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Arbuscular mycorrhizal fungi as a potential biofertilizers for agricultural sustainability

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ABSTRACT

Globally, by 2050, agricultural food production will be increased to feed the growing population. To achieve the objective in sustainable manner, scientific chronicles have explores the mutualistic interaction between plant roots and rhizosphere microbiome. One of the interactions of plants roots was found with arbuscular mycorrhiza fungi (AMF), a rhizosphere microbiome. Biofertilization process by the mean of AMF has depicted as a beneficial alternative to chemical fertilization practices. It has been recognized for having several potential applications such as plant fertilization (phosphorus, nitrogen and other micronutrients), alleviation of biotic (protecting plants from pest and pathogens), and abiotic stresses (drought, salinity, heavy metals, low and high temperature). AMF sustainably increases the plant growth and production by establishing within the host root with the help of set of genes and fulfilling the needs of the host. At present, worldwide total 340 species of AMF has been found. In the present review, global diversity, molecular crosstalk in AMF symbiosis and their potential application in sustainable agriculture has been reviewed.

1. INTRODUCTION

Soil contains the pool of biodiversity which aggregates a range of dynamic organisms such as microflora (bacteria and fungi), macrofuana (protozoa and nematodes), mesofana (*Collembola* and *Acari*), and macrofana (earthworm and termites). Among the soil microbiota, microflora (bacteria and fungi) are more dominant, as there are trillion or more species present in the rhizosphere [1]. Fungi are one of the inhabitants of soil, which alone contribute to the millions of species. As an important component of soil microbial diversity, fungi can function as ecosystem regulators, biological controllers, and decomposers. As ecosystem regulators, fungi regulate the physiological process in the soil, which are responsible structure formation of soil, whereas Biol Controller fungi regulates the pest, diseases and growth of other organism. Mycorrhizal fungi are one of the Biol Controllers that enhance growth of host plant and protect them from pathogens [2].

Mycorrhiza is an important terrestrial mutualistic fungus, which are associated with roots of the plant. Mycorrhizal association helps the host plant to fight against the adverse soil conditions (example in drought situations it helps in increasing the surface of the roots) and provide several nutrients constitute a key functional group of soil biota [3]. Mycorrhizal fungi are categorized into two types of root biotrophic association namely endomycorrhizal fungi and ectomycorrhizal fungi (EcM) [4]. Endomycorrhizal fungi are root colonizers which grow inside the plant roots cell, whereas ectomycorrhizal fungi grow around root cells. Endomycorrhizal fungi is the one major type, and it is further classified into five major groups, namely arbuscular, arbutoid, monotropoid, ericoid, and orchidaceous mycorrhizae [5]. Among these types of fungi, arbuscular mycorrhizal fungi (AMF) formerly known vesicular arbuscular mycorrhizae are well-studied and known [4,3].

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AMF (phylum: *Glomeromycota*) are the obligate symbionts, which was appeared back 460 million years ago and now believed to be associated with 80% of the land plant species including agricultural crop plants (cereals and vegetable crops). This type of fungus has been known have nearly 200 species which falls in 10 different genera. Being obligate symbionts, AMF is totally depends upon the host plant for their food and life cycle and in return AMF offers a competitive benefits to the plants [6]. AMF is benefits the plant by enhancing the sufficient nutrients availability like phosphorus (P), potassium (K), nitrogen (N) and uptake of the water and also benefits for alleviating the environmental stresses such as drought, salinity, heavy metals, and temperature (low and high) as they helps in increasing the root surface area by producing antimetabolites and hormones which promote root growth. By the increasing the root surface area, they also helps in alleviating the abiotic stresses on the plants [7].

AMF is considered as ecological important organism of ecosystem because of their function. Hence, the researchers have given an idea of using this organism as a biofertilizer for enhancing the crops productivity. Biofertilizer is major need of agriculture for both enhancement of crop productivity and sustainability, as now sustainability is one of the main criteria of the scientists. This review, details the global diversity of AMF, their role in the enhancement of plant and their mechanisms.

2. GLOBAL DIVERSITY AND DISTRIBUTION OF AM FUNGI

Till the date, global diversity count of AMF reached to 340. All the species of AMF are classified into four orders namely, Archaeosporales, Glomerales, Diversisporales, and Paraglomerales and 12 families known as *Ambisporaceae*, *Archaeosporaceae*, *Geosiphonaceae*, *Claroideoglomeraceae*, *Glomeraceae*, *Acaulosporaceae*, *Diversisporaceae*, *Gigasporaceae*, *Pacisporaceae*, *Sacculosporaceae*, *Paraglomeraceae*, and *Pervetustaceae* [Table 1 and Figure 1]. In this review, 160 different species of AMF have been reviewed from different sources. These species belong to 20 different genera and the most predominant was *Glomus* followed by *Acaulospora*, *Diversispora*, *Gigaspora*, *Scutellospora*, *Pacispora*, *Funneliformis*, *Septoglomus*, *Entrophospora*, *Kamienskia*, *Rhizoglomus*, *Claroideoglomus*, *Ambispora*, *Sclerocystis*, *Dominikia*, *Archaeospora*, *Paraglomus*, *Racocetra*, *Otospora*, and *Sclerocarpum* [Table 2 and Figure 2].

