



Diversity, Distribution, and applications of *arbuscular mycorrhizal* fungi in the Arabian Peninsula

Khazna Alrajhi^a, Shazia Bibi^a, Mohammed Abu-Dieyh^{b,*}

^a Department of Biological and Environmental Sciences, College of Arts and Sciences, Qatar University, P.O. Box 2713, Doha, Qatar

^b Biological Science Program, Department of Biological and Environmental Sciences, College of Arts and Sciences, Qatar University, P.O. Box 2713, Doha, Qatar

ARTICLE INFO

Keywords:

Diversity
Glomeromycota
Arbuscular mycorrhizal fungi
Arabian Peninsula
Funneliformis, *Rhizophagus*

ABSTRACT

Investigations of arbuscular mycorrhizal fungi (AMF) received extreme interests among scientist including agronomists and environmental scientists. This interest is linked to advantages provided by AMF in enhancing the nutrients of their hosts via improving photosynthetic pigments and antioxidant production. Further, it also positively alters the production of plant hormones. AMF through its associations with plants obtain carbon while in exchange, provide nutrients. AMF have been reported to improve the growth of *Tagetes erecta*, *Zea mays*, *Panicum turgidum*, *Arachis hypogaea*, *Triticum aestivum* and others. This review further documented the occurrence, diversity, distribution, and agricultural applications of AMF species reported in the Arabian Peninsula. Overall, we documented 20 genera and 61 species of Glomeromycota in the Arabian Peninsula representing 46.51 % of genera and 17.88 % of species of AMF known so far.

Funneliformis mosseae has found to be the most widely distributed species followed by *Claroideoglossum etunicatum*. There are 35 research articles focused on Arabian Peninsula where the stress conditions like drought, salinity and pollutants are prevailed. Only one group studied the influence of AMF on disease resistance, while salinity, drought, and cadmium stresses were investigated in 18, 6, and 4 investigations, respectively. The genus *Glomus* was the focus of most studies. The conducted research in the Arabian Peninsula is not enough to understand AMF taxonomy and their functional role in plant growth. Expanding the scope of detection of AMF, especially in coastal areas is essential. Future studies on biodiversity of AMF are essential.

1. Introduction

Fungi diversity remained largely unexplored throughout the globe specially in Arabian Peninsula in regions with harsh environmental conditions. However, recent efforts have been undertaken to characterize different fungal isolates with different approaches such as phylogenetic and genomic (Tamura et al., 2013). Nevertheless, morphological classification and characterization of fungi based on geographical locations are still inadequate. Moreover, microbial species are mainly studied for their antimicrobial role while studies about their diversity are often overlooked.

Biodiversity studies are generally carried out at taxonomic levels, including genera and family, and are significant to reveal the distribution pattern of species within the given genera. Soil microbial community includes archaea, bacteria, algae, protozoa, viruses and fungi (Shah et al., 2021). Fungi are among them and make up a significant portion of

the soil biomass. They play several roles, including but not limited to aiding in the decomposition of organic nitrogen (N) in the form of ammonia and weathering of soil minerals and the decomposition of organic matter in the form of litter. By promoting hyphal development and protein synthesis, they also affect the soil's composition (Cromack, 1992). Following insects, fungi rank to be the second group with the largest number of species but the influence of fungal diversity on ecosystem productivity and biodiversity has still received less attention from scientists and agriculturists. Presently, there are almost 69,000 fungal species that exists independently (Satyanarayana et al., 2019) however, based on the vascular plant to fungus ratio across the globe, the number is estimated to be more than 1.5 million species respectively (Stürmer & Siqueira, 2006). Another study reported the fungal species to be 5.1 million based on the high throughput sequencing techniques (Blackwell, 2011; Wu et al., 2019).

Plants undergo different environmental stressors in terrestrial

* Corresponding author.

E-mail addresses: khalrajhi@moi.gov.kw, ka1704870@student.qu.edu.qa (K. Alrajhi), sb2100091@student.qu.edu.qa (S. Bibi), dandelion@qu.edu.qa (M. Abu-Dieyh).

<https://doi.org/10.1016/j.sjbs.2023.103911>

Received 30 July 2023; Received in revised form 6 December 2023; Accepted 15 December 2023

Available online 25 December 2023

1319-562X/© 2023 The Author(s). Published by Elsevier B.V. on behalf of King Saud University. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

ecosystems. Ecological systems that are specific to arid or desert regions has inadequate precipitation and other related seasonal rainfall patterns, therefore, they undergo several abiotic stresses like drought (Madouh & Qureshi, 2023). There are several adaptive strategies among which the use of fungal species specifically AMF is one. AMF plays a major role in driving the ecosystem processes as well as in improving economic productivity. According to fossil evidence, AMF likely first appeared between 353 and 462 million years ago, during the Devonian era, and since then, it has exhibited its presence across diverse geographical locations and has developed associations with different plant species (Lewis, 2016; Morton, 2000). Fungi are home to different habitats and are isolated from the roots of Pteridophytes to Gymnosperms, the sand dunes and the tropical grasslands. The diversity of AMF in terms of richness and evenness suggests that the fungi lack host specificity (Muneer et al., 2019), and it only competes with bacteria (Apple, 2010). However, recent studies have reflected that AMF could not only exhibit mutualism or commensalism with plant species but also indirectly with specific bacterial species.

This review documents an up-to-date scenario of the occurrence, distribution, and diversity of AMF species in the Arabian Peninsula by gathering information from different studies on various AMF species and their role in different plant stress conditions. Moreover, the review also discusses the climatic changes and its impact on the growth of AMF along with highlighting the plant-mycorrhizal associations, their role in minimizing the pathogenicity of plant pathogens and the commercialization of AMF products.

2. Overview of AMF

Plants and their symbiotic relationships are known from the early evolutionary period. The early plants are known to be the result of endosymbiotic phenomenon of non-photosynthetic eukaryotes engulfing photosynthetic cyanobacterium. During this phase, early plants required a source to fulfill their nutritious requirements. Fungal associations helped plants to attain nutrients in the absence of proper and complex plant roots system. AM interaction with early plants is reported to be a unique type of interaction. While investigating the plant lineages, it is reported that due to these fungal associations, plants were able to develop and survive. Even now, the majority of the plants are seen to have fungal associations, however, plants in aquatic environment do not opt for this option (Chen et al., 2018).

AMF are obligatory symbiotic creatures and they depend on plant roots to complete their life cycle. Almost 80 % of the plants around the world exhibit symbiotic association with fungal species (Brundrett, 2009; Tang et al., 2023a). (Brundrett, 2009 #148} AMF has been noted in Taiwan, Cuba, India, the Arabian Peninsula, Central and South America, Japan, Mexico and many other regions globally. In their symbiotic relationship, plants provide AMF with the necessary sources of C and other nutrients that promote sporulation. Likewise, fungal species help plants in absorbing water from soil with the help of their developed hyphal system. Hence, it is not surprising why AMF species are profoundly located in plants found in arid and desert climates (Golotte et al., 2004; Ma et al., 2022b). However, helping plants with water or providing C sources to fungi is an oversimplification of the structure-function correlation with respect to host interactions (Luo et al., 2023; Newsham et al., 1995). The AMF forms meristic structures that have distinct symbiotic functions within the cortex of the root, extending into the soil. AMF is named so because of the presence of arbuscules, which are characteristic structures of the fungal species (Augusto, 2015). Arbuscules are specialized branched hyphae that are formed between the plasma membrane and cell wall of plant cells and significantly contribute to the exchange of nutrients between the symbiotic organisms. On the other hand, vesicles are globose or elliptical structures found in AMF. They act as a storage organ as it stores lipids and glycogen for them. These structures are formed between the cortex cells and are only intrinsic to the fungal families of Acaulosporaceae and

Glomeraceae (Augusto, 2015).

The major role of AMF is to supplement the plants with nutrients and water. Phosphorus (P) is a major nutrient that is provided by AMF to the host plants because of their extraradical hyphae which could grow beyond P depleted zone (Johri et al., 2015; Qi et al., 2022). This helps the fungus in scavenging P ions from the bulk soil. AMF also exhibits nematocidal properties that prevent destruction and ensures the health of the host plant in the presence of nematode species. Hence, the mycorrhizal relationship between AMF and plant species is viewed as multifunctional as it is an important indicator of ecosystem sustainability and soil quality. Initially, AMF were classified in the order Glomales of Zygomycota, followed by Glomeromycota (Schwarzott & Walker, 2001; Volk, 2013). Presently they are all classified under the subphylum Glomeromycotina (Spatafora et al., 2016). In the past, these fungal species were named endomycorrhiza, which was later changed to vesicular-arbuscular mycorrhizae and eventually into AMF. In natural ecosystems, fungi make up most of the rhizosphere's flora but their population in each habitat is significantly influenced by biotic and abiotic communities (Hazard et al., 2013; Jansa et al., 2014; Wahab et al., 2023). Hence, the diversification of AMF is dependent on the changes in the soil environment, dynamics and characteristics of the ecosystem, and the agricultural practices as well as the density of the spores, mycelia, and the presence of other species.

2.1. Diversity and distribution of *Funneliformis mosseae*

Funneliformis mosseae is a species of AMF that is widespread throughout the world's ecosystems. It is a widespread and most dominating AMF species found in agricultural soils. A helpful fungus called *F. mosseae* creates a symbiotic relationship with plants by supplying them with vital nutrients and enhancing their stress tolerance (Marinho et al., 2018; Tang et al., 2023b).

Numerous variables, such as climate, soil type, and composition of plant community have an impact on the diversity and distribution of *F. mosseae*. The fungus is more ubiquitous in warm, temperate regions than in cold or dry ones. Moreover, the prevalence of *F. mosseae* is more in sandy soils when compared with clay soils. Although it can be found in many different plant groups, the fungus is most prevalent in grasslands, woodlands, and agricultural fields.

F. mosseae is a crucial fungus for both the environment and plants. It gives plants vital nutrients, such phosphorus and nitrogen, and aids in their ability to withstand stress. By reducing organic matter and raising the soil's capacity to hold water, the fungus also aids in enhancing soil quality. Considering the useful properties of *F. mosseae*, it can be considered a potential candidate for boasting sustainable agriculture through enhanced crop yields and low provision of artificial fertilizers (Shi et al., 2021).

3. AMF ecological significance

AMF plays a significant role in plant nutrition, especially in the recycling of nutrients and in retaining the water content. AMF is also found to initiate nutrient uptake in sand dunes that play an important part in sand stabilization (Apple, 2010; Tenzin et al., 2022) AMF provides significant benefits to the plant species from economic viability to disease resistance. The increase in biomass of the hosts indicates the advantage of AMF relationships with the plants. Regarding the flux of C in the symbiotic relationship of plants and AMF, C is found to be present all the time not only in the root of plants but also in the intra-radical fungal structures. Moreover, various research has been conducted to identify the exact location of C flux. Comparatively, P flux is much better studied. The transfer of P in the symbiotic relationship occurs at the arbuscule interface. With the help of the fungal association, plants can directly uptake P from the soil. Moreover, N, being an important mineral in soil, has a greater mobility in the form of ammonium and nitrate ions. The role of AMF in capture of N is considered a bit challenging due to its

mobile nature and therefore in this area, few studies have been conducted. However, some studies indicate that the fifth part of the total N held by plants is the result of AMF associations (Hodge & Fitter, 2010). An overview of the contributions of AMF is shown in Fig. 1 below.

A study showed that *Glomus fasciculatum* significantly improved the concentrations of N, calcium (Ca), P, and zinc (Zn) in *Vigna aconitifolia* (moth bean plant) grown predominantly in Rajasthan, India (Tarafdar & Praveen, 1996). Desert agriculture would remain an important provision for sustained food supply across the globe, and it is going to intensify with desertification. Mycorrhizal relationships could play a significant role in improving the quality and productivity of desert crops. Greenhouses are majorly used for production of crops in semiarid areas. Inoculating the desert soil with AMF would help to prevent the dwarfing or stunting of plants that occurs because of greenhouse gases (Koltai et al., 2008). AMF is also beneficial for preventing diseases in desert plants. It is reported that seedlings of date palms that were treated with the mycorrhizal spores of various AMF species of the genera *Glomus* exhibited more resistance to Bayoud disease than those treated with species of other genera (Jaiti et al., 2007). More than 15 million date palm trees were known to have been killed by the *Fusarium sp.* caused Bayoud disease in Morocco and Algeria (Apple, 2010). Such incidences have expedited desertification in both countries during the last century. Apart from increasing the economic yield of desert plants, AMF also increases the food value of the crop (Allen, 2007; Begum et al., 2019). One of the main advantages of AMF is water provision to the desert plants which is made possible by a widespread hyphal net of the fungal species that can distribute water to different plant species with which they exhibit the mycorrhizal relationships. For example, a 10 mm segment of the root of a desert plant could have a 1000 cm of hyphae from the AMF which extends in all directions in the soil (Al-wahaibi, 2009). AMF also helps in the ecological succession of desert plants by influencing the early succession stages in the colonization of volcanic deserts, mostly by storing water for the growth of the plants (Muñoz et al., 2021; Peter, 2003). AMF also assists majorly in growth of seedlings of desert plants despite the harsh edaphic factors that sometimes override the beneficial effects that are extended by the mycorrhizal fungi. For example, the inoculation of AMF improves and enhances the soil water holding capacity as well as the content of N and C in mesquite

tree (*P. articulata*) (Bashan et al., 2000). This property of soil is further enhanced by Glomalin, which is very sticky in nature and is made up of iron-containing glycoprotein that is produced by AMF. These compounds are the source of 15 % to 20 % of the C needs of the desert plants. Further, glomalin acts as a glue in stabilizing the soil by forming soil aggregates (Li et al., 2022; Wright & Upadhyaya, 1998). When the glomalin content in the soil increases, it improves water infiltration, root development, and enhancement of microbial activity hence improving soil resistance to erosion. Apart from increasing the water holding capacity of the soil, the glomalin content plays a significant role in increasing the agricultural yield of desert plants (Kalamulla et al., 2022; Treseder & Turner, 2007). It was shown that the hyphal networks remained intact without the mechanical effects of tilling. However, the content of glomalin and the respective population of AMF would not increase if *Brassicaceae* species of crops are grown (Apple, 2010). This is because such plant species do not form AMF associations, and the glomalin content is dependent upon the hyphal concentrations.

AMF are regarded as natural biofertilizers due to their ability to provide the host plants with nutrients, water, and protection against pathogens and in return consume the photosynthetic compounds and products formed, which aid in the formation of their C skeleton (Berruti et al., 2016). The loss of AMF from the soil reduces the efficient functioning of the ecosystem (Addisu, 2022; Campanelli et al., 2013). Initially, it was believed that AMF lack host- and niche-specificity, however, studies conducted by Błazzkowski et al. (2002) and Castillo et al. (2016) have endorsed that such assumptions are dependent on environmental conditions. AMF helps in the sustainable cultivation of date palms because such plants have a limited root system due to the low density of root hairs. The combination of poor nutrients and low water levels further limit the cultivation of date palms. However, AMF, due to its extensive hyphae network, develops a symbiotic relationship with date palms and nurture them by providing water and nutrients, even in the periods of drought (Al-Karaki, 2013). The drought stress relieving capacity of AMF is also witnessed by Abdel-Salem et al. (2018) where it was demonstrated that AMF mitigates the negative impacts of drought stress on *Rosa damascena* plant. Inoculation with AMF substantially enhanced nutrient content, gas exchange, and water potential in the referred plant. It was reported that the level of improvement was

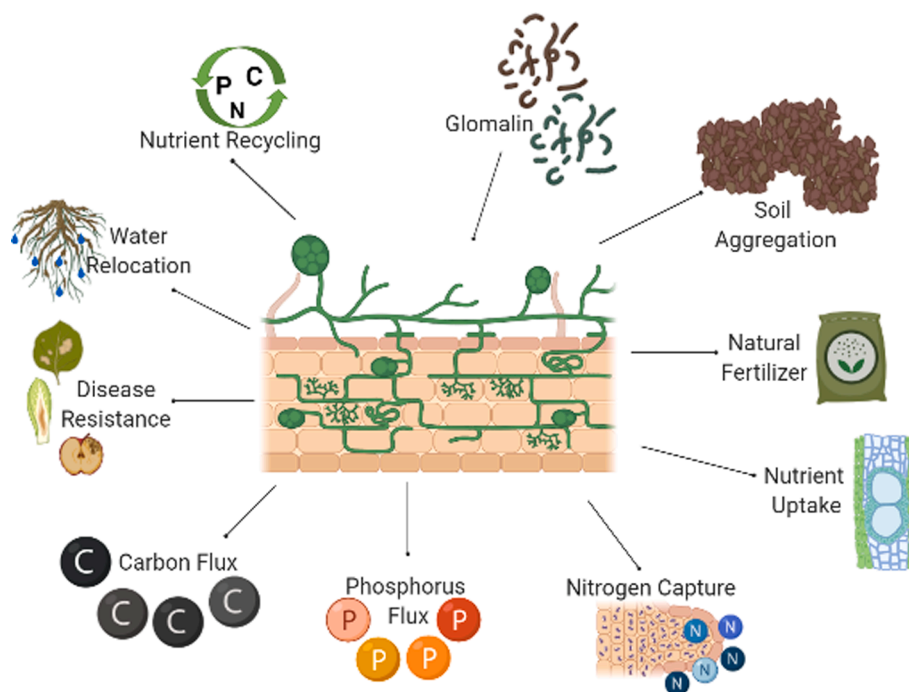


Fig. 1. Overview of the contributions of AMF.

precisely proportionate to the mycorrhizal colonization in the roots of *R. damascene*. Moreover, AMF improved the flower health, and improved resistance of desert rose to drought stress (Abdel-Salam et al., 2018).