3. MOLECULAR CROSSTALK IN MYCORRHIZAL SYMBIOSES

An obligate biotrophs, AMF, colonization mechanisms comprise of three main steps namely searches of host, penetration and finally establishment, which involve several genes [8]. In the first step, initial recognition, plants secretes some bioactive molecules like strigolactones (signaling molecule which helps AMF to identify their host and stimulates their growth and branching [9,10]. Reciprocally, AMF secretes a set of factors known as mycorrhizal factors (Myc), which plays a major role in the communication of AMF and N fixing bacteria [6,11]. Further, AMF and plant interaction are established with the induction of seven set genes (*SYM* genes; CYCLOPS). The Myc factor receptors of host when perceive Myc signals, the root cells induced the secretion of cytosolic calcium (Ca) and second membrane proteins (SYMPK) is activated. This protein codes for receptor-like kinase that have a potential to recognize signals of AMF directly and indirectly. Afterward, SYMPK transduce incoming signals to nucleus from cytoplasm by phosphorylating an unknown substrate through its kinase domains. All the downstream elements present in cytoplasm localization activates rapid signal transduction into nucleus, and there is repeated oscillation of Ca ion (Ca^{2+}). These repeated oscillations occur in cytoplasm and nucleus through alternate activity of Ca^{2+} channels and transporters, decoded by a calmodulin-dependent protein kinase, the product of one of the *SYM* gene. This all leads to the other gene regulation and finally root colonization [5].

After initiation and chemical acquaintance, long thread-like fungal filaments and mycelium known as fungal hyphae interacts with the roots of host. After interaction hyphae gradually starts its propagation by forming hyphopodium (branch hyphal composed

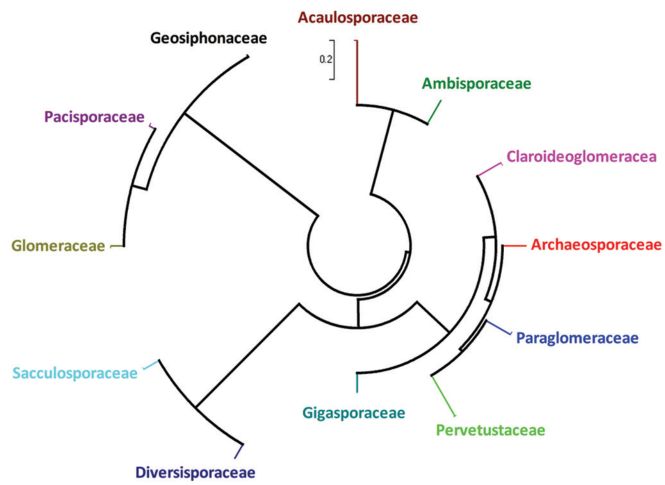

Figure 1: Phylogenetic profiling of arbuscular mycorrhizal fungi (AMF) showing 12 different families of AMF. The Sequences were obtained from NCBI GenBank Databases and phylogenetic tree was constructed using MEGA 4 software.

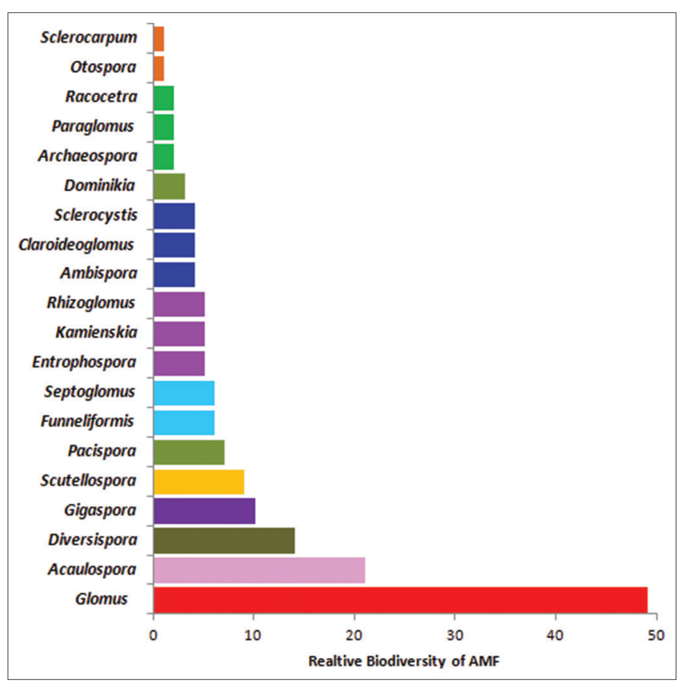

Figure 2: Relative distributions of arbuscular mycorrhiza fungal communities from different soil and plant association worldwide. Sauces: Supplementary material SM-1.

Table 1: Phylogenetic profiling and taxonomical classification of phylum Glomeromycota (class: Glomeromycetes).

Orders (4)	Families (12)	Genera (41)	Generic type	Generic type basionym
Archaeosporales	*Ambisporaceae*	*Ambispora*	*A. fennica*	*Ambispora fennica*
	Archaeosporaceae	*Archaeospora*	*A. trappei*	*Acaulospora trappei*
	Geosiphonaceae	*Geosiphon*	*G. pyriformis*	*Geosiphon pyriformis*
Glomerales	*Claroideoglomeraceae*	*Claroideoglomus*	*C. claroideum*	*Glomus claroideum*
	Glomeraceae	*Dominikia*	*D. minuta*	*Glomus minutum*
		Funneliformis	*F. mosseae*	*Endogone mosseae*
		Funneliglomus	*F. sanmartinense*	*Funneliglomus sanmartinense*
		Glomus	*G. macrocarpum*	*Glomus macrocarpum*
		Halonatospora	*H. pansihalos*	*Halonatospora pansihalos*
		Kamienskia	*G. bistratum*	*Glomus bistratum*
		Microdominikia	*D. litorea*	*Dominikia litorea*
		Microkamienskia	*M. peruviana*	*Microkamienskia peruviana*
		Nanoglomus	*N. plukenetiae*	*Nanoglomus plukenetiae*
		Oehlia	*G. diaphanum*	*Glomus diaphanum*
		Orientoglomus	*D. emiratia*	*Dominikia emiratia*
		Rhizophagus	*R. populinus*	*Rhizophagus populinus*
		Sclerocarpum	*S. amazonicum*	*Sclerocarpum amazonicum*
		Sclerocystis	*S. coremioides*	*Sclerocystis coremioides*
		Septoglomus	*G. constrictum*	*Glomus constrictum*
Diversisporales	*Acaulosporaceae*	*Acaulospora*	*A. laevis*	*Acaulospora laevis*
	Diversisporaceae	*Corymbiglomus*	*C. corymbiforme*	*Corymbiglomus corymbiforme*
		Diversispora	*G. spurcum*	*Glomus spurcum*
		Desertispora	*D. omaniana*	*Diversispora omaniana*
		Otospora	*O. bareai*	*Otospora bareai*
		Redeckera	*G. megalocarpum*	*Glomus megalocarpum*
		Sieverdingia	*S. tortuosum*	*Glomus tortuosum*
		Tricispora	*E. nevadensis*	*Entrophospora nevadensis*
	Gigasporaceae	*Bulbospora*	*B. minima*	*Bulbospora minima*
		Cetraspora	*G. gilmorei*	*Gigaspora gilmorei*
		Dentiscutata	*G. nigra*	*Gigaspora nigra*
		Intraornatospora	*R. intraornata*	*Racocetra intraornata*
		Gigaspora	*E. gigantea*	*Endogone gigantea*
		Paradentiscutata	*P. bahiana*	*Paradentiscutata bahiana*
		Racocetra	*G. coralloidea*	*Gigaspora coralloidea*
		Scutellosproa	*E. calospora*	*Endogone calospora*
	Pacisporaceae	*Pacispora*	*G. scintillans*	*Glomus scintillans*
	Sacculosporaceae	*Sacculospora*	*E. baltica*	*Entrophospora baltica*
Paraglomerales	*Paraglomeraceae*	*Innospora*	*P. majewskii*	*Paraglomus majewskii*
		Paraglomus	*P. occultum*	*Paraglomus occultum*
	Pervetustaceae	*Pervetustus*	*P. simplex*	*Pervetustus simplex*
Unclear	Insertae sedis	*Entrophospora*	*G. infrequens*	*Glomus infrequens*

Source: http://www.amf-phylogeny.com

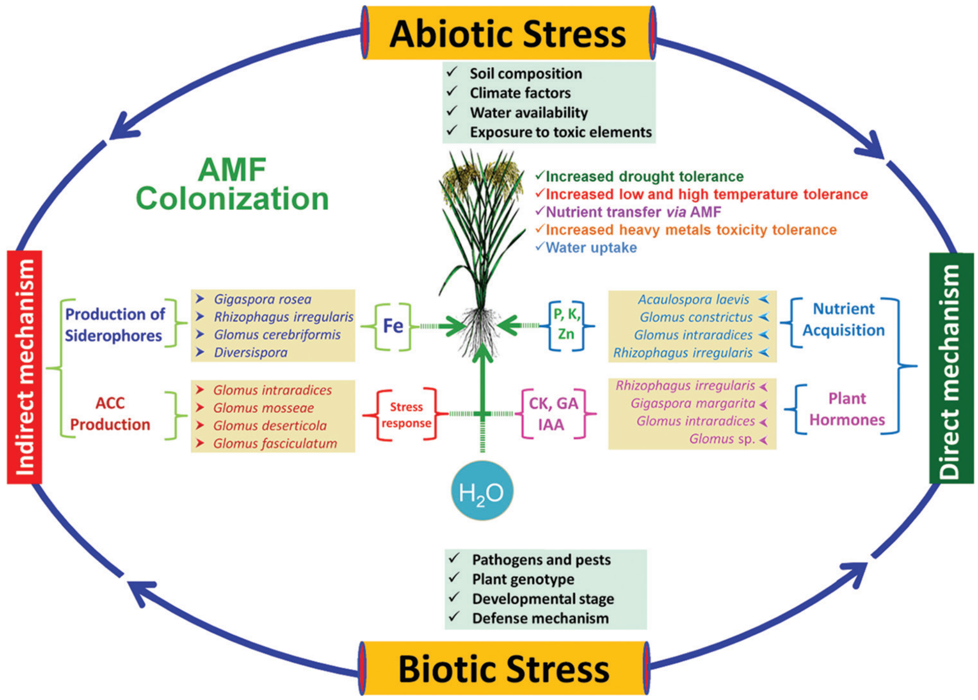

Figure 3: A schematic representations of arbuscular mycorrhiza fungal colonization and their potential role in plant growth promotion, management of abiotic/ biotic stresses and uptake of nutrients.

of lobed cells) into the host roots. This step gets many genes activated and pre-penetration apparatus is developed which allows the fungi to grow inside the plant without breaking cell membrane integrity. Then, finally, the formation of small tree like structure called arbuscules begins. This structure helps fungi to house into cytoplasm of host cell [5].