3.1. Plant-Mycorrhizal interaction

It is true that the plant-mycorrhizal interaction is a very mutualistic association between both. The fruitful outcome of this relationship is what makes the competition among different plant species tough. Presence of AMF association in some plants enhances their competitiveness while in others, it decreases. One might not consider this association anything but nutrient exchange, however, it is much more than this. AMF and plant association can drive the whole plant community dynamics and hence, controls the ecosystem functioning (Sun et al., 2022).

The ability of AMF to build a large hyphal network, often known as the “wood-wide web,” that may connect various plant communities and provide effective horizontal nutrition and water transport is an unusually well-known trait of these organisms. Symbiotic interfaces, which the fungi create regions, serve as a platform for interaction with the plant host. The mutualistic connection is typically dependent on the nutrient exchange because the mycorrhizal fungi’s life cycle depends on absorbing the organic C produced by plants, much like any other fungi linked with plants (Kumar et al., 2016; Shi et al., 2023). Mycorrhizal connections’ main benefits include better plant growth, higher nutrient and water uptake, enhanced soil properties, and defense against environmental hazards. In exchange, the host plant partner provides the mycorrhizal fungus with their energy supply in the form of carbohydrates.

AMF have symbiotic relationships with plants that, in certain environments, greatly aid in the development and growth of plants by altering the root system (an increase in the root area) and enhancing nutrient intake and mobilization (Mitra et al., 2022; Sylvia & Williams, 1992). Additionally, they stimulate the development of non-enzymatic defence mechanisms and enzymatic antioxidants in plants so that they can tolerate and survive stress (Ahmad et al., 2016; Wang et al., 2018), production of phytohormones (Navarro-Ródenas et al., 2013; Zhao et al., 2022), and lipid peroxidation (Abd Allah et al., 2015). It is reported in literature that the symbiotic associations are found in ancient species as well that confirms the symbiotic relationship to be one of the principal of fungi, which were important in the evolution of plants (Abd Allah et al., 2015) (EF et al., 2015). The symbiotic relationship between rhizobia bacteria, which fixes nitrogen, on the other hand, developed later and is consequently exclusive to a certain plant lineage (Abd Allah et al., 2015). The fungus is usually coenocytic or septate hyphae, with many nuclei in the spores. The vast genome and polymorphic character of these nuclei have made the sequencing and annotation of the fungal group’s genomes difficult. Generally they are asexual, but anastomosis have also been reported (Richter et al., 2023; Sanders et al., 1996).

The AMF create an appressorium on the host’s surface known as the hyphopodium. The hyphae originating from the former go through the root cells and into the cortex via an apparatus of penetration. The fungus’ hyphae, however, enter the cortex through the apoplast and proceed through the root’s axis, entering the cortical cells of the inner root. The fungi penetrate the plants through hyphal branches that later develop intracellular hyphal coils (Bonfante & Genre, 2010; Yuan-Yuan et al., 2020). The hyphal coils do not enter the symplast nor the cytoplasm of the host plant. The exclusion of the fungi from the cytoplasm of the host is achieved through a membrane derived from the host cells known as the periarbuscular membrane (PAM) (Bonfante & Genre, 2010). Arbuscular mycorrhizae fungi penetrate cortical cells in plant roots, leading to morphological changes in the roots, hence, enhancing weeds, pests, and disease tolerance (Enebe & Erasmus, 2023; Schouteden et al., 2015). They develop arbuscules inside the cortical cells, which they employ as sites for nutrition exchange. Additionally, vesicles

are developed between the cortical cells to serve as nutrient storage compartments (Yadav et al., 2017).

AMF are unculturable without a host. Since AMF cannot store food (carbohydrate) except when they are within a plant, they are stringent biotrophs since they are entirely dependent on their hosts for growth and reproduction. According to developmental and evolutionary theories, the strict association that AM fungus have with plants has enabled them to survive the environmental hazards associated with the loss of their saprotrophic powers (Bonfante & Genre, 2010).

3.2. The role of arbuscular mycorrhizae fungi in the induction of systemic resistance and minimizing or inhibiting the pathogenicity of plant diseases

Rhizosphere functioning is the outcome of a dynamic and complex microbiome which is altered or controlled by several biotic and abiotic factors (Haldar & Sengupta, 2015; Xun et al., 2021). AMF is one of the primary components in the rhizosphere system. They are useful because they can protect the host against a wide range of phytopathogenic illnesses through different mechanisms (Ciancio et al., 2019). Induced systematic resistance, improved root tolerance, changed rhizospheric interactions, and direct competition for few resources of space and nutrients are some of these mechanisms. In order to prevent or eradicate the plant diseases that lower the crops’ productivity and quality, the AMF can create systemic resistance through several pathways (Ciancio et al., 2019). Moreover, AMF not only improves the plant growth and productivity, but also enrich the defensive phytochemical production (Balestrini et al., 2021; Song et al., 2015).

3.3. The role of AMF in increasing crop yield

AMF involvement in improving crop yield occurs by its capability to absorb micronutrients and macronutrients that include but are not limited to P, Zn, K, and N, and then transferred to plants. It is reported that in the presence of AMF, 90 % of the P and 20 % of N is taken up through its complex hyphal network (Wu et al., 2022). Similarly, AMF is involved in the solubilization of potassium (K) as it is trapped in a crystal lattice and only 0.1 to 2 % is available for the plant uptake. AMF releases organic acids like p-coumaric acid, p-hydroxybenzoic acid, and caffeic acid which helps to solubilize K and make it available for plant’s uptake (Ma et al., 2022a; Priyadharsini & Muthukumar, 2016).

Despite AMF’s potential to raise agricultural productivity, it is crucial to consider the factors that may influence their relationship; as a result, an increase in crop yield should not always imply the presence of fungi. In general, AMF colonization is reported to promote the growth of plants but the physicochemical composition of the soil may also directly affect their relationship (Kim et al., 2017). Therefore, while examining the effects of AMF on different properties of crops such as its growth, development, and overall yield improvement, soil conditions must be a crucial issue to consider. Before implementing the use of AMF products, it is highly recommended for researchers, and other related practitioners to assess the targeted site for the presence of local or native AMF species. This will not only help in determining the local communities present on site, but also avoid any detrimental consequences of adding AMF products.

3.4. Commercialization of mycorrhizal products

With an increase in the world population, an up-surge in food demand and land for agriculture has been reported. According to United Nations estimates, the world’s population will reach 8.5 billion by 2030 and 9.7 billion by 2050. In the year 2050, the food demand will rise in tandem with the rise in population (Hunter et al., 2017). One of the many approaches to tackle the issue of increased food demand is to intensify the agricultural practices, however, it will impose a high threat to the environment that includes increase in greenhouse gas release, pollution of water bodies, alteration of soil properties, and decrease in

microbial diversity (Basiru & Hijri, 2022). Therefore, the focus of conventional agriculture should be substituted with sustainable agriculture by including environmentally friendly practices. Among the available eco-friendly practices, AMF has been recognized as a promising approach both environmentally and economically as its usage maintains the health of soil. AMF inoculants are very well known for their use as biofertilizers, but only a limited number of AMF inoculants are benchmarked and available commercially (Basiru et al., 2020). The reasons reported on AMF products not to be commercialized are several based on laboratory research and controlled environment studies. The inconsistency of AMF inoculants under different field conditions that includes incompatibility of symbionts with abiotic factors like soil is one of the many reasons. Moreover, failure of AMF products to be commercialized is not only restricted to environmental factors but also includes technical mishaps like poor product quality (Salomon et al., 2022). Some products successfully make it to the commercialization process and are utilized by practitioners, however, it has also been reported in certain cases that these products are less effective or do not produce the desired results at all. The efficiency of AMF commercialized products can be assessed by comparing the properties of control and treatment groups and to determine whether the effect of the product is coupling the plant-AMF symbiotic interaction or de-coupling it. Another reason where a commercialized AMF product might decouple the beneficial association is because of lack of co-adaptability between the already available on-site species and the inoculated species (Duell et al., 2022).

4. The Arabian Peninsula: Geography and vegetation

The Arabian Peninsula is located on the Asian continent and is bordered by the Red Sea to the southwest and west, the Arabian Gulf to the east and northeast, the Strait of Hormuz and the Gulf of Oman to the east, the Arabian Sea to the southeast, the Gulf of Aden, the Guardafui Channel, and the Somali Sea to the south. With a total area of 1,250,000 sq mi (3,237,500 km²), the Arabian Peninsula is the largest peninsula in the world. It is in Asia and comprises of six countries: The Kingdom of Saudi Arabia, Kuwait, Qatar, the United Arab Emirates, Oman, and Yemen. The Arabian Peninsula is a land of contrasts as it is featured by soaring summer temperatures of the Rub' al Khali (650,000 km²) to the moderate climate and scanty rainfall on the southwest and the Hajar Mountains in Oman. Therefore, one passes from hyper-arid coasts and plains (<100 mm rainfall) through the arid higher plains and foothills (100–250 mm rainfall), and the semi-arid mountain slopes and summits (250–500 mm rainfall), and finally to the temperate mountains of the extreme southwest (>500 mm of rainfall) (Ghazanfar & Fisher, 1998). The topography of the Arabian Peninsula significantly influences its meteorology. For example, the mountains on the west effects the weather conditions along the Red Sea from Sinai (North) to Bab al Mandab (South) by affecting precipitation rates and surface wind (Ghazanfar & Fisher, 1998). The winter circulation is predominated by the Siberian anticyclone and represents the polar continental air masses. One of the key characteristics of its topography is the presence of the sand dunes that are formed due to the atmospheric circulation since 160,000 years (Preusser et al., 2002). The genesis of dune activity is correlated to periods of low global sea levels and reduced monsoon intensity. Dust from the Arabian Gulf is carried to the Arabian Sea during times of high-latitude glaciations. Reconstruction of paleo-circulation indicated that the dried out Arabian Gulf became an important source of fine material which was lifted and transported to the higher layers of the troposphere.

Most of the Arabian Peninsula are semi-arid and arid lands and exhibits a desert climate. Deserts comprise about 40 % of land surface and stretches around a longitude of 30° north and south of the equator (Al-wahaibi, 2009). Desert lands are areas of high pressure and receive extremely low rainfall in the range of 245 mm. The soil is sandy and is devoid of organic nutrients resulting in scattered vegetation with succulents, C4, and CAM plants as the predominant ones (Al-wahaibi, 2009).

Fungi are noted across a range of desert plants exhibiting mycorrhizal relationship.

4.1. Studies on distribution and diversity of AMF in the Arabian Peninsula

There are different genera and species of AMF. Mosbah et al. (2017) characterized the AMF that is found in coffee plants in Kingdom of Saudi Arabia (KSA). The authors collected the plants from two sites of KSA and subjected the large subunit of AMF rDNA regions to nested PCR, cloning, sequencing, and phylogenetic analysis which revealed 10 phenotypes belonging to *Glomeraceae*, two belonging to *Claroideoglomeraceae*, and one each to *Acaulosporaceae* and *Gigasporaceae*. The major genus was *Glomus* while the genus *Gigaspora* was obtained from one site only. This was the first study that reported the presence of AMF in the coffee roots in KSA. These findings are aligned with the findings from a Brazilian and Chile study that showed coffee plants could harbor AMF which reflected its host-specific attributes. However, the same study showed that the mycorrhizal intensity and spore density was more in site 2 (located at a higher altitude) as compared to site 1 (located at a lower altitude). These results suggested that host-specificity of AMF was significantly influenced by the topographical factors (Al-Arequi et al., 2013). The diversity of AMF is less impacted compared to their abundance and dominance under environmental extremes. Although the lack of host specificity for AMF has been reflected by several studies, the change in dominance pattern of AMF species in the desert ecosystem was evidenced from a Polish study which showed that *Scutellospora* was the most abundant genus of AMF compared to *Glomus* or *Gigaspora* whose dominance pattern was relatively lower. Twenty species of AMF were identified from the given geographical location among which *Scutellospora armeniaca* was the most dominant (Błaszowski et al., 2002).

The distribution of AMF in Arabian Peninsula has been reported in different plant roots and rhizospheres (Table 1). The plant families from where such mycorrhizal relationships were witnessed include herbs, shrubs, and trees. The distribution of AMF varied within and between different plant species indicating their non-host specific character at least in the Arabian Peninsula. Rather, the AMF species to some extents were niche specific, and the niche specificity was primarily dependent on the soil conditions and land usage patterns (Brito et al., 2012; Yang et al., 2012). Such findings are supplemented by previous studies which showed that the host specificity of AMF differed between cultivated and uncultivated lands within the same geographical locations (Brown & Jumpponen, 2013).

Table 1 depicts 20 genera and 61 species of AMF that were recorded in the Arabian Peninsula (Fig. 2) representing 46.51 % of genera and 17.88 % of species of AMF known so far. The predominant genus was *Rhizophagus* which was reported in thirteen studies. It consisted of 10 (+5 unknown) species. The next abundant genus was *Funneliformis* which was recorded in ten studies and had five species only. On the other hand, *Glomus* was reported in five studies and consisted of five (+5 unknown) species, while *Acaulospora* and *Diversispora* genera were reported in seven studies and consisted of seven (+2 unknown) and five species respectively.

In species, the most common one was *Funneliformis mosseae* (*Glomus mosseae*) which was reported in 8 studies, followed by *Claroideoglomus etunicatum* (*Glomus etunicatum*) and *Rhizophagus intraradices* (*Glomus intraradices*) which were reported in 6 studies and *Rhizophagus aggregatus* (*Glomus aggregatum*) which was found in 5 studies. The most dominant genera of AMF in the Arabian Peninsula were *Rhizophagus* representing 16.39 % of all genera and *Acaulospora* representing 14.75 %, followed by *Diversispora*, *Glomus*, and *Funneliformis* representing 8.20 % each (Table 2). AMF are assigned in twenty genera, nine families and four orders according to the website <https://www.amf-phylogeny.com>.

The diversity of the microbial communities is known to be affected by the type of agricultural practices being carried out in a particular region. In a study conducted by Kutty and his colleagues (2020), organic farming and its impact on the parameters; the AMF abundance, richness

Table 1
Site description and geographical position of the ecosystems of the Arabian Peninsula.