This symbiotic association of AMF and plants use to benefits each. In case of AMF, plant provides carbon along with hexose, the photosynthetic products. Hexose is transported into the arbuscular part of fungal cytoplasm which is converted further into suitable carbohydrates forms like glycogen and triacylglycerol that can be easily transported to long distance networks of fungi. On the other hand, in plant, AMF helps in increasing the root surface area that improves nutrients and water uptake. AMF can also improve absorption of immobile nutrients and depleted nutrients (example: tropical regions with excessive rainfall) through diffusion and by extending external hyphae beyond the depleted zone, respectively [11,12].

4. APPLICATIONS OF AM FUNGI FOR SUSTAINABLE AGRICULTURE

Tremendous potentials of AMF fungi includes in improving growth of host plant species due to increased absorption, tolerance to salinity, drought, and collaborative inter change with other favorable microorganisms [13] [Figure 3]. As compared with conventional agriculture, the conditions of soil is prevalent in sustainable agriculture are likely to be more favorable to AM fungi [14-17]. With more than 80% of terrestrial plants, liverworts, ferns, woody gymnosperms and angiosperms [18], the AMF are widely distributed in association with natural and agricultural environments. Since microbial communities in conventional farming systems have been modified due to agronomy [19-21], and high inputs of manures, defoliants and toxicants [22-24] the natural role of mycorrhizospheric organisms may have been marginalized in intensive agriculture.

In AMF, there is no clear-cut sheath formation on the surface of roots. Rather a loose, weft of hyphae lies in the soil which is connected with the internal mycelium by connections through the epidermal mass. Mycorrhizal fungal hyphae lengthen into the soil, invading into nutrient depletion zone which increases the uptake of quiescent elements by as much as 60 times. There is greater soil exploration and increasing uptake of N, P, K, zinc (Zn), copper (Cu), sulfur (S), iron (Fe), Ca, magnesium (Mg), and manganese (Mn) supply to the host roots, which is one of the main advantages of mycorrhiza [17,25,26]. Root colonized plants are better able to obtain their nourishment from the soil and resist environmental stresses [27]. Due to this, some important role of fungal symbionts is seen as biofertilizers and also in crop protection. AMF enhances the resistance to root-related diseases and secondary disease controlling agent and are responsible for a transiently stimulate of host plant disease resistance mechanisms.

There is beneficial effect on the hydraulic status and soil accumulation, resulting in more uniform plant culture due to the fungal hyphae. Reduced soil erosion with improved soil texture - Some chemicals is produced by AMF fungi that prevent compression of humus. It makes them more porous and facilitates root permeation in the soil. AMF use not only it increases income for farmers, but it also improves crop yield. It translocates nutrients; it leads to improvement in plant photosynthesis, and plant metabolism processes. As a result, the plant has better growth and yield and it will reduce the use of chemical fertilizers, sometimes up to half.

4.1. Plants Fertilization

Plants require 16 different types of macro and micronutrients including N, P, K, aluminum (Al), boron (B), Cu, Ca, chlorine (Cl), Fe, Mg, Mn, nickel (Ni), molybdenum (Mo), selenium (Se), S, Zn, for their growth and development. They generally absorb those nutrients from soil or either air in the inorganic or fixed form. Nowadays, amount of inorganic or fixed amount of nutrients in soil has been depleted due to

Table 2: Biodiversity of arbuscular mycorrhiza fungi from different soil and plant association worldwide.

SN	AMF	Soil and plant association	References
1.	*Acaulospora bireticulata*	Rice	Martins and Rodrigues [189]
2.	*Acaulospora denticulata*	Date palm	Sghir *et al*. [190]
3.	*Acaulospora spinosa*	Tea	Singh *et al*. [191]
4.	*Claroideoglomus hanlinii*	*Plantago lanceolata*	Błaszkowski *et al*. [192]
5.	*Claroideoglomus luteum*	*Crataegus pontica*	Mirzaei, Noorbakhsh [193]
6.	*Diversispora aurantia*	*Asteriscus maritimus*	Estrada *et al*. [194]
7.	*Diversispora celata*	*Glycine max*	Gamper *et al*. [195]
8.	*Diversispora clara*	*Asteriscus maritimus*	Estrada *et al*. [196]
9.	*Dominikia difficilevidera*	Lowiński National Park	Błaszkowski *et al*. [197]
10.	*Dominikia disticha*	Sand dunes, South Africa	Błaszkowski *et al*. [198]
11.	*Dominikia duoreactiva*	Giftun Island, Egypt, Africa	Błaszkowski *et al*. [197]
12.	*Entrophospora colombiana*	fruit orchards	Ragupathy, Mahadevan [199]
13.	*Entrophospora infrequens*	*Crataegus pontica*	Mirzaei, Noorbakhsh [193]
14.	*Entrophospora kentinensis*	date palm	Sghir *et al*. [190]
15.	*Funneliformis badium*	*Crataegus pontica*	Mirzaei, Noorbakhsh [193]
16.	*Funneliformis caledonium*	Soil, South Korea	Krishnamoorthy *et al*. [200]
17.	*Funneliformis coronatus*	*Asteriscus maritimus*	Estrada *et al*. [194]
18.	*Gigaspora calospora*	Litchi	Sharma *et al*. [201]
19.	*Gigaspora decipiens*	Rice	Martins and Rodrigues [189]
20.	*Gigaspora ramisporophora*	Rice	Martins and Rodrigues [189]
21.	*Gigaspora rosea*	Collection center	Clark *et al*. [202]
22.	*Gigaspora margarita*	*Puspalum nototum*	Douds Jr, Schenck [203]
23.	*Glomus hoi*	fruit orchards	Ragupathy, Mahadevan [199]
24.	*Glomus insculptum*	Sand dunes of Poland	Błaszkowski *et al*. [204]
25.	*Glomus tenebrosum*	fruit orchards	Ragupathy, Mahadevan [199]
26.	*Glomus tetrastratosum*	forest of Poland	Jobim *et al*. [205]
27.	*Glomus viscosum*	Chinese magnolia	Walker *et al*. [206]
28.	*Kamienskia achrum*	Sand dunes, South Africa	Błaszkowski *et al*. [198]
29.	*Kamienskia bistratum*	Sand dunes, South Africa	Błaszkowski *et al*. [198]
30.	*Kamienskia iranicum*	Sand dunes, South Africa	Błaszkowski *et al*. [198]
31.	*Otospora bareai*	*Thymus granatensis*	Palenzuela *et al*. [207]
32.	*Pacispora franciscana*	Natural forest	Oehl and Sieverding [208]
33.	*Paraglomus majewskii*	*Plantago lanceolata*	Błaszkowski *et al*. [209]
34.	*Paraglomus occultum*	*Asteriscus maritimus*	Estrada *et al*. [194]
35.	*Rhizoglomus fasciculatum*	Rice	Martins and Rodrigues [189]
36.	*Rhizoglomus melanum*	*Isoëtes lacustris*	Sudová *et al*. [210]
37.	*Rhizophagus arabicus*	Soil, South Arabia	Symanczik *et al*. [211]
38.	*Rhizophagus clarus*	Soil, South Korea	Krishnamoorthy *et al*. [200]
39.	*Rhizophagus irregularis*	Cabo de Gata Natural Park	Estrada *et al*. [212]
40.	*Sclerocarpum amazonicum*	Amazonian forest	Jobim *et al*. [205]
41.	*Sclerocystis coremioides*	Litchi	Sharma *et al*. [201]
42.	*Sclerocystis sinuosa*	*Rhododendron lepidotum*	Chaurasia *et al*. [213]
43.	*Scutellispora nigra*	*Rhododendron barbatum*	Chaurasia *et al*. [213]
44.	*Scutellospora calospora*	*Asteriscus maritimus*	Estrada *et al*. [194]
45.	*Scutellospora castanea*	Leek	Hijri *et al*. [214]
46.	*Scutellospora gregaria*	*Cucurbita* sp.	Mbogne *et al*. [215]
47.	*Scutellospora pellucida*	Litchi	Sharma *et al*. [201]
48.	*Septoglomus constrictum*	Cabo de Gata Natural Park	Estrada *et al*. [212]
49.	*Septoglomus furcatum*	*Cordia oncocalyx*	Błaszkowski *et al*. [216]
50.	*Septoglomus jasnowskae*	*Plantago lanceolata* L.	Błaszkowski *et al*. [217]

AMF: Arbuscular mycorrhizal fungi.

over exploitation and contamination and complete the requirement of plants chemically synthesized fertilizer were being provided from the beginning of green revolution. These use of chemical products in the agricultural farms have arose pollution and destruction of soil quality like problems [28]. In recent years, use of AMF is also considered along with other nutrients solubilizing or fixing microbes [29]. AMF play a paramount role in mobilizing nutrients to the plants from the soil [30]. The plant roots are attached by mycorrhizal hyphae through which the nutrients move from soil to the plants. AMF has been reported for improving mobilization of nutrients such as N, P, Zn, and Ca [31].

4.1.1. P mobilization

P is one the most pivotal microelements required by the plant as it builds up about 0.2% dry weight. This element has both structural (nucleic acid and phospholipids) and metabolic (energy transfer) functions in plants. In addition, formation of seeds, elongation of roots, tolerance from disease, and cold are also important functions of P. This much more important nutrient is diffusion limited nutrient [32]. AMF or presence of mycorrhiza are considered for enhance P uptake 3.1-4.7 times higher than nonmycorrhizal plants [33]. Hence, AMF is considered the best to increase the P supply over use of chemical fertilizers [34,35]. On our review, it was found that from back 1982 various reports have published and concluding, AMF is good source of mobilizing P. In a report, barley used as for experiment was inoculated with two different species of *Glomus* (*Glomus constrictus* and *Glomus fasciculatus*) and one species of *Gigaspora* (*Gigaspora margarita*) differently. After analysis of it was concluded that plant inoculated with AMF *G. constrictus* and *G. fasciculatus* has showed increased uptake of P along with Cu and Zn [36]. In another report by [37] found that AMF *Glomus etunicatum* has enhanced P uptake 500–6000 folds higher.