Country/ Area	Geographic location	Host plant/ Colonization percentage	Number of AMF species (genus)	Dominance genus	AMF species (new names)	Country/ Area (Reference)
KSA	King Saud University Farm, at Dirab, Riyadh, Saudi Arabia.	<i>Calendula officinalis</i> L <i>Catharanthus roseus</i> (L.) <i>Convolvulus arvensis</i> L <i>Cynodon dactylon</i> (L.) Mill <i>Gaillardia pulchella</i> Foug <i>Ocimum sanctum</i> L <i>Phoenix dactylifera</i> L <i>Petunia hybrida</i> (L.) <i>Sesuvium portulacastrum</i> (L.) <i>Tagetes patula</i> L	6 (4)	<i>Rhizophagus</i>	<i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>), <i>Glomus etunicatum</i> (<i>Claroideoglomus etunicatum</i>), <i>Glomus aggregatum</i> (<i>Rhizophagus aggregatus</i>), <i>Glomus intraradices</i> (<i>Rhizophagus intraradices</i>), <i>Glomus fasciculatum</i> (<i>Rhizophagus fasciculatus</i>), and <i>Glomus macrocarpum</i> .	(Al-Qarawi et al., 2012)
KSA/ between Jeddah and Macca	25 sites between (21°54'11.034" N) (39°21'12.031" E) and (21°40'15.114" N) (39°35'14.874" E)	<i>Abutilon pannosum</i> (Forst. F.) Schlecht <i>Acacia ehrenbergiana</i> Hayne <i>Aerva javanica</i> (Burm.f.) Spreng <i>Calotropis procera</i> (Ait.) Ait. f. <i>Dipterygium glaucum</i> Decaisne <i>Farsetia longisiliqua</i> Decaisne <i>Indigofera argentea</i> Burm. f. <i>Leptadenia pyrotechnica</i> (Forssk.) Decaisne <i>Suaeda monoica</i> Forssk <i>Tribulus parvispinus</i> Presl <i>Zygophyllum simplex</i> L. <i>Rhazya stricta</i> Decaisne	13 (8)	<i>Rhizophagus</i>	<i>Acaulospora</i> sp. <i>Glomus aggregatum</i> (<i>Rhizophagus aggregatus</i>), <i>Glomus clarum</i> (<i>Rhizophagus clarus</i>), <i>Glomus coronatum</i> (<i>Funneliformis coronatus</i>), <i>Glomus deserticola</i> (<i>Septoglomus deserticola</i>), <i>Glomus etunicatum</i> (<i>Claroideoglomus etunicatum</i>), <i>Glomus invermaium</i> (<i>Rhizophagus invermaius</i>), <i>Glomus macrocarpum</i> , <i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>), <i>Glomus multicaule</i> , <i>Glomus sinuosum</i> (<i>Sclerocystis sinuosa</i>), <i>Glomus</i> sp., <i>Scutellospora</i> sp.	(Abdelmoneim et al., 2014; Abdelmoneim et al., 2013)
KSA	Different parts of Saudi Arabia	Rangeland, Ephemerals, crops, Forest plants, Horticultural crops etc	1	<i>Funneliformis</i>	<i>Funneliformis mosseae</i>	(Al-Qarawi et al., 2013)
KSA/ Riyadh (3 sites)	Raudhat Khuraim, Washlah and Wadi Huraymila at Riyadh	<i>Acacia tortilis</i> , <i>Acacia ehrenbergiana</i> and <i>Acacia gerrardii</i>	3 (3)	<i>Funneliformis</i>	<i>Glomus intraradices</i> (<i>Rhizophagus intraradices</i>), <i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>) and <i>Glomus Etunicatum</i> (<i>Claroideoglomus etunicatum</i>)	(Elmaki et al., 2017)
KSA/Tihama Plains (2 sites) and Asir Mountains	17°11'53.7"N, 42°36'54.5"E 17°41'18.1"N, 42°19'31.4" E 18°13'29.6"N, 42°26'11.8"E	<i>Acacia ehrenbergiana</i> <i>Acacia tortilis</i> <i>Acacia negrii</i>	11 (3)	<i>Acaulospora</i>	<i>Glomus microaggregatum</i> (<i>Rhizoglomus microaggregatum</i>), <i>G. mosseae</i> (<i>Funneliformis mosseae</i>), <i>Glomus geosporum</i> (<i>Funneliformis geosporus</i>), <i>G. intraradices</i> (<i>Rhizophagus intraradices</i>), <i>Glomeromycota</i> sp. (JN937539), <i>Acaulospora tuberculata</i> , <i>Glomus</i> sp. (AJ459354), <i>Acaulospora longula</i> , <i>Acaulospora mellea</i> , <i>Gigaspora gigantea</i> , and <i>Gigaspora rosea</i>	(Mosbah et al., 2017)
KSA/Fifa Mountains	17°17'27.1"N 43°08'33.4"E; at 700 m altitude (17°15'20.6"N 43°06'21.1"E; at 1400 m	<i>Coffea arabica</i> L.	6 (6)	–	<i>Claroideoglomus claroideum</i> (FR750074) <i>Glomus microaggregatum</i> (AF389021) (<i>Rhizoglomus microaggregatum</i>), <i>Glomus mosseae</i> (AF145736) (<i>Funneliformis mosseae</i>), <i>Rhizophagus intraradices</i> (<i>Acaulospora longula</i> (AF389007) and <i>Gigaspora rosea</i> (FR750185))	(Mosbah et al., 2017)
KSA/ Riyadh and Qassim	Rawdat Khuraim (25° 38' N, 47° 29' E,) Aba Alworood (27° 2' N, 44° 7' E, 576 m a. s. l.)	<i>Anthemis deserti</i> <i>Arnebiadecumbens</i> <i>Calendula arvensis</i> 14 % <i>Echiumrauwolfia</i> <i>Erucaiahispanica</i> <i>Picris</i> sp./75.00 % <i>Pulicariaguestii</i>	6 (5)	<i>Funneliformis</i>	<i>Glomus geosporum</i> (<i>Funneliformis geosporus</i>), <i>Glomus deserticola</i> (<i>Septoglomus deserticola</i>), <i>Diversispora spurca</i> , <i>G. aggregatum</i> (<i>Rhizophagus aggregatus</i>), <i>G. etunicatum</i> (<i>Claroideoglomus etunicatum</i>), <i>Glomus mosseae</i>	(Albaqami et al., 2018)

(continued on next page)

Table 1 (continued)

Country/ Area	Geographic location	Host plant/ Colonization percentage	Number of AMF species (genus)	Dominance genus	AMF species (new names)	Country/ Area (Reference)
KSA/ Riyadh region, Holy Madina region	Houta Bani Tamim, Rawdhat Khuraim, Werqaan Mountain, Ola city	<i>Rumexvesicarius</i> <i>Zilla spinose</i> Talh trees - <i>Acacia gerrardii</i>	15 (8)	<i>Funnelformis</i>	(<i>Funnelformis mosseae</i>) <i>Funnelformis geosporum</i> (<i>Funnelformis geosporus</i>) <i>Funnelformis badii</i> <i>Funnelformis verruculosum</i> , <i>Funnelformis mosseae</i> , <i>G. segmentatum</i> , <i>G. arenarium</i> (<i>Diversispora arenaria</i>), <i>G. pansihalos</i> , <i>G. sinuosum</i> (<i>Sclerocystis sinuosa</i>), <i>Rhizophagus aggregatus</i> , <i>Rhizophagus fasciculatus</i> , <i>Acaulospora denticulata</i> , <i>Funnelformis constrictum</i> , <i>Acaulospora mellea</i> , <i>Claroideoglossum etunicatum</i> , <i>Archaeospora trappei</i>	(Abeer et al., 2018)
Kuwait /Sabah Al-Ahmad natural reserve	29°34.909'N, 047°47.734'E	<i>Vachellia pachyceras</i> (<i>Acacia</i>)	10	<i>Rhizophagus</i>	<i>Rhizophagus</i> (5)Unclassified (5)	(Suleiman et al., 2019)
UAE/ sandy desert -Abu Dhabi	24°25'07 N, 54°49'40E	<i>Punica granatum</i> L, <i>Ammophila arenaria</i> (L.)	2		<i>Dominikia emiratia</i> , (<i>Orientoglossum emiratium</i>), <i>Rhizoglossum dunense</i> (<i>Rhizophagus dunensis</i>)	(Al-Yahya'ei et al., 2017)
Oman/ Oasis, Exp. Station Undisturbed habitat, and sand dunes	22°12'56"N, 59°12'9"E 22°14'13"N, 59°11'5"E 22°14'11"N,59°10'53"E	Date palm, <i>Polygala erioptera</i> , <i>Zygophyllum hamiense</i> , <i>Salvadora persica</i> , <i>Prosopis cineraria</i> , Inter-plant and <i>H. kotschy</i>	25 (11)	<i>Glomus</i>	<i>Acaulospora spinosa</i> , <i>Ambispora gerdemannii</i> , <i>Glomus aggregatum</i> (<i>Rhizophagus aggregatus</i>), <i>G. constrictum</i> (<i>Septoglossum constrictum</i>), <i>G. eburneum</i> (<i>Diversispora eburneum</i>), <i>G. etunicatum</i> (<i>Claroideoglossum etunicatum</i>), <i>Glomus macrocarpum</i> , <i>Glomus microaggregatum</i> (<i>Rhizoglossum microaggregatum</i>), <i>Glomus microcarpum</i> , <i>Glomus sinuosum</i> (<i>Sclerocystis sinuosa</i>), <i>Glomus</i> sp. OMA9, <i>Glomus</i> sp. OMA11, <i>Glomus</i> sp. OMA12, <i>Glomus</i> sp. OMA13, <i>Glomus</i> sp. OMA2, <i>Glomus</i> sp. OMA3, <i>Glomus</i> sp. OMA5, <i>Glomus</i> sp. OMA6, <i>Glomus</i> sp. OMA7, <i>Glomus</i> sp. OMA8, <i>Paraglossum occultum</i> , <i>Racocetra fulgida</i> , <i>Racocetra gregaria</i> , <i>Scutellospora</i> sp. OMA10 and <i>Scutellospora calospora</i>	(Al-Yahya'ei et al., 2011)
Oman/ date palm, a natural, undisturbed, a sand dune site.	22°12'56"N,59°12'9"E 22°14'11"N,59°10'53"E 21°52'39"N,58°52'44"E	<i>Phoenix dactylifera</i> <i>Salvadora persica</i> <i>Tetraena qatariensis</i> dry grass <i>Heliotropium kotschy</i>	4 (3)	<i>Diversispora</i>	<i>Claroideoglossum drummondii</i> , <i>Diversispora aurantia</i> , <i>Diversispora spurca</i> and <i>Funnelformis africanum</i> (<i>Septoglossum africanum</i>)	(Symanczik et al., 2014)
Oman/ Al-Sharqiya Sands and Oman Mountains	Undisturbed site: 22°14'11" N,59°10'53" E Oasis of Al-Kamel: 22°12'56" N, 59°12'9" E	<i>Tetraena qatariensis</i> <i>Salvadora persica</i> <i>Prosopis cineraria</i> Inter-plant area date palms	3 (3)		<i>Diversispora omaniana</i> , <i>Septoglossum nakheelum</i> , <i>Rhizophagus arabicus</i> spp	(Symanczik et al., 2014)
Yemen (5 sites)	2348,1746, 1726,1530,1355	<i>Coffea arabica</i>	5	<i>Acaulospora</i>	<i>Glomus proliferum</i> (<i>Rhizophagus prolifer</i>), <i>Glomus etunicatum</i> (<i>Claroideoglossum etunicatum</i>), <i>Acaulospora sporocarpia</i> , <i>Acaulospora</i> sp.1 <i>Scutellospora nigra</i> , <i>Archeospora</i> sp. 1	(Al-Arequi et al., 2013)
Qatar	25.454167/51.300564 25.662816/51.393684 26.049472/51.208722 26.041618/ 51.249680 25.715596/51.449514 25.303106/51.192371 25.374962/51.490011 25.370381/51.495726	<i>Zygophyllum qatariense</i> <i>Tamarix aphylla</i> <i>Launaea nudicaulis</i> <i>Sclerocephalus arabicus</i> <i>Fagonia indica</i> <i>Spergula fallax</i> <i>Cynodon</i> sp <i>Plantago ovata</i> <i>Salvia aegyptiaca</i>	13 (8)	<i>Rhizophagus</i>	<i>Claroideoglossum claroideum</i> EP0039 <i>Claroideoglossum drummondii</i> EP0097 <i>Rhizophagus irregularis</i> EP0009 <i>Rhizophagus invermaius</i> EP 0035 <i>Rhizophagus intraradices</i> EP0032 <i>Rhizophagus arabicus</i> EP0031 <i>Dominikia distichi</i> EP0126	(Alrajhei et al., 2022)

(continued on next page)

Table 1 (continued)

Country/ Area	Geographic location	Host plant/ Colonization percentage	Number of AMF species (genus)	Dominance genus	AMF species (new names)	Country/ Area (Reference)
		<i>Lycium shawii</i> <i>Aizoon canariense</i> <i>Pulicaria undulata</i> <i>Blepharis ciliaris</i> <i>Paronychia arabica</i> <i>Sporobolus ioclados</i> <i>Malva parviflora</i> <i>Medicago sativa</i> *			<i>Kamienskia bistrata</i> EP0119 <i>Nanoglomus plukenetiae</i> EP0323 <i>Sclerocystis sinuosa</i> EP0204 <i>Diversispora peloponnesiaca</i> EP0322 <i>Diversispora aurantia</i> EP0074 <i>Funnelformis coronatus</i> EP0043	
Qatar	25.374962/51.490011		13 (9)	<i>Rhizophagus</i>	<i>Acaulospora herrerae</i> EP0295 <i>Archaeospora schenckii</i> EP0213b <i>Claroideoglomus drummondii</i> EP0097 <i>Claroideoglomus hanlinii</i> EP0098 <i>Diversispora aurantia</i> EP0074 <i>Kamienskia bistrata</i> EP0119 <i>Nanoglomus plukenetiae</i> EP0323 <i>Paraglomus occidentale</i> EP0324 <i>Pervetustus simplex</i> EP0264 <i>Rhizophagus arabicus</i> EP0031b <i>Rhizophagus intraradices</i> EP0032 <i>Rhizophagus irregularis</i> EP0009 <i>Rhizophagus natalensis</i> EP0206	(Khazna and Abu-Dieyh, 2021 unpublished)

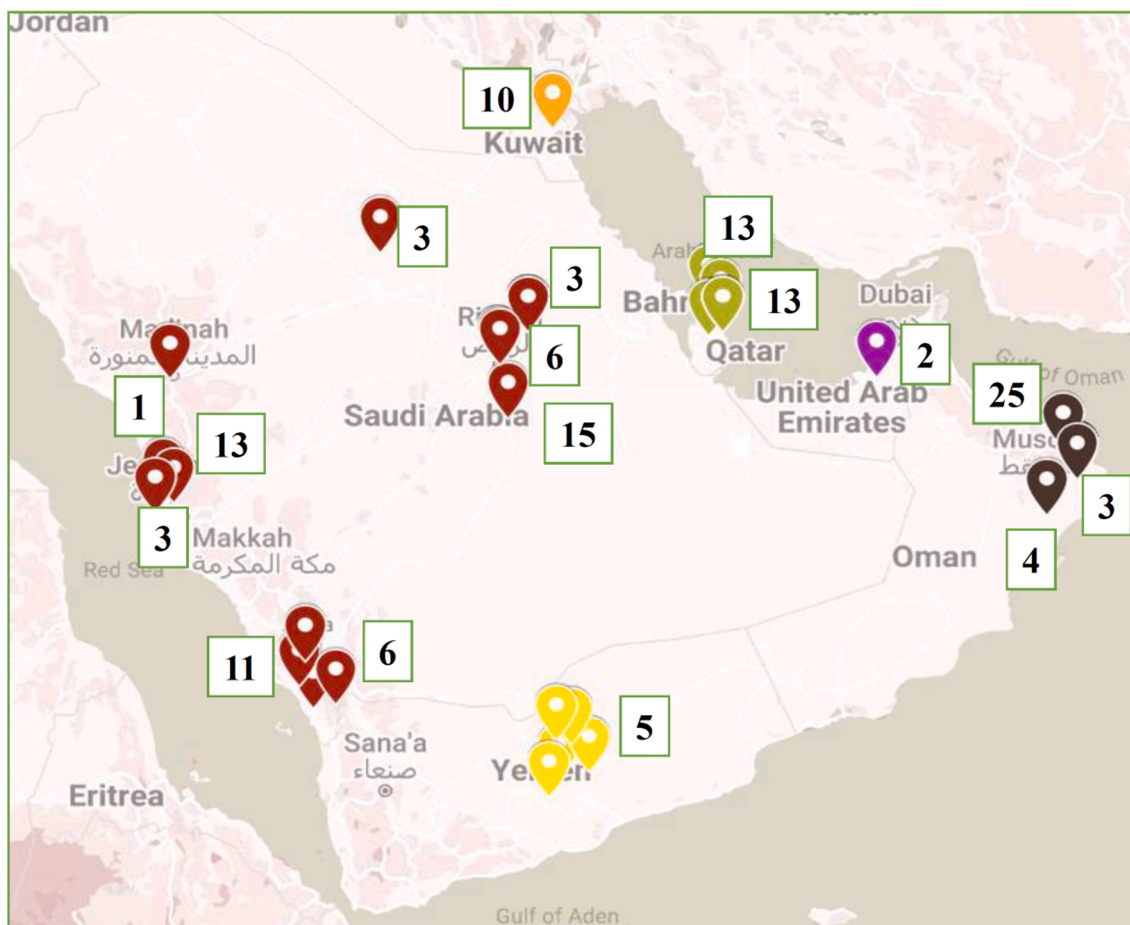


Fig. 2. Distribution of 61 AMF species in different locations in the Arabian Peninsula. Numbers indicate species of AMF.

and diversity was evaluated. A comparative study was done where the parameters were compared with the conventional agricultural practice and local vegetation. It was revealed that from twelve sites, 21 species of AMF were isolated from region with organic farming as compared to fourteen from region with both conventional farming and the presence

of native species. The parameters were all high for organic farming than conventional farming in desert conditions (Kutty et al., 2020). Based on this study, it can be concluded that AMF plays a significantly positive role in desert habitat by promoting sustainable food production.

Table 3 shows the studies that were conducted in the Arabian

Table 2

Genera, families, and orders of AMF discovered in Arabian Peninsula. The number of known species in each genus is indicated in brackets after the genera name.

Genera (*)	Family	Order
<i>Acaulospora</i> (9)	Acaulosporaceae	Diversisporales
<i>Ambispora</i> (1)	Ambisporaceae	Archaeosporales
<i>Archaeospora</i> (3)	Archaeosporaceae	Archaeosporales
<i>Claroideoglomerum</i> (4)	Claroideoglomeraceae	Glomerales
<i>Diversispora</i> (5)	Diversisporaceae	Diversisporales
<i>Dominikia</i> (1)	Glomeraceae	Glomerales
<i>Funnelformis</i> (5)	Glomeraceae	Glomerales
<i>Gigaspora</i> (2)	Gigasporaceae	Diversisporales
<i>Glomus</i> (5 + 12 unknown)	Glomeraceae	Glomerales
<i>Kamienskia bistrata</i> (1)	Glomeraceae	Glomerales
<i>Nanoglomerum</i> (1)	Glomeraceae	Glomerales
<i>Orientoglomerum</i> (1)	Glomeraceae	Glomerales
<i>Paraglomerum</i> (2)	Paraglomeraceae	Paraglomerales
<i>Pervetustus</i> (1)	Pervetustaceae	Paraglomerales
<i>Racocetra</i> (2)	Gigasporaceae	Diversisporales
<i>Rhizoglomerum</i> (1)	Glomeraceae	Glomerales
<i>Rhizophagus</i> (10 + 5 unknown)	Glomeraceae	Glomerales
<i>Sclerocystis</i> (1)	Glomeraceae	Glomerales
<i>Scutellospora</i> (2 + 2 unknown)	Gigasporaceae	Diversisporales
<i>Septoglomerum</i> (4)	Glomeraceae	Glomerales

(*) Number of species.

Peninsula to study the influence of native isolated AMF species on improving the plant growth under stressed conditions. A total of 35 studies were available on this research area. Although the number of species discovered so far has exceeded 61 species, but species used for studying the impact on plants were found to be 12 only. Furthermore, these experiments were limited to KSA only. AMF species tested were isolated from different regions of KSA to study their effect on improving plant growth under various stress conditions such as salinity, drought, and cadmium. 18 studies covered salinity factor, six studies covered drought and four studies covered cadmium stress, while one study examined the effect of these fungi on disease resistance. 21 studies used an inoculum consisting of a mixture of three native species: *F. mosseae*, *R. intraradices*, and *C. etunicatum*. The most studied species was *Funnelformis mosseae* which was used in 26 studies. In three studies, the effect of *F. mosseae* was examined individually, while one study did not specify the type of AMF that was studied. All these studies were conducted under controlled environmental conditions, the greenhouse, and the growth chambers. The effects of AMF are often conducted under controlled conditions but not in the field. Moreover, little or no studies are conducted where the effects of AMF on the most demanded and consumed vegetables and fodder that include tomatoes, potatoes, onions, barley, and alfalfa were reported.

Upon the detailed analysis of the effects of different stressors (drought, salinity, cadmium) in the presence of AMF on plant parameters, it was found that AMF improved the growth parameters, photosynthetic pigments, macronutrients (N, P, K, Ca, Mg), soluble proteins, N metabolism, ammonium availability, antioxidant enzymes (ascorbate, GSH, GSSG, and GSNO), glucose, sucrose phosphate synthase, plant hormones, alkaline and acid phosphatase enzymes, total phenols, nodulation and leghemoglobin content, polyamines content (spermine, spermidine putrescine), TWC, phytohormones, glycine betaine, auxin synthesis, cell membrane stability, and osmolytes accumulation respectively (Table 3). Based on careful investigation, it can be reported that all the parameters that increased with AMF inoculation play a significant role in growth of plants one way or the other. For instance, N metabolism is very crucial in terms of fighting stress conditions as almost all the physiological plant processes are associated with it (Zhong et al., 2017). Similarly, increase in ammonium availability under stressed conditions and with AMF inoculation is another indication of plants' physiological and morphological response towards stress. Increase in ammonium ions enhances the plants' ability to fight

pathogens, carryout ammonium assimilation, tolerate drought, promote lateral root branches, and increase root hair biomass (Liu & von Wirén, 2017). All these eventually protect the plant and promote its growth.

On the other hand, under stressful conditions and with AMF inoculation, certain parameters were found to be decreased that includes, glutathione, ROS, lipid peroxidation, H₂O₂, malonaldehyde, PPKK, PEPC, and TBARS. The ROS are mainly released by the plants when they are under stressed conditions, however, they can be harmful to certain biological entities such as DNA, or proteins. With inoculation of AMF under stressed conditions, the ROS are decreased through an increased production of antioxidative enzymes and non-enzymatic antioxidant compounds. Together, this process inhibits the production of ROS, hence, prevent the damage to biological cells of the plants (Kapoor & Singh, 2017).

Prolonged drought and extensive land usage in arid regions such as the deserts have significantly impacted soil and plant productivity (Powell et al., 2015). Therefore, the risk of desertification has further increased in these areas. Coupled with the changes in the biotic and abiotic features of a geographical location, the diversity and distribution of AMF have also seen radical transition with respect to host- and niche-specificity (Lyu et al., 2020).

The necessity of the mycorrhizal relationship has been fostered by low density of the root hairs of the referred plants that makes them unsuitable to pull water and nutrients such as P from the soil (Bever et al., 2009). On the other hand, the fungal species depend upon the source of C from the host plants. AMF due to their extensive and deep-rooted hyphal networks are able to supply the plants with water and minerals while deriving C skeleton from the referred plants (Allen, 2011). Microorganisms such as AMF play a significant role in ecosystem sustainability and plant growth in desert climates.

However, most of the studies on the extent of AMF diversity have been conducted in the KSA and Oman while studies in Kuwait, UAE and Yemen are limited. In Qatar, high through-put sequencing techniques have been used to study the diversity of AMF in arid regions along with the chemical drivers associated with it (Adenan et al., 2021).

It could be possible that the abiotic conditions impose significant challenges to the host plant species applying selection pressure on the fungi that affects their distribution, diversity, colonization, and reproduction (Li et al., 2023; Weber et al., 2011). These assumptions are not surprising considering the diversity of AMF especially with respect to the hyphal structure and organization (Xu et al., 2017). Very few studies have explored the structure–function correlation of AMF and their colonization or application of selection pressure by the host plant species. Future studies should explore the structure–function correlation of AMF and their colonization or application of selection pressure by the host plant species. Such information could help to design the inoculums of AMF as per the host plant species which could help in improving crop yield and ensuring ecosystem sustainability (Al-Karaki & Othman, 2007; Al-Qarawi et al., 2012; Sene et al., 2012a; Sene et al., 2012b). Sustainability of the desert ecosystem is necessary because the deserts are home to some economically viable plants.

5. Climatic changes and impact on growth of AMF

Global warming and climatic changes are at their peak in the 21st century. There is a lot of research work done to study the impact of climatic changes on the microbiota, however, its impact on the AMF is not studied very well (Rillig et al., 2002). There are contradictory responses reported in terms of impact of climatic change on the activity and association of AMF.

5.1. High temperature

With climate change, the temperature of different regions is changing. Perhaps, the soil temperature is also impacted. Soil respiration and increase in temperature are linked with each other. With an increase in

Table 3
Studies that evaluated the effect of amf isolated from arabia peninsula on plant growth.

Stress	AMF species (new name)	Source of inoculum	Trap plant	Experimental plant	Experiment place	Parameters	Reference
Drought	<i>Glomus constrictum</i> (<i>Septoglomus constrictum</i>)	Isolated from the Dirab Experimental Station Riyadh region	onion (<i>Allium cepa</i> L. 'White Lisbon')	<i>Tagetes erecta</i> (marigold)	Greenhouse	Growth parameters ↑, Photosynthetic pigments (carotene, chlorophyll a, chlorophyll b) ↑, Total pigments ↑, P content ↑	(Asrar & Elhindi, 2011)
	<i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>)	rhizosphere of green grass growing in soil at King Abdulaziz University in Jeddah	<i>Cynodon dactylon</i>	<i>Zea mays</i> (L.)	Greenhouse	Soluble protein ↑, P uptake ↑, Proline ↓	(Abdelmoneim et al., 2013)
	Not specified	various locations cultivated with rose plants subjected to drought in Taif region,	Sudan grass	<i>Rosa damascena</i> Mill (Damask rose)	Greenhouse	Macronutrients (N, P, K, Ca, Mg) ↑, Total chlorophyll ↑	(Abdel-Salam et al., 2018)
	<i>Glomus intraradices</i> (<i>Rhizophagus intraradices</i>), <i>Glomus etunicatum</i> (<i>Claroideoglomus etunicatum</i>) and <i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>)	KSA	<i>Zea mays</i> L.	<i>Panicum turgidum</i> forssk.	Growth chamber	Root growth ↑, Antioxidant activity ↑, Hydrogen Peroxide (H ₂ O ₂) ↓, Lipid peroxidation rate ↓, Synthesis of Indole Acetic Acid ↑	(Abd Allah et al., 2019)
	<i>Glomus etunicatum</i> (<i>Claroideoglomus etunicatum</i>), <i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>) and <i>Glomus intraradices</i> (<i>Rhizophagus intraradices</i>)	KSA	<i>Zea mays</i> L.	<i>Cicer arietinum</i> L., cv Giza 531 (chickpea)	Greenhouse	Plant growth ↑, Photosynthetic pigments (Chlorophyll a, chlorophyll b, carotenoid, total chlorophylls) ↑, Stomatal pore aperture ↑, Stomatal density ↑, Photosynthetic rate ↑, Relative water content ↑, Membrane stability index (MSI) ↑, Total shoot and root N ↑, Total shoot and root P ↑	(Hashem et al., 2019c)
	<i>Glomus etunicatum</i> (<i>Claroideoglomus etunicatum</i>), <i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>) and <i>Glomus intraradices</i> (<i>Rhizophagus intraradices</i>)	Isolated from the rhizosphere of <i>Acacia gerrardii</i>	<i>Zea mays</i> L.	<i>Ephedra foliata</i> Boiss	Growth chamber	N metabolism ↑, Ammonium availability ↑, Antioxidant enzyme activity ↑, Ascorbic acid ↑, Glutathione level ↓, Reactive oxygen species (ROS) ↓, Proline ↑, glucose ↑, Total soluble protein ↑, Sucrose phosphate synthase activity ↑, Nutrient's uptake (K, Mg, Ca) ↑, Plant hormones (IAA, IBA, GA, ABA) ↑, Alkaline and acid phosphatase enzyme activity ↑	(Al-Arjani et al., 2020)
Salinity	<i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>)	Rhizosphere soil from sand dune community	Sudan grass	<i>Arachis hypogaea</i> (peanut)	Greenhouse	Chlorophyll ↑, Leaf Water ↑	(Al-Khaliel, 2010a)
	<i>G. mosseae</i> , (<i>Funneliformis mosseae</i>) <i>G. deserticola</i> (<i>Septoglomus deserticola</i>) and <i>Gigaspora gergaria</i>	Al-Kassb region 185 km from Riyadh, KSA	Sudan grass (<i>Sorghum halepense</i> L.)	<i>Triticum aestivum</i> L wheat	Greenhouse	Growth responses ↑, Nutrient contents ↑, Acid and alkaline phosphatases ↑, Proline ↑, Total soluble protein ↑, P, N, K, Mg ↑, Na ↓	(Abdel-Fattah & Asrar, 2012)
	<i>Glomus etunicatum</i> (<i>Claroideoglomus etunicatum</i>), <i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>) and <i>Glomus intraradices</i> (<i>Rhizophagus intraradices</i>)	Isolated from under the <i>Zea mays</i> grown in salt march habitat from Alserw, Dakahlia, Egypt. (Origin: KSA, propagated in Egypt)	<i>Zea mays</i>	<i>Ephedra aphylla</i> Forssk	Greenhouse	Proline ↑, Total phenols ↑, Lipid peroxidation (MDA) ↓, Antioxidant enzyme activity ↑, K/Na ↑	(Alqarawi et al., 2014)
	<i>Glomus etunicatum</i> (<i>Claroideoglomus etunicatum</i>), <i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>) and <i>Glomus intraradices</i> (<i>Rhizophagus intraradices</i>)	Origin: KSA, propagated in Egypt	Wheat plants	<i>Vicia Faba</i> L. (Faba Bean)	Greenhouse	Nodule activity ↑, Pigment content ↑, Polyamines ↑, Acid and alkaline phosphate ↑, Enzymatic antioxidants ↑	(Abeer et al., 2014)
	<i>Glomus deserticola</i> (<i>Septoglomus deserticola</i>)	Al-Kassb region 185 km from Riyadh, KSA	Sudan grass (<i>Sorghum halepense</i> L.)	<i>Kalanchoe blossfeldiana</i> (kalanchoe)	Greenhouse	Chlorophyll content ↑, Biomass ↑, Plant height ↑, Leaf area ↑, Flower yield ↑, Salt tolerance index (STI) ↑, Nutrient concentration (P, N, K, Ca, Mg) ↑, Na ↓, Cl ↓	(Asrar et al., 2014)

(continued on next page)

Table 3 (continued)

Stress	AMF species (new name)	Source of inoculum	Trap plant	Experimental plant	Experiment place	Parameters	Reference
	<i>Glomus etunicatum</i> (<i>Claroideoglossum etunicatum</i>), <i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>) and <i>Glomus intraradices</i> (<i>Rhizophagus intraradices</i>)	Origin: KSA, Salt marshland in Egypt Alserw, Dakahlia, Egypt. Origin: KSA, propagated in Egypt	<i>Zea mays</i> L.	<i>Rhizolobos sesban</i> (L.) Murr. Syn. <i>Sesban aegyptiaca</i> Poiret	Growth experiment	Nodulation and legume nodule formation, chlorophyll a, chlorophyll b, carotenoids, total phenolic compounds, total polyphenolic pigments, flavonoid content (FIC), membrane stability index (MSI), malonaldehyde (MDA) ↓, indole acetic acid (IAA) (TWC) ↑, proline content (PC) (PCA) ↑, gibberellic acid (GA) ↑, phytoalexin (PA) ↑, antioxidant enzymes ↑, elements (K, Ca, P) ↑	(Abd Allah et al., 2015e)
	<i>Glomus etunicatum</i> (<i>Claroideoglossum etunicatum</i>), <i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>) and <i>Glomus intraradices</i> (<i>Rhizophagus intraradices</i>)	Origin: KSA, propagated in Egypt	<i>Zea mays</i>	<i>Vigna unguiculata</i> L. (Cowpea)	Greenhouse	Chlorophyll a ↑, chlorophyll b ↑, carotenoid ↑, total pigment content ↑, Membrane stability index (MSI) ↑, Proline ↑, Antioxidant enzyme activities ↑, Mineral ions (K, Mg, P, Ca) ↑, Na accumulation ↓,	(Abeer et al., 2015a)
	<i>Funneliformis mosseae</i> (syn. <i>Glomus mosseae</i>), <i>Rhizophagus intraradices</i> (syn. <i>Glomus intraradices</i>), and <i>Claroideoglossum etunicatum</i> (<i>Glomus etunicatum</i>)	Origin: KSA, propagated in Egypt	<i>Zea mays</i> L.	<i>Panicum turgidum</i> Forssk	Growth chamber	Enzymatic antioxidants ↑, H ₂ O ₂ ↓, Malonaldehyde ↓, Pyruvate orthophosphate dikinase (PPDK) ↓, phosphoenolpyruvate carboxylase (PEPC) ↓, malate dehydrogenase ↓, P ↑, K ↑, Ca ↑	(Hashem et al., 2015)
	<i>Glomus etunicatum</i> (<i>Claroideoglossum etunicatum</i>), <i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>) and <i>Glomus intraradices</i> (<i>Rhizophagus intraradices</i>)	Origin: KSA, propagated in Egypt	<i>Zea mays</i> L.	<i>Solanum lycopersicum</i> L.	Pot experiment	Proline ↑, antioxidants ↑,	(Abeer et al., 2015b)
	<i>Glomus etunicatum</i> (<i>Claroideoglossum etunicatum</i>), <i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>) and <i>Glomus intraradices</i> (<i>Rhizophagus intraradices</i>)	Isolated from the soil surrounding the roots of <i>A.gerrardii</i> .	<i>Sorghum sudanense</i>	<i>Acacia gerrardii</i> (Talh tree)	Greenhouse	Loss of nutritive value ↓, H ₂ O ₂ ↓, Malonaldehyde ↓, Glycine Betaine ↑, Proline ↑, Total Phenol ↑, Antioxidants ↑	(Hashem et al., 2016a)
	<i>Glomus etunicatum</i> (<i>Claroideoglossum etunicatum</i>), <i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>) and <i>Glomus intraradices</i> (<i>Rhizophagus intraradices</i>)	Isolated from the soil surrounding the roots of <i>A.gerrardii</i> .	<i>Sorghum sudanense</i>	<i>Acacia gerrardii</i> (Talh tree)	Growth chamber	N ↑, P ↑, K ↑, Mg ↑, Ca ↑, phosphatase activities ↑, Na ↓, Cl ↓, Shoot growth ↑, Root growth ↑, Nodules ↑, Nodule fresh weight ↑, Leghemoglobin content ↑, Nitrate ↑, Nitrite reductase ↑, Nitrogenase activity ↑, Photosynthetic pigments (chlorophyll a, chlorophyll b, carotenoids, total chlorophyll content) ↑, Nutrient content (Na ⁺ , P, K ⁺ , Mg ²⁺ , Ca ²⁺), Acid and alkaline phosphatases ↑	(Hashem et al., 2016d)
	<i>Glomus etunicatum</i> (<i>Claroideoglossum etunicatum</i>), <i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>) and <i>Glomus intraradices</i> (<i>Rhizophagus intraradices</i>)	Origin: KSA, propagated in Egypt	<i>Zea mays</i> L.	<i>Lupinus termis</i> Forsk (Lupine)	Growth chamber	Antioxidant enzymes ↑, proline ↑, glycine ↑, betaine ↑, sugars ↑, lipid peroxidation ↓, membrane stability ↑	(Hashem et al., 2016d)
	<i>Glomus etunicatum</i> (<i>Claroideoglossum etunicatum</i>), <i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>) and <i>Glomus intraradices</i> (<i>Rhizophagus intraradices</i>)	Origin: KSA, propagated in Egypt	<i>Zea mays</i> L.	<i>Ocimum basilicum</i> L. cv. Cinnamon and thyriflorum (basil)	Greenhouse	Chlorophyll pigments ↑, lipid peroxidation ↓, antioxidant enzymes ↑, lipids ↑, proline ↑, soluble sugars ↑, Na ⁺ accumulation ↓, nutrient acquisition ↑	(Abd Allah and Egamberdieva, 2016)
	<i>Glomus deserticola</i>	Isolated from saline soils of Al-Kassab region	Sudan grass (<i>Sorghum halepense</i> L.)	<i>Ocimum basilicum</i> L.	Greenhouse	Shoot growth ↑, Root growth ↑, K ⁺ ↑, P ↑, Ca ²⁺ ↑, Na ⁺ ↓, Cl ⁻ ↓, K ⁺ / Na ⁺ ↑, Chlorophyll content ↑, Photosynthetic rate ↑, Transpiration rates ↑, Stomatal conductance ↑, Salt tolerance index (STI) ↑	(Elhindi et al., 2017)