AMF species *Acaulospora laevis* and *Glomus fasciculatum* was reported for the enhancement of roots and uptake of P from the soil to plant *Trifolium subterraneum* L. [38]. In another study, wheat crop is inoculated with P- solubilizing bacteria (*Bacillus circulans* and *Cladosporium herbarum*) and AMF (*Glomus* sp.) individually and in combination. It was concluded that inoculation of PSM and AMF in combination has increased P uptake over singly inoculated cultures [39]. In a report, barley was inoculated with another AMF species identified as *Glomus mosseae* and founds that there is enhancement of P mobilization with this species inoculation [40]. In similar report *G. mosseae*, *Glomus claroideum* and *Glomus intraradices* were inoculated in maize plant individually and concluded that plant containing *G. mosseae,* were having 10 cm longer roots surface area, whereas *G. claroideum* was 6 cm longer. On the other hand, *G. intraradices* were found to improve P uptake more than other AMF species inoculation [41].

In 2011, *Medicago truncatula* was used as a test plant and it was inoculated with two different species of *Glomus*, that is, *G. intraradices, G. claroideum*, and *G. margarita.* The result of this experiment founds to deliver P to plant and maximum was observed in plant inoculated with *G. intraradices* followed by *G. claroideum* and *G. margarita* [42]. Another report also concluded *G. mossea* for increasing P uptake when tested in the plant *Capsicum annuum* L. [43]. In an investigation, three different AMF species *Acaulospora scrobiculata*, *Glomus cerebriforme*, and *G. intraradices* was experimented on two crop plants (*Phaseolus mungo* and *Triticum aestivum*) and two multipurpose tree species (*Eucalyptus tereticornis* and *Albizia procera*). It was observed that species *G. cerebriforme* enhanced P uptake in plants *P. mungo* and *A. procera*, whereas, *A. scrobiculata* and *G. intraradices* enhanced P mobilization in *T. aestivum*, *E. tereticornis* respectively [44]. *G. intraradices* was also tested in another study on *Allium porrum* L. and *Plantago lanceolata* L. and found P uptake more as compare to control [45].

G. intraradices, a commercial AMF, was also reported for enhancing P uptake when inoculated in maize plant [29]. In another report, *Rhizophagus irregularis* was reported for enhancing P uptake under well- water condition in *Sorghum bicolor* plant [46]. Another investigation, concluded AMF, *R. irregularis* also enhances uptake when inoculated in plant *M. truncatula* grown in PAH polluted soil [47]. In similar report, two AMF *Funneliformis mosseae* and *R. irregularis* were tested on tomato plant and improvement of P uptake was observed [48].

4.1.2. N uptake

The major constitute of chlorophyll, proteins, amino acids, purines, and pyrimidine, N is also an important nutrient of plant required in bulk amount. It is mobile element of soil, therefore different environmental conditions affects the fixation like under humid conditions is subjected to leaching, whereas under arid and semi-arid conditions limits the N use by plant due to deficiency of water. N is being provided to plants by two different ways, that is, chemical fertilization and biological fertilization. Chemical fertilization (urea) was being used from number of years which is considered to affects environment health. On the other hand biological fertilization uses various types of microbes including bacteria like *Rhizobium* and AMF. AMF is develops symbiotic association with plant which helps in uptake of fixed N (by bacteria) from soil and also improves nodulation initiated by rhizobia [49].

In maize, AMF then named *G. intraradices* was inoculated and found to observe N uptake more when ^{15}N tracer (inorganic N and organic N) was supplied [50]. Another report demonstrated, *G. mosseae* inoculated in wheat crop helps in acquisition of mineral N [51]. In a report, medicinal important plant neem (*Azadirachta indica* A. Juss) were co-inoculated with P-solubilizing, asymbiotic N-fixing bacteria (*Azospirillum brasilense*), along with AMF (*G. intraradices*). After the 60 and 120 days, the results emphasize that there were significant increase in the P, N, K uptake, and root collar diameter and plant biomass [52]. In a similar report, *Zea mays* was co-inoculated with N-fixer, P solubilizer, K solubilizer, and AMF *G. mosseae* and observed the increase in plant biomass and higher assimilation of N, P, and K mineral [53].

Another combination of AMF (*G. mosseae* and *G. intraradices*) and N-fixer (*Rhizobium leguminosarum*) bacteria was inoculated in pea. The combination of *G. mosseae* and *R. leguminosarum* efficiency was higher than *R. leguminosarum* and *G. intraradices.* The efficient combination also increases the higher N and P assimilation [54]. In a similar report combination of *G. mosseae, G. fasciculatum,* and *R. leguminosarum* was tested on common bean and observed total P and N content in plant [55]. In different study, red pepper (*C. annuum* L.) was grown with inoculating AMF and bacteria methylotrophic bacteria *Methylobacterium oryzae* as a biofertilizer and enhancement of N uptake and its content in plant [56]. Erman *et al*. [57] investigated co-inoculation of *Mesorhizobium ciceri* and *G. intraradices* on chickpea (C*icer arietinum* L.) under rain-fed conditions enhances nodulation of *Rhizobium* and N content in plant. In a similar report, pigeon pea was inoculation with *G. fasciculatum* and *Rhizobium* and found the chlorophyll, P and N content enhancement [58]. AMF, *R. irregularis* was also found to enhance N uptake according to a report by Pérez-Tienda *et al*. [59].