(continued on next page)

Table 3 (continued)

Stress	AMF species (new name)	Source of inoculum	Trap plant	Experimental plant	Experiment place	Parameters	Reference
	<i>Glomus etunicatum</i> (<i>Claroideoglomus etunicatum</i>), <i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>) and <i>Glomus intraradices</i> (<i>Rhizophagus intraradices</i>)	Isolated from the rhizosphere of the Talh tree (<i>Acacia gerrardii</i>) grown in a salt marsh habitat in the Riyadh region of Saudi Arabia	<i>Zea mays</i> L.	<i>Cucumis sativus</i> , cv. Dasher II (Cucumber)	Growth chamber	Phenols ↑, Proline ↑, jasmonic acid ↑, salicylic acid ↑, minerals ions ↑ (K, Ca, Mg, Zn, Fe, Mn, Cu), Antioxidant enzymes ↑, Na ⁺ accumulation ↓	(Hashem et al., 2018)
	<i>Glomus etunicatum</i> (<i>Claroideoglomus etunicatum</i>), <i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>) and <i>Glomus intraradices</i> (<i>Rhizophagus intraradices</i>)	Origin: KSA, propagated in Egypt	<i>Zea mays</i> L.	<i>Glycine max</i> Soybean	Greenhouse	Nodule formation ↑, leghemoglobin content ↑, nitrogenase activity ↑, auxin synthesis ↑, lipid peroxidation ↓, thiobarbituric acid reactive substances (TBARS) ↓	(Hashem et al., 2019b)
	<i>Glomus constrictum</i> (<i>Septoglomus constrictum</i>)	Isolated from saline site of Shaqra region	Not mentioned	<i>Capsicum annuum</i> L. (pepper)	Controlled conditions	Growth parameters ↑, Photosynthetic pigments ↑, Nutrient content ↑, Na ⁺ ↓, Gas exchange rate ↑, Antioxidant enzymes ↑	(Al-Amri, 2019)
Cadmium	<i>Glomus etunicatum</i> (<i>Claroideoglomus etunicatum</i>), <i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>) and <i>Glomus intraradices</i> (<i>Rhizophagus intraradices</i>)	Origin: KSA, propagated in Egypt	<i>Zea mays</i> L.	<i>Helianthus annuus</i> L. (sunflower)	Pot experiments	Growth ↑, Chlorophyll ↑, Cell membrane stability ↑, Enzymatic antioxidants ↑, Acid and alkaline phosphatases ↑	(Abd Allah et al., 2015b)
	<i>Glomus etunicatum</i> (<i>Claroideoglomus etunicatum</i>), <i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>) and <i>Glomus intraradices</i> (<i>Rhizophagus intraradices</i>)	Origin: KSA, propagated in Egypt	<i>Zea mays</i> L.	<i>Solanum lycopersicum</i>	Growth chamber	Malonaldehyde ↓, H ₂ O ₂ ↓, Antioxidant enzymes ↑, proline ↑, phenol ↑	(Hashem et al., 2016b)
	<i>Glomus etunicatum</i> (<i>Claroideoglomus etunicatum</i>), <i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>) and <i>Glomus intraradices</i> (<i>Rhizophagus intraradices</i>)	Origin: KSA, propagated in Egypt	<i>Zea mays</i> L.	<i>Cassia italica</i> Mill	Growth chamber	Chlorophyll pigment ↑, protein content ↑, lipid peroxidation ↓, proline ↑, phenol ↑, antioxidant enzymes ↑, osmolytes accumulation ↑	(Hashem et al., 2016c)
	<i>Glomus etunicatum</i> (<i>Claroideoglomus etunicatum</i>), <i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>) and <i>Glomus intraradices</i> (<i>Rhizophagus intraradices</i>)	Origin: KSA, propagated in Egypt	<i>Zea mays</i> L.	<i>Bassia indica</i> (Indian bassia)	Growth chambers	Lipid peroxidation ↓, H ₂ O ₂ ↓, non-enzymatic antioxidants [(ascorbate, reduced glutathione (GSH), oxidized glutathione (GSSG), S-nitroso glutathione (GSNO)] ↑, proline ↑	(Hashem et al., 2019a)
Heavy metal	<i>Glomus constrictum</i> (<i>Septoglomus constrictum</i>)	Experimental Agricultural Research Station at Dirab	Sudan grass (<i>Sorghum halepense</i> L.)	<i>Tagetes erecta</i> L. (marigold)	Greenhouse	Yield ↑, Chlorophyll content ↑, Leaf area ↑, Flower quality ↑, Element content (P, N, K, Mg) ↑, Heavy metals (Zn, Co, Mn, Cu) ↓	(Elhindi et al., 2018b)
Fusarium wilt stress	<i>Glomus etunicatum</i> (<i>Claroideoglomus etunicatum</i>), <i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>) and <i>Glomus intraradices</i> (<i>Rhizophagus intraradices</i>)	Talh trees (<i>Acacia gerrardii</i>) roots in Khuraim Meadow	<i>Sorghum sudanense</i>	<i>Solanum lycopersicum</i> L. (Tomato)	Greenhouse	Fusaric acid ↑, Chlorophyll content ↑, Phosphate metabolizing enzymes activity ↑, Antioxidant enzymes ↑, Reactive oxygen species ↓	(Hashem et al., 2021)
No stress	<i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>) and <i>Glomus fasciculatum</i> (<i>Rhizophagus fasciculatus</i>)	Sand dune community near Riyadh	Sudangrass	peanut	Greenhouse	Improve growth and production	(Al-Khaliel, 2010b)
	<i>Glomus constrictum</i> (<i>Septoglomus constrictum</i>)	Stock mycorrhizal cultures	<i>Allium cepa</i> L. (onion)	<i>Glycine max</i> L. (Soybean)	Greenhouse	Plant growth ↑, P ↑, N ↑, Acid and alkaline phosphatase activities ↑, Total soluble proteins ↑, Photosynthetic rate ↑, Stomatal conductance ↑, Transpiration rate ↑	(Abdel-Fattah et al., 2014)
	<i>Glomus mosseae</i> (<i>Funneliformis mosseae</i>)	–	Sudan grass (<i>Sorghum halepense</i> L.)	<i>Coriander sativum</i> L. (Coriander)	Greenhouse	Plant growth ↑, Nutrients (P, N) ↑, Acid and alkaline phosphatase ↑, Total soluble proteins ↑, Fruit yield ↑, Essential oil production ↑,	(Al-Amri et al., 2016)

(continued on next page)

Table 3 (continued)

Stress	AMF species (new name)	Source of inoculum	Trap plant	Experimental plant	Experiment place	Parameters	Reference
	<i>Glomus intraradices</i> (<i>Rhizophagus intraradices</i>), <i>Glomus etunicatum</i> (<i>Claroideoglomus etunicatum</i>), <i>Glomus deserticola</i> (<i>Septoglomus deserticola</i>)	Isolated from saline sites in the Algassab region	<i>Sorghum vulgare</i> var. <i>sudanese</i>	<i>Poa pratensis</i> L. and <i>Festuca arundinacea</i>	Greenhouse	Lialool↑, Net photosynthetic rate ↑, Stomata conductance ↑, Transpiration rate ↑, Biomass ↑, P ↑, Plant productivity ↑	(Elhindi et al., 2018a)
	<i>Funnelformis coronatum</i> , <i>Claroideoglomus etunicatum</i> , <i>Gigaspora albida</i> , <i>Glomus ambisporum</i> , <i>Funnelformis geosporus</i> , <i>Gigaspora gigantea</i> , <i>Gigaspora margarita</i> , <i>Septoglomus constrictum</i> , <i>Rhizophagus fasciculatus</i> , and <i>Rhizophagus intraradices</i>	Al-Baha region	–	<i>Senna alexandrina</i> and <i>Senna italica</i>	Growth chamber	Sennoside A ↑, Sennoside B ↑, Antibacterial action ↑	(AlZain et al., 2020)

temperature, soil respiration is expected to increase, thereby releasing excess of CO₂ in the atmosphere. Hence, atmosphere being a CO₂ sink will then be converted into CO₂ source by the end of 2050 (Cox et al., 2000).

Artificial warming using infrared radiation was used to evaluate the effect of temperature change on AMF. It was reported that AMF in association with annual grassland showed a change in its activity after crossing one growing season without showing any changes in the root parameters. As per the study, the AMF root colonization increased by 40 % with warmth, however, the hyphal AMF glycoprotein involved in aggregating the soil decreased, thereby decreasing the water holding capacity. Moreover, the increased temperature led to an increase in loss of C from soil, hence, making it prone to erosion (Rillig et al., 2002). Another study reported a low diversity of AMF in soils that are exposed to abiotic stresses like extreme temperatures, drought and alike. These abiotic stresses mainly affect the root colonization process, spore germination and sporulation, and/or hyphae health (Pascual et al., 2022).

Generally, higher temperature enhances the colonization of plant roots with AMF, but the structure alters with temperature. Low soil temperature enhances the vesicles formation in AMF which enhances the storage of nutrients while high soil temperature improves the hyphal growth by developing complex extraradical hyphal networks (Chourasiya et al., 2021).

5.2. Extreme precipitation and precipitation shift

Soil water content and its availability are important factors for the growth of AMF. The water availability directly influences the microbiota in soil. Generally, the relationship between extreme precipitation and its impact on the functioning of soil communities is not understood and studied deeply. Moreover, almost all the available data is extracted and based on lab scale experimental studies. Drought conditions drastically decline the functioning of soil microbiota. Some of the major symbiotic associations are dependent on the presence of water within the soil such as the symbiotic association of AMF with almost 80 % of plants on land. Soils with mycorrhizal associations develop water stable aggregates more than non-mycorrhizal soils, however this concept is not highly studied for water relation among both the groups. Extremely low levels of precipitation result in drought which severely affects not only the AMF community composition but also the species richness. It is important to mention here that this effect could either be direct or indirect

through loss of soil water content, richness of plant species and the overall productivity above the ground (Fu et al., 2022).

Antunes and team (2011) speculated that growing season, drought periods, and other climate related factors play a much more significant role in the symbiotic associations and functioning of AMF (Antunes et al., 2011). In another study, the relationship between AMF and diazotrophs were studied with respect to temperature and precipitation. It was found that the AMF diversity and richness both increased in response to an increasing temperature (≥ 20 °C) and precipitation. Moreover, the relative abundances of *Gigaspora*, *Glomus*, and *Septoglomus* increase with an increased temperature (> 18 °C). The researchers concluded that AMF are more prone to climatic changes as compared to diazotrophs (Xiao et al., 2021).

5.3. Elevation of atmospheric carbon dioxide (CO₂)

It is worthy to mention about the elevated CO₂ in relation to changing climate and global warming. With the global climatic changes, the atmospheric CO₂ is also increasing constantly (IPCC, 2007) and the current CO₂ levels is reported to be 418.39 parts per million (ppm) (Ahmed & Li, 2022). AMF fixes the C from the atmospheric CO₂ which is then transported and redistributed from rhizosphere through the mycorrhizal hyphae (Kakouridis et al., 2022; Vicca et al., 2009). AMF, being an obligate symbiont provide C from the fixed CO₂ to the plants and in return, take nutrients for their growth. Hence, with elevated CO₂, AMF will enhance C allocation, enhance plant-fungal relationship.

The increased C allocation around the roots impacts the composition of the exudates excreted by the roots that alters the chemo attractants and other signaling compounds. Similarly, any change in C allocation eventually impacts the nutrient concentrations mainly C/N ratio (Compant et al., 2010).

Research on the increased CO₂ and its effect were studied on the internal and external hyphae. It is reported that when CO₂ concentration is higher, more C is allocated in the root region, therefore, with higher CO₂, AMF external hyphae grew efficiently in the rhizosphere of host plant: *Prunella vulgaris*. The study concluded that this is because of the excessive C allocation in the external hyphae. Moreover, the internal hyphae also received more C which enhanced its growth (Sanders et al., 1998). In most of the cases of elevated CO₂, it is reported that it enhances the plant photosynthetic rates which in turn increases the photosynthates produced and transferred to the roots where the AMF are

supported through the availability of photosynthates. Overall, this allows the symbiotic relationship between AMF and plants to grow strong, hence, resulting in healthier plants in terms of root, stem, and leaf biomass (Goicoechea et al., 2014; Saleh et al., 2020; Zhu et al., 2016).

Based on the studied literature, it is significant to mention here that most of the research (92 %) that focuses on the reaction of AMF to climatic changes are based in Northern hemisphere, therefore, a strong conclusion cannot be made until and unless the other locations are studied (Bennett & Classen, 2020). In other words, even though it can be stated that elevated CO₂ concentration generally enhances the AMF activities, the same cannot be considered in terms of geographical distribution and variation. Similarly, there are a lot of studies available where the impact of increased CO₂ levels has been studied, however, all of them could not reach a similar conclusion with the affect stated as negative, positive, or insignificant (Cotton et al., 2015; Fu et al., 2022; Hu et al., 2022; Tang et al., 2006).

Based on the above-mentioned knowledge, it is true that climate change has an impact on the AMF species richness and abundance, but a strict conclusion could not be made about how positive or negative the effects are. Studying the climate change parameters individually might give the hypothesis a certain direction of having a positive, negative or a neutral effect, but it cannot be the same when studied with other biotic or abiotic factors and/or experimental variables. This knowledge gap is a hindrance towards the prediction of effects of climatic changes on the AMF community and its ecological impact.

6. Conclusion

This review article is an up-to-date view of the occurrence, distribution, and diversity of AMF species in the Arabian Peninsula. The review includes different studies where AMF species are used against plant stressors. Further, the review also highlights the plant-mycorrhizal relationships and how they play a role in minimization of plant pathogens. The review also highlights the climatic changes and how they could impact the growth of AMF and its related plant associations. Lastly, the review also discusses the challenges faced in developing and commercializing AMF products.

The major findings of the review article demonstrates that the distribution and diversity of fungi have been studied in most of the Arabian Peninsula except for Bahrain. However, most of the studies regarding AMF are concentrated in KSA and Oman whereas studies in Kuwait, UAE, and Yemen are less. In Qatar, on the other hand, advanced sequencing techniques are used to study AMF diversity and associated chemical drivers. In the Arabian Peninsula, *Rhizophagus* is the most common genus followed by *Acaulospora*. The predominance of *Acaulospora* species in most ecosystems of KSA, Oman, and Qatar suggests that this genus is adapted to the diverse and harsh environmental conditions that includes but are not limited to drought and salinity.

Among *Rhizophagus* species, we found that *Rhizophagus intraradices* was the dominant species in most of the studies. This indicates the significant role the genus might have in adaptation to the arid ecosystems. Future studies should explore such dynamics not only to identify the AMF of interest but also to explore the conditions under which host specificity could be predicted. The studies could include correlation between the structure and function of AMF. Future studies should identify the density-dependent and density-independent factors that influence the distribution and diversity of AMF in the Arabian Peninsula. Such measures could help to identify the changes in the environmental sustainability by considering the biodiversity of AMF species as markers of environmental degradation. Another recommendation for future studies is to carry out in-depth research that includes not only the parameters associated with climate change but also the biotic and abiotic factors. This could produce valuable data for predicting the influence of climatic changes on AMF community. Lastly, this study could be used for commercial and scientific purposes with respect to crop production and sustainability of the desert ecosystem.

Funding

This work was supported by Qatar University-QAFCO (Qatar Fertilizer Company) Grants, Grant No. QUEX-CAS-QAFCO-20/21-1.

CRediT authorship contribution statement

Khazna Alrajhi: Conceptualization, Validation, Formal analysis, Writing – original draft, Visualization. **Shazia Bibi:** Formal analysis, Writing – original draft, Visualization. **Mohammed Abu-Dieyeh:** Conceptualization, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- Abd Allah, E., Abeer, H., Alqarawi, A., Hnd, A., 2015b. Alleviation of adverse impact of cadmium stress in sunflower (*Helianthus annuus* L.) by arbuscular mycorrhizal fungi'. *Pak. J. Bot.* 47 (2), 785–795.
- Abd Allah, E., Egamberdieva, D., 2016. Arbuscular mycorrhizal fungi enhance basil tolerance to salt stress through improved physiological and nutritional status. *Pak. J. Bot.* 48 (1), 37–45.
- Abd Allah, E.F., Hashem, A., Alqarawi, A.A., Bahkali, A.H., Alwhibi, M.S., 2015a. Enhancing growth performance and systemic acquired resistance of medicinal plant *Sesbania sesban* (L.) Merr using arbuscular mycorrhizal fungi under salt stress. *Saudi J Biol Sci* 22 (3), 274–283. <https://doi.org/10.1016/j.sjbs.2015.03.004>.
- Abd Allah, E.F., Abeer, H., Alqarawi, A., Alwhibi, M., 2015c. Alleviation of adverse impact of salt in *Phaseolus vulgaris* L. by arbuscular mycorrhizal fungi. *Pak. J. Bot.* 47 (3), 1167–1176.
- Abd Allah, E.F., Tabassum, B., Alqarawi, A.A., Alshahrani, T.S., Malik, J.A., Hashem, A., 2019. Physiological markers mitigate drought stress in *Panicum turgidum* Forssk. By arbuscular mycorrhizal fungi. *Pak. J. Bot.* 51 (6), 2003–2011.
- Abdel-Fattah, G.M., Asrar, A.-W.-A., 2012. Arbuscular mycorrhizal fungal application to improve growth and tolerance of wheat (*Triticum aestivum* L.) plants grown in saline soil. *Acta Physiol. Plant.* 34 (1), 267–277.
- Abdel-Fattah, G., Asrar, A., Al-Amri, S., Abdel-Salam, E., 2014. Influence of arbuscular mycorrhiza and phosphorus fertilization on the gas exchange, growth and phosphatase activity of soybean (*Glycine max* L.) plants. *Photosynthetica* 52 (4), 581–588.
- Abdelmoneim, M.T., Almaghrabi, O.A., 2014. Survey of Indigenous Arbuscular Mycorrhizal Fungi under Ecosystem of Saudi Arabia. *Journal of Pure and Applied Microbiology* 8, 4525–4532.
- Abdelmoneim, Moussa, T., O.A. A., Alzahrani, H., & Abdelbagi, I. (2013). Increasing Plant Tolerance to Drought Stress by Inoculation with Arbuscular Mycorrhizal Fungi. *Life Science Journal*, 10, 3273–3280.
- Abdel-Salam, E., Alatar, A., El-Sheikh, M.A., 2018. Inoculation with arbuscular mycorrhizal fungi alleviates harmful effects of drought stress on damask rose. *Saudi Journal of Biological Sciences* 25 (8), 1772–1780. <https://doi.org/10.1016/j.sjbs.2017.10.015>.
- Abeer, H., Abd Allah, E., Alqarawi, A., El-Didamony, G., Alwhibi, M., Egamberdieva, D., Ahmad, P., 2014. Alleviation of adverse impact of salinity on faba bean (*Vicia faba* L.) by arbuscular mycorrhizal fungi. *Pak. J. Bot.* 46 (6), 2003–2013.
- Abeer, H., Abd Allah, E., Alqarawi, A., Egamberdieva, D., 2015a. Induction of salt stress tolerance in cowpea [*Vigna unguiculata* (L.) Walp.] by arbuscular mycorrhizal fungi. *Legume Research-An. Int. J.* 38 (5), 579–588.
- Abeer, H., Alqarawi, A., Egamberdieva, D., 2015b. Arbuscular mycorrhizal fungi mitigates NaCl induced adverse effects on *Solanum lycopersicum* L. *Pak. J. Bot.* 47 (1), 327–340.
- Abeer, H., Alqarawi, A.A., Al-Huqail, A.A., Abd Allah, E.F., 2018. Biodiversity of arbuscular mycorrhizal fungi associated with *Acacia gerrardii* Benth in different habitats of Saudi Arabia. *Pak. J. Bot.* 50 (3), 1211–1217.
- Addisu, E. (2022). Arbuscular Mycorrhizal Fungi (AMF) in Optimizing Nutrient Bioavailability and Reducing Agrochemicals for Maintaining Sustainable Agroecosystems. In S. Rodrigo Nogueira de (Ed.), *Arbuscular Mycorrhizal Fungi in Agriculture* (pp. Ch. 9). IntechOpen. <https://doi.org/10.5772/intechopen.106995>.
- Adenan, S., Oja, J., Alatalo, J.M., Shraim, A.M., Alsafran, M., Tedersoo, L., Zobel, M., Ahmed, T., 2021. Diversity of arbuscular mycorrhizal fungi and its chemical drivers across dryland habitats. *Mycorrhiza* 31 (6), 685–697. <https://doi.org/10.1007/s00572-021-01052-3>.
- Ahamed, G.J., Li, X., 2022. Elevated carbon dioxide-induced regulation of ethylene in plants. *Environ. Exp. Bot.* 202, 105025 <https://doi.org/10.1016/j.envexpbot.2022.105025>.
- Ahmad, P., Abdel Latef, A.A., Hashem, A., Abd Allah, E.F., Gucel, S., Tran, L.-S.-P., 2016. Nitric oxide mitigates salt stress by regulating levels of osmolytes and antioxidant enzymes in chickpea. *Front. Plant Sci.* 7, 347.

- Al-Amri, S., 2019. Mitigation of salinity stress of pepper (*Capsicum annuum* L.) by arbuscular mycorrhizal fungus, *glomus constrictum*. *Appl. Ecol. Environ. Res.* 17 (4), 9965–9978.
- Al-Amri, S.M., Elhindi, K.M., El-Din, A.F.S., 2016. Effects of arbuscular mycorrhizal fungus *Glomus mosseae* and phosphorus application on plant growth rate, essential oil content and composition of coriander (*Coriander sativum* L.). *Prog. Nutr.* 18 (4), 443–454.
- Al-Arequi, A., Chliyyeh, M., Sghir, F., Touhami, A., Benkirane, R., Douira, A., 2013. Diversity of arbuscular mycorrhizal fungi in the rhizosphere of *Coffea arabica* in the Republic of Yemen. *Journal of Applied Biosciences* 64, 4888. <https://doi.org/10.4314/jab.v64i1.88478>.
- Al-Arjani, A.-B.-F., Hashem, A., Abd Allah, E.F., 2020. Arbuscular mycorrhizal fungi modulates dynamics tolerance expression to mitigate drought stress in *Ephedra foliata* Boiss. *Saudi Journal of Biological Sciences* 27 (1), 380–394. <https://doi.org/10.1016/j.sjbs.2019.10.008>.
- Albaqami, F., Sohaibani, S., Kasi, M., 2018. Arbuscular Mycorrhizal Fungi Diversity in Two Different Regions in Saudi Arabia. *Int. J. Curr. Microbiol. App. Sci.* 7, 2492–2510. <https://doi.org/10.20546/ijcmas.2018.704.286>.
- Al-Karaki, G., 2013. Application of mycorrhizae in sustainable date palm cultivation. *Emirates Journal of Food and Agriculture* 25. <https://doi.org/10.9755/ejfa.v25i11.16499>.
- Al-Karaki, G., Othman, Y., 2007. Effects of mycorrhizal fungi inoculation on landscape turf establishment under Arabian Gulf region conditions. *Arab Gulf J. Sci. Res.* 25, 147–152.
- Al-Khalief, A.S., 2010a. Effect of salinity stress on mycorrhizal association and growth response of peanut infected by *Glomus mosseae*. *Plant Soil Environ.* 56, 318–324. <https://doi.org/10.17221/204/2009-PSE>.
- Al-Khalief, A.S., 2010b. Effects of arbuscular mycorrhization in sterile and non-sterile soils. *Trop. Life Sci. Res.* 21 (1), 55.
- Allen, 2007. Mycorrhizal Fungi: Highways for Water and Nutrients in Arid Soils. *Vadose Zone J.* 6, 291–297. <https://doi.org/10.2136/vzj2006.0068>.
- Allen, 2011. Linking water and nutrients through the vadose zone: A fungal interface between the soil and plant systems. *J. Arid. Land* 3. <https://doi.org/10.3724/SP.J.1227.2011.00155>.
- Alqarawi, A.A., Abd Allah, E., Hashem, A., 2014. Alleviation of salt-induced adverse impact via mycorrhizal fungi in *Ephedra aphylla* Forssk. *J. Plant Interact.* 9 (1), 802–810.
- Al-Qarawi, M.A.U., Alghamdi, O.M., 2012. Diversity of Structural Colonization and Spore Population of Arbuscular Mycorrhizal Fungi in Some Plants from Riyadh, Saudi Arabia. *Journal of Pure and Applied Microbiology* 6, 1119–1125.
- Al-Qarawi, M.A.U., Dhar, P., 2013. Report of Funneliformis *mosseae* (Nicol. & Gerd.) Gerd. and Trappe from Rangeland Soil of Saudi Arabia. *Research Journal of Biotechnology* 8, 96–99.
- Alrajhi, K., Saleh, I., Abu-Dieyeh, M.H., 2022. Biodiversity of arbuscular mycorrhizal fungi in plant roots and rhizosphere soil from different arid land environment of Qatar. *Plant Direct* 6 (1), e369.
- Al-whaibi, M., 2009. Desert Plants and Mycorrhizae (A mini-review). *Journal of Pure and Applied Microbiology* 3, 457–466.
- Al-Yahya'ei, M.N., Mullath, S.K., Aldhaheri, L.A., Kozłowska, A., Blaszkowski, J., 2017. *Dominikia emiratia* and *Rhizoglossum densum*, two new species in the Glomeromycota. *Botany* 95 (7), 629–639.
- Al-Yahya'ei, M.N., Oehl, F., Vallino, M., Lumini, E., Redecker, D., Wiemken, A., Bonfante, P., 2011. Unique arbuscular mycorrhizal fungal communities uncovered in date palm plantations and surrounding desert habitats of Southern Arabia. *Mycorrhiza* 21 (3), 195–209. <https://doi.org/10.1007/s00572-010-0323-5>.
- AlZain, M.N., AlAtar, A.A., Alqarawi, A.A., Mothana, R.A., Noman, O.M., Herqash, R.N., AlSheddi, E.S., Farshori, N.N., Alam, P., 2020. The Influence of Mycorrhizal Fungi on the Accumulation of Senosides A and B in *Senna alexandrina* and *Senna italica*. *Separations* 7 (4), 65.
- Antunes, P.M., Koch, A.M., Morton, J.B., Rillig, M.C., Klironomos, J.N., 2011. Evidence for functional divergence in arbuscular mycorrhizal fungi from contrasting climatic origins. *New Phytol* 189 (2), 507–514. <https://doi.org/10.1111/j.1469-8137.2010.03480.x>.
- Apple, M.E., 2010. Aspects of Mycorrhizae in Desert Plants. In: Ramawat, K.G. (Ed.), *Desert Plants: Biology and Biotechnology*. Springer, Berlin Heidelberg, pp. 121–134. https://doi.org/10.1007/978-3-642-02550-1_6.
- Asrar, A., Abdel-Fattah, G.M., Elhindi, K.M., Abdel-Salam, E.M., 2014. The impact of arbuscular mycorrhizal fungi in improving growth, flower yield and tolerance of *Kalanchoe* (*Kalanchoe blossfeldiana* Poelin) plants grown in NaCl-stress conditions. *J. Food Agric. Environ.* 12 (1), 105–112.
- Asrar, A.-W.-A., Elhindi, K.M., 2011. Alleviation of drought stress of marigold (*Tagetes erecta*) plants by using arbuscular mycorrhizal fungi. *Saudi Journal of Biological Sciences* 18 (1), 93–98. <https://doi.org/10.1016/j.sjbs.2010.06.007>.
- Augusto, T., 2015. Handbook of Arbuscular Mycorrhizal Fungi. <https://doi.org/10.1007/978-3-319-24850-9>.
- Balestrini, R., Brunetti, C., Cammareri, M., Caretto, S., Cavallaro, V., Cominelli, E., De Palma, M., Docimo, T., Giovanazzo, G., Grandillo, S., 2021. Strategies to modulate specialized metabolism in Mediterranean crops: From molecular aspects to field. *Int. J. Mol. Sci.* 22 (6), 2887.
- Bashan, Y., Davis, E.A., Carrillo-Garcia, A., Linderman, R.G., 2000. Assessment of VA mycorrhizal inoculum potential in relation to the establishment of cactus seedlings under mesquite nurse-trees in the Sonoran Desert. *Appl. Soil Ecol.* 14 (2), 165–175. [https://doi.org/10.1016/S0929-1393\(00\)00050-0](https://doi.org/10.1016/S0929-1393(00)00050-0).
- Basiru, S., Hijri, M., 2022. The Potential Applications of Commercial Arbuscular Mycorrhizal Fungal Inoculants and Their Ecological Consequences. *Microorganisms* 10 (10), 1897.
- Basiru, S., Mwanza, H.P., Hijri, M., 2020. Analysis of Arbuscular Mycorrhizal Fungal Inoculant Benchmarks. *Microorganisms* 9 (1). <https://doi.org/10.3390/microorganisms9010081>.
- Begum, N., Qin, C., Ahanger, M.A., Raza, S., Khan, M.I., Ashraf, M., Ahmed, N., Zhang, L., 2019. Role of Arbuscular Mycorrhizal Fungi in Plant Growth Regulation: Implications in Abiotic Stress Tolerance [Review]. *Front. Plant Sci.* 10 <https://doi.org/10.3389/fpls.2019.01068>.
- Bennett, A.E., Classen, A.T., 2020. Climate change influences mycorrhizal fungal-plant interactions, but conclusions are limited by geographical study bias. *Ecology* 101 (4), e02978.
- Berruti, A., Lumini, E., Balestrini, R., Bianciotto, V., 2016. Arbuscular Mycorrhizal Fungi as Natural Biofertilizers: Let's Benefit from Past Successes. *Front. Microbiol.* 6, 1559. <https://doi.org/10.3389/fmicb.2015.01559>.
- Bever, J.D., Richardson, S.C., Lawrence, B.M., Holmes, J., Watson, M., 2009. Preferential allocation to beneficial symbiont with spatial structure maintains mycorrhizal mutualism. *Ecol Lett* 12 (1), 13–21. <https://doi.org/10.1111/j.1461-0248.2008.01254.x>.
- Blackwell, M., 2011. The fungi: 1, 2, 3 5.1 million species? *Am J Bot* 98 (3), 426–438. <https://doi.org/10.3732/ajb.1000298>.
- Blaszkowski, J., Tadych, M., Tadeusz, M., 2002. Arbuscular mycorrhizal fungi (Glomales, Zygomycota) of the Bledowska Desert, Poland. *Acta Societatis Botanicorum Poloniae* 71, 71–85. <https://doi.org/10.5586/asbp.2002.008>.
- Bonfante, P., Genre, A., 2010. Mechanisms underlying beneficial plant–fungus interactions in mycorrhizal symbiosis. *Nat. Commun.* 1 (1), 1–11.
- Brito, I., Goss, M.J., de Carvalho, M., Chatagnier, O., van Tuinen, D., 2012. Impact of tillage system on arbuscular mycorrhiza fungal communities in the soil under Mediterranean conditions. *Soil Tillage Res.* 121, 63–67. <https://doi.org/10.1016/j.still.2012.01.012>.
- Brown, S., Jumpponen, A., 2013. Contrasting primary successional trajectories of fungi and bacteria in retreating glacier soils. *Mol. Ecol.* 23 <https://doi.org/10.1111/mec.12487>.
- Brundrett, M.C., 2009. Mycorrhizal associations and other means of nutrition of vascular plants: understanding the global diversity of host plants by resolving conflicting information and developing reliable means of diagnosis. *Plant and Soil* 320 (1), 37–77.
- Campanelli, A., Ruta, C., De Mastro, G., Morone-Fortunato, I., 2013. The role of arbuscular mycorrhizal fungi in alleviating salt stress in *Medicago sativa* L. var. icon. *Symbiosis* 59 (2), 65–76.
- Chen, M., Arato, M., Borghi, L., Nouri, E., Reinhardt, D., 2018. Beneficial Services of Arbuscular Mycorrhizal Fungi - From Ecology to Application. *Front Plant Sci* 9, 1270. <https://doi.org/10.3389/fpls.2018.01270>.
- Chourasiya, D., Gupta, M.M., Sahni, S., Oehl, F., Agnihotri, R., Buade, R., Maheshwari, H. S., Prakash, A., Sharma, M.P., 2021. Unraveling the AM fungal community for understanding its ecosystem resilience to changed climate in agroecosystems. *Symbiosis* 84 (3), 295–310. <https://doi.org/10.1007/s13199-021-00761-9>.
- Ciancio, A., Pieterse, C.M., Mercado-Blanco, J., 2019. Harnessing useful rhizosphere microorganisms for pathogen and pest biocontrol. *Front. Microbiol.* 10, 1935.
- Compant, S., Clément, C., Sessitsch, A., 2010. Plant growth-promoting bacteria in the rhizo- and endosphere of plants: their role, colonization, mechanisms involved and prospects for utilization. *Soil Biol. Biochem.* 42 (5), 669–678.
- Cotton, T.A., Fitter, A.H., Miller, R.M., Dumbrell, A.J., Helgason, T., 2015. Fungi in the future: interannual variation and effects of atmospheric change on arbuscular mycorrhizal fungal communities. *New Phytol.* 205 (4), 1598–1607.
- Cox, P.M., Betts, R.A., Jones, C.D., Spall, S.A., Totterdell, I.J., 2000. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature* 408 (6809), 184–187. <https://doi.org/10.1038/35041539>.
- Cromack, K. (1992). The role of fungi in litter decomposition and nutrient cycling. In: AGRIS.
- Duell, E.B., Cobb, A.B., Wilson, G.W., 2022. Effects of Commercial Arbuscular Mycorrhizal Inoculants on Plant Productivity and Intra-Radical Colonization in Native Grassland: Unintentional De-Coupling of a Symbiosis? *Plants* 11 (17), 2276.
- EF, A. A., Abeer, H., & AA, A. (2015). Alleviation of adverse impact of cadmium stress in sunflower (*Helianthus annuus* L.) by arbuscular mycorrhizal fungi'. *Pak. J. Bot.* 47 (2), 785–795.
- Elhindi, K.M., Al-Mana, F.A., El-Hendawy, S., Al-Selwey, W.A., Elgorban, A.M., 2018b. Arbuscular mycorrhizal fungi mitigates heavy metal toxicity adverse effects in sewage water contaminated soil on *Tagetes erecta* L. *Soil Sci. Plant Nutr.* 64 (5), 662–668.
- Elhindi, K., Al-Suhaibani, N., El-Hendawy, S., Al-Mana, F., 2018a. Effects of arbuscular mycorrhizal fungi on the growth of two turfgrasses grown under greenhouse conditions. *Soil Sci. Plant Nutr.* 64 (2), 238–243.
- Elhindi, K.M., El-Din, A.S., Elgorban, A.M., 2017. The impact of arbuscular mycorrhizal fungi in mitigating salt-induced adverse effects in sweet basil (*Ocimum basilicum* L.). *Saudi Journal of Biological Sciences* 24 (1), 170–179.
- Elmakkī, K., Barakah, F., Assaeed, A., 2017. Structural colonization of Arbuscular mycorrhizal fungi in three acacia species of different sizes in Riyadh, Saudi Arabia. *International Journal of Biosciences* 10, 308–318.
- Enebe, M.C., Erasmus, M., 2023. Susceptibility and plant immune control—a case of mycorrhizal strategy for plant colonization, symbiosis, and plant immune suppression [Review]. *Front. Microbiol.* 14 <https://doi.org/10.3389/fmicb.2023.1178258>.
- Fu, W., Chen, B., Rillig, M.C., Jansa, J., Ma, W., Xu, C., Luo, W., Wu, H., Hao, Z., Wu, H., Zhao, A., Yu, Q., Han, X., 2022. Community response of arbuscular mycorrhizal fungi to extreme drought in a cold-temperate grassland. *New Phytol.* 234 (6), 2003–2017. <https://doi.org/10.1111/nph.17692>.
- Ghazanfar, S.A., Fisher, M., 1998. *Vegetation of the Arabian Peninsula*. Springer.