In a different report, maize grown during wheat straw decomposition and it was inoculated with combination of *G. intraradices* and an earthworm species named *Aporrectodea trapezoids.* After inoculation, it was observed earthworm enhanced 15N mineralization, whereas AMF enhances mobilization of N by 36.2% into the plant [60]. Another report investigated, the dual inoculation of *G. mosseae* and N fixing bacteria into woody invasive legume *Acacia cyclops* under nutrient limiting conditions. The results demonstrated that enhancement of

N and P uptake into the plant through extended roots of AMF [61]. In different studies, *Stevia rebaudiana*, a unique medicinal plant was inoculated with both plant growth promoting rhizobacteria (*Azotobacter chroococcum*, *Bacillus polymixa,* and *Pseudomonas putida*) and AMF (*G. intraradices*).

The results showed NPK content and other growth parameters in plant was higher with the combination of *G. intraradices* and *A. chroococum*, followed by *G. intraradices* and *B. polymixa* combination and *A. chroococum* and *P. putida* combination [62]. In a similar report, *Miscanthus sacchariflorus* growing on nutrient deficient river bank soil was inoculated with AM, *G. margarita* and observed increased plant biomass, chlorophyll, nutrient content (N, P, K, Mg, Fe, Cu, and Zn) [63]. Another report combination of earthworm (*Eisenia fetida*) and AMF (*Rhizophagus intraradices*) has been used in maize grown in soil contaminated with oxytetracycline pollutant. The result showed the enhancement of N content in plant [64].

4.2. Alleviation of Environmental Stresses

Plants are often exposed to combination of stresses like abiotic and biotic that adversely affects their growth, development and yield [65]. The stress caused by the attack of plant pathogens such as bacteria, fungi, nematodes, oomycetes, and harbivores are included in biotic stresses. On the other hand, the abiotic stress included drought, radiation, floods, heavy metals, and temperature extremes (low and high temperatures) [66]. Alleviation of environmental stresses is one of the needs to increase the plant productivity and AMF can be an alternative of method to overcome this problem.

4.2.1. Biotic stress

Functioning of plants in the complex environment is considered as holobionts that functions in genetic, evolutionary and physiological units with their associated biota [67]. The biota (macrobiota and microbiota) can be beneficial, detrimental or neutral for the plant fitness. The biota that are detrimental to plant can be result in the damaging the crop, which can reduce their productivity. AMF also have an ability to reduce the extremity of diseases caused by root pathogenic fungi, bacteria and nematodes [68]. Probability exists that AMF appear to decrease plant susceptibility to disease, or increase tolerance against the attack of root pathogens. In the mycorrhizosphere, AMF had antagonistic function to soil borne disease pathogen. It could suppress the growth of pathogen and increase the resistance or tolerance of mycorrhizal plants to soil borne diseases [69]. AM fungus could suppress the growth of pathogen and promote the growth of beneficial microbe because of interactions among microbial community. AMF may be used as biocontrol fungi with other antagonism microbe.

A number of postulates have been put forth regarding the defiance in mycorrhizal plants. These are competition, changed microbial flora in rhizosphere; they improve the plant nutrient status, induced resistance or systemic resistance in plant. Local defense response or systemic defense response occurs after colonization by AM fungus, phenolic compounds assemble in plants. In forthcoming works, AM fungus can be utilized as a new biocontrol method to control soil borne disease in agriculture. AM fungus having significant role in the bio control of plant disease and also in the chemo-ecological study as reported in last couple of years. More than two decades back, a report was published that concluded, use of *Trichoderma harzianum* and *G. intraradices* in combination and individually have reduced the incidence and severity of disease, Fusarium crown and root rot of tomato pathogens caused by *Fusarium oxysporum* f. sp. *radicis-lycopersici* [70]. Another study came year later also documented AMF *G. fasciculatum* have reduced root necrosis caused by *Phytophthora fragariae* in strawberry cultivars Cambridge Favourite and Elsanta up to 60–30% [71].

Another report have concluded, the use of *G. mosseae* helps in the biocontrol of root rot pathogen *Fusarium solani* of common bean (*Phaseolus vulgaris*) [72]. In 1998, a report came to a conclusion that inoculation of AMF; *G. intraradices* control the disease severity of root rot (*Aphanomyces euteiches*) of pea (*Pisum sativum*) [73]. In similar study, root rots pathogens of pea, *A. euteiches* was controlled using AM fungi, *G. mosseae* [74]. Another study have showed that AMF, *G. mosseae* were significantly controlling soil-borne *Phytophthora parasitica* of tomato plant [75]. In a report, out of six AM fungi, *Glomus aggregatum*, *Glomus clarum*, *G. etunicatum*, *G. intraradices*, *G. mosseae* and *Glomus versiforme*, *G. mosseae* were found to be significant controller of apple pathogen *Pratylenchus penetrans* [76]. In different study, AMF (*G. etunicatum* and *G. intraradices*) was evaluated against potato pathogen *Rhizoctonia solani.* The result showed AMF, *G. etunicatum* and *G. intraradices* reduced its pathogen mortality rate by 77% and 26%, respectively [77].