- Goicoechea, N., Baslam, M., Erice, G., Irigoyen, J.J., 2014. Increased photosynthetic acclimation in alfalfa associated with arbuscular mycorrhizal fungi (AMF) and cultivated in greenhouse under elevated CO₂. *J. Plant Physiol.* 171 (18), 1774–1781.
- Gollotte, A., Van Tuinen, D., Atkinson, D., 2004. Diversity of arbuscular mycorrhizal fungi colonising roots of the grass species *Agrostis capillaris* and *Lolium perenne* in a field experiment. *Mycorrhiza* 14 (2), 111–117. <https://doi.org/10.1007/s00572-003-0244-7>.
- Haldar, S., Sengupta, S., 2015. Plant-microbe Cross-talk in the Rhizosphere: Insight and Biotechnological Potential. *Open Microbiol J* 9, 1–7. <https://doi.org/10.2174/1874285801509010001>.
- Hashem, A., Abd Allah, E.F., Alqarawi, A.A., Aldubise, A., Egamberdieva, D., 2015. Arbuscular mycorrhizal fungi enhances salinity tolerance of *Panicum turgidum* Forsk by altering photosynthetic and antioxidant pathways. *J. Plant Interact.* 10 (1), 230–242.
- Hashem, A., Abd Allah, E., Alqarawi, A., Al Huqail, A.A., Egamberdieva, D., Wirth, S., 2016b. Alleviation of cadmium stress in *Solanum lycopersicum* L. by arbuscular mycorrhizal fungi via induction of acquired systemic tolerance. *Saudi Journal of Biological Sciences* 23 (2), 272–281.
- Hashem, A., Abd Allah, E., Alqarawi, A., Egamberdieva, D., 2016c. Bioremediation of adverse impact of cadmium toxicity on *Cassia italica* Mill by arbuscular mycorrhizal fungi. *Saudi Journal of Biological Sciences* 23 (1), 39–47.
- Hashem, A., Abd Allah, E.F., Alqarawi, A.A., Al-Huqail, A.A., Wirth, S., Egamberdieva, D., 2016d. The interaction between arbuscular mycorrhizal fungi and endophytic bacteria enhances plant growth of *Acacia gerrardii* under salt stress. *Front. Microbiol.* 7, 1089.
- Hashem, A., Alqarawi, A.A., Radhakrishnan, R., Al-Arjani, A.-B.-F., Aldehais, H.A., Egamberdieva, D., Abd Allah, E.F., 2018. Arbuscular mycorrhizal fungi regulate the oxidative system, hormones and ionic equilibrium to trigger salt stress tolerance in *Cucumis sativus* L. *Saudi Journal of Biological Sciences* 25 (6), 1102–1114. <https://doi.org/10.1016/j.sjbs.2018.03.009>.
- Hashem, A., Abd Allah, E.F., Alqarawi, A.A., Malik, J.A., Wirth, S., Egamberdieva, D., 2019a. Role of calcium in AMF-mediated alleviation of the adverse impacts of cadmium stress in *Bassia indica* [Wight] AJ Scott. *Saudi Journal of Biological Sciences* 26 (4), 828–838.
- Hashem, A., Abd Allah, E.F., Alqarawi, A.A., Wirth, S., Egamberdieva, D., 2019b. Comparing symbiotic performance and physiological responses of two soybean cultivars to arbuscular mycorrhizal fungi under salt stress. *Saudi Journal of Biological Sciences* 26 (1), 38–48.
- Hashem, A., Akhter, A., Alqarawi, A.A., Singh, G., Almutairi, K.F., Abd Allah, E.F., 2021. Mycorrhizal fungi induced activation of tomato defense system mitigates Fusarium wilt stress. *Saudi Journal of Biological Sciences* 28 (10), 5442–5450.
- Hashem, A., Abd Allah, E., Alqarawi, A., Al-Huqail, A., & Shah, M. (2016a). Induction of osmoregulation and modulation of salt stress in *Acacia gerrardii* Benth. by arbuscular mycorrhizal fungi and *Bacillus subtilis* (BERA 71). *BioMed Research International*, 2016.
- Hashem, A., Kumar, A., Al-Dbass, A.M., Alqarawi, A.A., Al-Arjani, A.-B.-F., Singh, G., Farooq, M., Abd Allah, E.F., 2019c. Arbuscular mycorrhizal fungi and biochar improves drought tolerance in chickpea. *Saudi Journal of Biological Sciences* 26 (3), 614–624. <https://doi.org/10.1016/j.sjbs.2018.11.005>.
- Hazard, C., Gosling, P., Van Der Gast, C.J., Mitchell, D.T., Doohan, F.M., Bending, G.D., 2013. The role of local environment and geographical distance in determining community composition of arbuscular mycorrhizal fungi at the landscape scale. *ISME J.* 7 (3), 498–508.
- Hodge, A., Fitter, A.H., 2010. Substantial nitrogen acquisition by arbuscular mycorrhizal fungi from organic material has implications for N cycling. *Proc Natl Acad Sci U S A* 107 (31), 13754–13759. <https://doi.org/10.1073/pnas.1005874107>.
- Hu, H., He, L., Ma, H., Wang, J., Li, Y., Wang, J., Guo, Y., Ren, C., Bai, H., Zhao, F., 2022. Responses of AM fungal abundance to the drivers of global climate change: A meta-analysis. *Sci. Total Environ.* 805, 150362 <https://doi.org/10.1016/j.scitotenv.2021.150362>.
- Hunter, M.C., Smith, R.G., Schipanski, M.E., Atwood, L.W., Mortensen, D.A., 2017. Agriculture in 2050: recalibrating targets for sustainable intensification. *Bioscience* 67 (4), 386–391.
- IPCC. (2007). *AR4 Climate Change 2007: Synthesis Report*.
- Jaiti, F., Meddich, A., El Hadrami, I., 2007. Effectiveness of arbuscular mycorrhizal fungi in the protection of date palm (*Phoenix dactylifera* L.) against bayoud disease. *Physiol. Mol. Plant Pathol.* 71 (4), 166–173. <https://doi.org/10.1016/j.pmp.2008.01.002>.
- Jansa, J., Erb, A., Oberholzer, H.R., Šmilauer, P., Egli, S., 2014. Soil and geography are more important determinants of indigenous arbuscular mycorrhizal communities than management practices in Swiss agricultural soils. *Mol. Ecol.* 23 (8), 2118–2135.
- Johri, A.K., Oelmüller, R., Dua, M., Yadav, V., Kumar, M., Tuteja, N., Varma, A., Bonfante, P., Persson, B.L., Stroud, R.M., 2015. Fungal association and utilization of phosphate by plants: success, limitations, and future prospects. *Front. Microbiol.* 6, 984.
- Kakouridis, A., Hagen, J.A., Kan, M.P., Mambelli, S., Feldman, L.J., Herman, D.J., Weber, P.K., Pett-Ridge, J., Firestone, M.K., 2022. Routes to roots: direct evidence of water transport by arbuscular mycorrhizal fungi to host plants. *New Phytol.* 236 (1), 210–221.
- Kalamulla, R., Karunarathna, S.C., Tibpromma, S., Galappaththi, M.C.A., Suwannarach, N., Stephenson, S.L., Asad, S., Salem, Z.S., Yapa, N., 2022. Arbuscular Mycorrhizal Fungi in Sustainable Agriculture. *Sustainability* 14 (19), 12250. <https://www.mdpi.com/2071-1050/14/19/12250>.
- Kapoor, R., Singh, N., 2017. Arbuscular Mycorrhiza and Reactive Oxygen Species. In: Wu, Q.-S. (Ed.), *Arbuscular Mycorrhizas and Stress Tolerance of Plants*. Springer Singapore, pp. 225–243. https://doi.org/10.1007/978-981-10-4115-0_10.
- Kim, S.J., Eo, J.-K., Lee, E.-H., Park, H., Eom, A.-H., 2017. Effects of arbuscular mycorrhizal fungi and soil conditions on crop plant growth. *Mycobiology* 45 (1), 20–24.
- Koltai, H., Meir, D., Shlomo, E., Resnick, N., Ziv, O., Wininger, S., Ben-Dor, B., & Kapulnik, Y. (2008). Exploiting arbuscular mycorrhizal technology in different cropping systems under greenhouse conditions in semi-arid regions. International Workshop on Greenhouse Environmental Control and Crop Production in Semi-Arid Regions 797.
- Kumar, R., Pankaj, V.P., Tarafdar, A., Biswas, K., Kumar, S., 2016. Soil microbes and their interaction with plants. In: *Plant Pathogen Interaction: Recent Trends*. Sharma publications and distributors, New Delhi, pp. 1–46.
- Kutty, M., Błaszowski, J., Govindan, B., Dhaheri, L., Symanczik, S., Al-Yahya'ei, M., 2020. Organic farming practices in a desert habitat increased the abundance, richness, and diversity of arbuscular mycorrhizal fungi. *Emirates Journal of Food and Agriculture* 969. <https://doi.org/10.9755/ejfa.2019.v31.i12.2057>.
- Lewis, J.D., 2016. Mycorrhizal Fungi, Evolution and Diversification of. In: Klaman, R.M. (Ed.), *Encyclopedia of Evolutionary Biology*. Academic Press, pp. 94–99. <https://doi.org/10.1016/B978-0-12-800049-6.00251-1>.
- Li, Y., Xu, J., Hu, J., Zhang, T., Wu, X., Yang, Y., 2022. Arbuscular mycorrhizal fungi and glomalin play a crucial role in soil aggregate stability in Pb-contaminated soil. *Int. J. Environ. Res. Public Health* 19 (9), 5029.
- Li, Y., Xie, Y., Liu, Z., Shi, L., Liu, X., Liang, M., Yu, S., 2023. Plant species identity and mycorrhizal type explain the root-associated fungal pathogen community assembly of seedlings based on functional traits in a subtropical forest [Original Research]. *Front. Plant Sci.* 14 <https://doi.org/10.3389/fpls.2023.1251934>.
- Liu, Y., von Witrén, N., 2017. Ammonium as a signal for physiological and morphological responses in plants. *J. Exp. Bot.* 68 (10), 2581–2592. <https://doi.org/10.1093/jxb/erx086>.
- Luo, X., Liu, Y., Li, S., He, X., 2023. Interplant carbon and nitrogen transfers mediated by common arbuscular mycorrhizal networks: beneficial pathways for system functionality [Review]. *Front. Plant Sci.* 14 <https://doi.org/10.3389/fpls.2023.1169310>.
- Lyu, Y., Shi, P., Han, G., Liu, L., Guo, L., Hu, X., Zhang, G., 2020. Desertification Control Practices in China. *Sustainability* 12 (8). <https://doi.org/10.3390/su12083258>.
- Ma, X., Li, J., Ding, F., Zheng, Y., Chao, L., Liu, H., Liu, X., Qu, H., Bao, Y., 2022b. Changes of Arbuscular Mycorrhizal Fungal Community and Glomalin in the Rhizosphere along the Distribution Gradient of Zonal Stipa Populations across the Arid and Semiarid Steppe. *Microbiology Spectrum* 10 (5) e01489-e1422.
- Ma, J., Wang, W., Yang, J., Qin, S., Yang, Y., Sun, C., Pei, G., Zeeshan, M., Liao, H., Liu, L., Huang, J., 2022a. Mycorrhizal symbiosis promotes the nutrient content accumulation and affects the root exudates in maize. *BMC Plant Biol.* 22 <https://doi.org/10.1186/s12870-021-03370-2>.
- Madouh, T.A., Qureshi, A.M., 2023. The Function of Arbuscular Mycorrhizal Fungi Associated with Drought Stress Resistance in Native Plants of Arid Desert Ecosystems: A Review. *Diversity* 15 (3), 391. <https://www.mdpi.com/1424-2818/15/3/391>.
- Marinho, F., da Silva, I.R., Oehl, F., Maia, L.C., 2018. Checklist of arbuscular mycorrhizal fungi in tropical forests. *Sydowia* 70, 107–127.
- Mitra, D., Saritha, B., Janeesha, E., Gusaïn, P., Khoshru, B., Abo Nouh, F.A., Rani, A., Olatunbosun, A.N., Ruparella, J., Rabari, A., Mosquera-Sánchez, L.P., Mondal, R., Verma, D., Panneerselvam, P., Das Mohapatra, P.K., B.e., g. s., 2022. Arbuscular mycorrhizal fungal association boosted the arsenic resistance in crops with special responsiveness to rice plant. *Environ. Exp. Bot.* 193, 104681 <https://doi.org/10.1016/j.envexpbot.2021.104681>.
- Morton, J.B., 2000. Evolution of Endophytism in Arbuscular Mycorrhizal Fungi. *Microbial Endophytes* 121.
- Mosbah, M., Tounekti, T., Al-Turki, T., Khemira, H., 2017. Composition of the root mycorrhizal community associated with *Coffea arabica* in Fifea Mountains (Jazan region, Saudi Arabia). *J. Basic Microbiol.* 57 <https://doi.org/10.1002/jobm.201700075>.
- Muneer, M., Wang, M., Jing, Z., Zhou, X., Wang, P., Li, L., Ji, B., 2019. Low host specificity of arbuscular mycorrhizal fungi associated with dominant steppe plants in inner Mongolia. *Appl. Ecol. Environ. Res* 17 (5), 12073–12089.
- Muñoz, G., Orlando, J., Zuñiga-Feest, A., 2021. Plants colonizing volcanic deposits: root adaptations and effects on rhizosphere microorganisms. *Plant and Soil* 461, 265–279.
- Navarro-Ródenas, A., Bárzana, G., Nicolás, E., Carra, A., Schubert, A., Morte, A., 2013. Expression analysis of aquaporins from desert truffle mycorrhizal symbiosis reveals a fine-tuned regulation under drought. *Mol. Plant Microbe Interact.* 26 (9), 1068–1078.
- Newsham, K.K., Fitter, A.H., Watkinson, A.R., 1995. Multi-functionality and biodiversity in arbuscular mycorrhizas. *Trends Ecol. Evol.* 10 (10), 407–411. [https://doi.org/10.1016/S0169-5347\(00\)89157-0](https://doi.org/10.1016/S0169-5347(00)89157-0).
- Pascual, L.S., Segarra-Medina, C., Gómez-Cadenas, A., López-Climent, M.F., Vives-Peris, V., Zandalinas, S.L., 2022. Climate change-associated multifactorial stress combination: A present challenge for our ecosystems. *J. Plant Physiol.* 276, 153764 <https://doi.org/10.1016/j.jplph.2022.153764>.
- Peter, M., 2003. Volcanic deserts and primary succession – when and how do mycorrhizal fungi participate? *New Phytol.* 159, 534–536. <https://doi.org/10.1046/j.1469-8137.2003.00869.x>.
- Powell, J.T., Chatziefthimiou, A.D., Banack, S.A., Cox, P.A., Metcalf, J.S., 2015. Desert crust microorganisms, their environment, and human health. *J. Arid Environ.* 112, 127–133. <https://doi.org/10.1016/j.jaridenv.2013.11.004>.
- Preusser, F., Radies, D., Matter, A., 2002. A 160,000-Year Record of Dune Development and Atmospheric Circulation in Southern Arabia. *Science (New York, N.Y.)* 296, 2018–2020. <https://doi.org/10.1126/science.1069875>.

- Priyadharsini, P., Muthukumar, T., 2016. Interactions Between Arbuscular Mycorrhizal Fungi and Potassium-Solubilizing Microorganisms on Agricultural Productivity. In: Meena, V.S., Maurya, B.R., Verma, J.P., Meena, R.S. (Eds.), Potassium Solubilizing Microorganisms for Sustainable Agriculture. Springer, India, pp. 111–125. https://doi.org/10.1007/978-81-322-2776-2_8.
- Qi, S., Wang, J., Wan, L., Dai, Z., da Silva Matos, D.M., Du, D., Egan, S., Bonser, S.P., Thomas, T., Moles, A.T., 2022. Arbuscular mycorrhizal fungi contribute to phosphorus uptake and allocation strategies of *Solidago canadensis* in a phosphorus-deficient environment. *Front. Plant Sci.* 13, 831654.
- Richter, F., Calonne-Salmon, M., van der Heijden, M. G., Declerck, S., & Stanley, C. E. (2023). AMF-SporeChip provides new insights into arbuscular mycorrhizal fungal pre-symbiotic hyphal growth dynamics at the cellular level. *bioRxiv*, 2023.2006.2029.546436.
- Rillig, M.C., Wright, S.F., Shaw, M.R., Field, C.B., 2002. Artificial climate warming positively affects arbuscular mycorrhizae but decreases soil aggregate water stability in an annual grassland. *Oikos* 97 (1), 52–58. <https://doi.org/10.1034/j.1600-0706.2002.970105.x>.
- Saleh, A.M., Abdel-Mawgoud, M., Hassan, A.R., Habeeb, T.H., Yehia, R.S., Abdelgawad, H., 2020. Global metabolic changes induced by arbuscular mycorrhizal fungi in oregano plants grown under ambient and elevated levels of atmospheric CO₂. *Plant Physiol. Biochem.* 151, 255–263.
- Salomon, M.J., Watts-Williams, S.J., McLaughlin, M.J., Bücking, H., Singh, B.K., Hutter, I., Schneider, C., Martin, F.M., Vosatka, M., Guo, L., Ezawa, T., Saito, M., Declerck, S., Zhu, Y.-G., Bowles, T., Abbott, L.K., Smith, F.A., Cavagnaro, T.R., van der Heijden, M.G.A., 2022. Establishing a quality management framework for commercial inoculants containing arbuscular mycorrhizal fungi. *iScience* 25 (7), 104636. <https://doi.org/10.1016/j.isci.2022.104636>.
- Sanders, I.R., Clapp, J.P., Wiemken, A., 1996. The genetic diversity of arbuscular mycorrhizal fungi in natural ecosystems—a key to understanding the ecology and functioning of the mycorrhizal symbiosis. *New Phytol.* 133 (1), 123–134.
- Sanders, I., Streitwolf-Engel, R., Van der Heijden, M., Boller, T., Wiemken, A., 1998. Increased allocation to external hyphae of arbuscular mycorrhizal fungi under CO₂ enrichment. *Oecologia* 117 (4), 496–503.
- Satyanarayana, T., Deshmukh, S., Deshpande, M., 2019. Advancing Frontiers in Mycology & Mycotechnology Basic and Applied Aspects of Fungi: Basic and Applied Aspects of Fungi. <https://doi.org/10.1007/978-981-13-9349-5>.
- Schouteden, N., De Waele, D., Panis, B., Vos, C.M., 2015. Arbuscular mycorrhizal fungi for the biocontrol of plant-parasitic nematodes: a review of the mechanisms involved. *Front. Microbiol.* 6, 1280.
- Schwarzott, D., Walker, C., 2001. A new fungal phylum, the Glomeromycota: phylogeny and evolution [J]. *Mycol. Res.* 105, 1413–1421.
- Sene, G., Samba-Mbaye, R., Thiao, M., Khasa, D., Kane, A., Manga, A., Mbaye, M.S., Sylla, S.N., 2012a. The abundance and diversity of legume-nodulating rhizobia and arbuscular mycorrhizal fungal communities in soil samples from deforested and man-made forest systems in a semiarid Sahel region in Senegal. *Eur. J. Soil Biol.* 52, 30–40.
- Sene, G., Thiao, M., Manga, A., Kane, A., Samba-Mbaye, R., Mbaye, M.S., Khasa, D., Sylla, S.N., 2012b. Arbuscular mycorrhizal soil infectivity and spores distribution across plantations of tropical, subtropical and exotic tree species: a case study from the forest reserve of Bandia, Senegal. *African Journal of Ecology* 50 (2), 218–232. <https://doi.org/10.1111/j.1365-2028.2011.01315.x>.
- Shah, K., Tripathi, S., Tiwari, I., Shrestha, J., Modi, B., Paudel, N., & Das, B. (2021). Role of soil microbes in sustainable crop production and soil health: A review. *Agricultural Science & Technology* (1313-8820), 13(2).
- Shi, S., Luo, X., Wen, M., Dong, X., Sharifi, S., Xie, D., He, X., 2021. Funneliformis mosseae improves growth and nutrient accumulation in wheat by facilitating soil nutrient uptake under elevated CO₂ at daytime, not nighttime. *Journal of Fungi* 7 (6), 458.
- Shi, J., Wang, X., Wang, E., 2023. Mycorrhizal Symbiosis in Plant Growth and Stress Adaptation: From Genes to Ecosystems. *Annu. Rev. Plant Biol.* 74 (1), 569–607. <https://doi.org/10.1146/annurev-arplant-061722-090342>.
- Song, Y., Chen, D., Lu, K., Sun, Z., Zeng, R., 2015. Enhanced tomato disease resistance primed by arbuscular mycorrhizal fungus. *Front. Plant Sci.* 6, 786.
- Spatafora, J.W., Chang, Y., Benny, G.L., Lazarus, K., Smith, M.E., Berbee, M.L., Bonito, G., Corradi, N., Grigoriev, I., Gryganskyi, A., 2016. A phylum-level phylogenetic classification of zygomycete fungi based on genome-scale data. *Mycologia* 108 (5), 1028–1046.
- Stürmer, S., Siqueira, J., 2006. Diversidade de Fungos Micorrízicos Arbusculares em Ecossistemas Brasileiros. *Biodiversidade Do Solo Em Ecossistemas Brasileiros* 537–584.
- Suleiman, M. K., Dixon, K., Commander, L., Nevill, P., Quoreishi, A. M., Bhat, N. R., Manuvel, A. J., & Sivadasan, M. T. (2019). Assessment of the Diversity of Fungal Community Composition Associated With *Vachellia pachyceras* and Its Rhizosphere Soil From Kuwait Desert [Original Research]. *10(63)*. <https://doi.org/10.3389/fmicb.2019.00063>.
- Sun, D., Yang, X., Wang, Y., Fan, Y., Ding, P., Song, X.E., Yuan, X., Yang, X., 2022. Stronger mutualistic interactions with arbuscular mycorrhizal fungi help Asteraceae invaders outcompete the phylogenetically related natives. *New Phytol.* 236 (4), 1487–1496. <https://doi.org/10.1111/nph.18435>.
- Sylvia, D.M., Williams, S.E., 1992. Vesicular-arbuscular mycorrhizae and environmental stress. *Mycorrhizae in Sustainable Agriculture* 54, 101–124.
- Symanczik, S., Błazkowski, J., Koegel, S., Boller, T., Wiemken, A., & ei, M. (2014). Isolation and identification of desert habituated arbuscular mycorrhizal fungi newly reported from the Arabian Peninsula. *Journal of Arid Land*, 6. <https://doi.org/10.1007/s40333-013-0213-8>.
- Tamura, K., Stecher, G., Peterson, D., Filipski, A., Kumar, S., 2013. MEGA6: Molecular Evolutionary Genetics Analysis version 6.0. *Mol Biol Evol* 30 (12), 2725–2729. <https://doi.org/10.1093/molbev/mst197>.
- Tang, J., Chen, J., Chen, X., 2006. Response of 12 weedy species to elevated CO₂ in low-phosphorus-availability soil. *Ecol. Res.* 21 (5), 664–670.
- Tang, B., Man, J., Lehmann, A., Rillig, M.C., 2023a. Arbuscular mycorrhizal fungi benefit plants in response to major global change factors. *Ecol. Lett.* 26 (12), 2087–2097. <https://doi.org/10.1111/ele.14320>.
- Tang, C., Sun, B., Zeeshan, M., Li, J., Zhang, X., 2023b. Funneliformis mosseae-induced changes of rhizosphere microbial community structure enhance Capsicum annum L. plant growth and fruit yield. *Soil Sci. Soc. Am. J.* 87 (4), 843–855. <https://doi.org/10.1002/saj2.20528>.
- Tarafdar, J.C., Praveen, K., 1996. The role of vesicular arbuscular mycorrhizal fungi on crop, tree and grasses grown in an arid environment. *J. Arid Environ.* 34 (2), 197–203. <https://doi.org/10.1006/jare.1996.0101>.
- Tenzin, U.W., Noirungsee, N., Runsaeng, P., Noppradit, P., Klinnawee, L., 2022. Dry-season soil and co-cultivated host plants enhanced propagation of arbuscular mycorrhizal fungal spores from sand dune vegetation in trap culture. *Journal of Fungi* 8 (10), 1061.
- Treseder, K., Turner, K., 2007. Glomalin in Ecosystems. *Soil Science Society of America Journal - SSSAJ* 71. <https://doi.org/10.2136/sssaj2006.0377>.
- Vicca, S., Zavalloni, C., Fu, Y., Voets, L., Dupré de Boulois, H., Declerck, S., Ceulemans, R., Nijs, I., & Janssens, I. (2009). Arbuscular mycorrhizal fungi may mitigate the influence of a joint rise of temperature and atmospheric CO₂ on soil respiration in grasslands. *International Journal of Ecology*, 2009, ID 209768.
- Volk, T.J., 2013. Fungi. In: Levin, S.A. (Ed.), Encyclopedia of Biodiversity, Second Edition. Academic Press, pp. 624–640. <https://doi.org/10.1016/B978-0-12-384719-5.00062-9>.
- Wahab, A., Muhammad, M., Munir, A., Abdi, G., Zaman, W., Ayaz, A., Khizar, C., Reddy, S.P.P., 2023. Role of arbuscular mycorrhizal fungi in regulating growth, enhancing productivity, and potentially influencing ecosystems under abiotic and biotic stresses. *Plants* 12 (17), 3102.
- Wang, Y., Wang, M., Li, Y., Wu, A., Huang, J., 2018. Effects of arbuscular mycorrhizal fungi on growth and nitrogen uptake of *Chrysanthemum morifolium* under salt stress. *PLoS One* 13 (4), e0196408.
- Weber, C.F., Zak, D.R., Hungate, B.A., Jackson, R.B., Vilgalys, R., Evans, R.D., Schadt, C. W., Megonigal, J.P., Kuske, C.R., 2011. Responses of soil cellulolytic fungal communities to elevated atmospheric CO₂ are complex and variable across five ecosystems. *Environ Microbiol* 13 (10), 2778–2793. <https://doi.org/10.1111/j.1462-2920.2011.02548.x>.
- Wright, S.F., Upadhyaya, A., 1998. A survey of soils for aggregate stability and glomalin, a glycoprotein produced by hyphae of arbuscular mycorrhizal fungi. *Plant and Soil* 198 (1), 97–107. <https://doi.org/10.1023/A:1004347701584>.
- Wu, B., Hussain, M., Zhang, W., Stadler, M., Liu, X., Xiang, M., 2019. Current insights into fungal species diversity and perspective on naming the environmental DNA sequences of fungi. *Mycology* 10 (3), 127–140. <https://doi.org/10.1080/21501203.2019.1614106>.
- Wu, S., Shi, Z., Chen, X., Gao, J., Wang, X., 2022. Arbuscular mycorrhizal fungi increase crop yields by improving biomass under rainfed condition: a meta-analysis. *PeerJ* 10, e12861.
- Xiao, D., Chen, Y., He, X., Xu, Z., Bai, S.H., Zhang, W., Cheng, M., Hu, P., Wang, K., 2021. Temperature and precipitation significantly influence the interactions between arbuscular mycorrhizal fungi and diazotrophs in karst ecosystems. *For. Ecol. Manage.* 497, 119464.
- Xu, X., Chen, C., Zhang, Z., Sun, Z., Chen, Y., Jiang, J., Shen, Z., 2017. The influence of environmental factors on communities of arbuscular mycorrhizal fungi associated with *Chenopodium ambrosioides* revealed by MiSeq sequencing investigation. *Sci. Rep.* 7 (1), 45134. <https://doi.org/10.1038/srep45134>.
- Xun, W., Shao, J., Shen, Q., Zhang, R., 2021. Rhizosphere microbiome: Functional compensatory assembly for plant fitness. *Comput. Struct. Biotechnol. J.* 19, 5487–5493.
- Yadav, R., Mahatma, M., Thirumalaisamy, P., Meena, H., Bhaduri, D., Arora, S., Panwar, J., 2017. In: Arbuscular Mycorrhizal Fungi (AMF) for Sustainable Soil and Plant Health in Salt-Affected Soils. Springer, pp. 133–156.
- Yang, H., Zang, Y., Yuan, Y., Tang, J., Chen, X., 2012. Selectivity by host plants affects the distribution of arbuscular mycorrhizal fungi: evidence from ITS rDNA sequence metadata. *BMC Evol. Biol.* 12 (1), 50. <https://doi.org/10.1186/1471-2148-12-50>.
- Yuan-Yuan, L., Shun-Xing, G., Yung, L., 2020. Ultrastructural changes during the symbiotic seed germination of *Gastrodia elata* with fungi, with emphasis on the fungal colonization region. *Botanical Studies (online)* 61 (1).
- Zhao, Y., Cartabia, A., Lalaymia, I., Declerck, S., 2022. Arbuscular mycorrhizal fungi and production of secondary metabolites in medicinal plants. *Mycorrhiza* 32 (3–4), 221–256.
- Zhong, C., Cao, X., Hu, J., Zhu, L., Zhang, J., Huang, J., Jin, Q., 2017. Nitrogen Metabolism in Adaptation of Photosynthesis to Water Stress in Rice Grown under Different Nitrogen Levels [Original Research]. *Front. Plant Sci.* 8 <https://doi.org/10.3389/fpls.2017.01079>.
- Zhu, C., Ling, N., Guo, J., Wang, M., Guo, S., Shen, Q., 2016. Impacts of fertilization regimes on arbuscular mycorrhizal fungal (AMF) community composition were correlated with organic matter composition in maize rhizosphere soil. *Front. Microbiol.* 7, 1840.