In another report combination of AMF, *Glomus coronatum* and non-pathogenic *F. oxysporum* were reported to control *Meloidogyne incognita* (nematode) on tomato [78]. Another investigation carried to control the pea root-rot pathogen *A. euteiches* using different AMF including *G. intraradices* and *G. claroideum.* Results showed that plant inoculated with both AMF have reduced disease incidence and plant with *G. intraradices* were more pronounced then *G. claroideum* [79]. In another study, rhizosphere microflora, AMF (*G. intraradices*), and rhizobacteria (*Pseudomonas fluorescens, P. putida*, and *Enterobacter cloacae*) were inoculated as combination and singly. The inoculation resulted in disease severity reduction by 58.6 and 8.6%, respectively [80]. Co-inoculation of AMF, *G. mosseae* and plant growth promoting fungi (PGPF), *Phoma* sp. and *Penicillium simplicissimum,* respectively, in cucumber plant was evaluated against plant cucumber plant disease anthracnose. Results showed that combination of AMF and *Phoma* sp. are more effective biocontrol agent then the bioformulations of AMF and *P. simplicissimum* [81,82].

Complex of *G. intraradices, Paenibacillus polymyxa* and *P. putida* were also reported for reducing galling, and multiplication root-rot disease causal nematode, *M. incognita* and *Macrophomina phaseolina*, along with this chlorophyll, N, P, and K content was also enhanced [83]. In similar report, root-knot nematode *M. incognita* was also reported to be suppressed by the combination of *G. intraradices* and *Rhizobium etli* when tested on tomato plant [84]. Another study concluded that utilization of *Ulocladium atrum* and *G. mosseae* in combination against gray molds causal organism, *Botrytis cinerea* reduced the disease incidence in pot roses over control [85]. Similarly, co-inoculation of AMF, *Glomus hoi*, *G. fasciculatum* and bacteria, *R. leguminosarum*, were efficiently control the disease *Fusarium* wilt of chickpea [86]. In a study, inoculation of AMF, *G. mosseae* and PGPF, *Fusarium equiseti* in cucumber seedlings affected with diseases like anthracnose and damping-off pathogens *Colletotrichum orbiculare* and *R. solani*, respectively was studied. The results showed that co-inoculation of AMF and PGPF efficiently increased percent of protection of disease anthracnose then damping-off [87].

In 2012, another study has concluded that AMF, *G. mosseae* induced resistance against, nematode *M. incognita* in plant [88]. Combination of AMF, *Glomus clarum* and fungi, *T. harzianum* were also reported as biocontrol agent of southern stem rot causal organism *Sclerotium rolfsii* in Jerusalem artichoke [89]. Moreover, AMF, *G. mosseae* was also reported for the depression of root hemiparasitic *Pedicularis kansuensis* of *Elymus nutans* [90]. In another report, combination of *G. intraradices*, *G. clarum* and *Pseudomonas aeruginosa* were reported for reducing disease development of disease basal stem rot in oil palm [91]. Microbial consortia of *T. harzianum* and *G. mosseae* were also reported as biocontrol agent of tobacco bacterial wilt causal organism *Ralstonia solanacearum* [92]. In another report, co-inoculation of *R. irregularis* and root-knot nematode, *M. incognita* in tomato resulted in the reduction of root-knot nematodes [93].

Another study concluded that both AMFs, *G. clarum* and *Glomus deserticole* can used as biocontrol agent against ear rot causal organism *Fusarium verticillioides* of *Z. mays* L. [94]. Combination and individual inoculation of AMF, *Funneliformis geosporum* and endophytic fungi, *Epicoccum nigrum* in potato plant were significantly reducing the disease potato blackleg caused by bacterial species *Pectobacterium carotovora.* The results also concluded that combination of AMF and fungal endophyte is effective for suppressing this particular disease pathogen then individual inoculation [95]. Another study has investigated that out of AMF *F. mosseae*, *R. irregularis*, *Claroideoglomus claroideum, F, mosseae* fully counteracted against pathogen *Pythium ultimum* causing root rot in *Cucumis sativus*, followed by *R. irregularis* [96].

4.2.2. Abiotic stress

Abiotic stress causes damage not only to growth but also affects the productivity of plants. Adverse changes in climate and some of the malpractices as such excessive use of pesticides and fertilizers have aggravated the effects of abiotic stress on crop productivity and have also degraded our ecosystems. In view of the above, we need to adopt some of the environment friendly management techniques such as AMF to increase the crop productivity. Furthermore, it has been seen that AMF provides tolerance to host plants against most of the stressful situations such as heat, salinity, drought, metals, and extreme temperature.

4.2.2.1. Drought stress

Drought, the most serious abiotic stress provides detrimental effects on plant growth by affecting enzyme activity, nutrient assimilation and ion uptake [97,98]. The desertification can be caused by several factors like irregular rainfall distribution, and lack of rainfall capacity [99]. To overcome the stress plant gets activates and change the biochemical, nutritional, hormonal and physiological mechanisms to mitigate the detrimental effect. Symbiosis of AMF with plant growing in drought affected area can make the host more tolerant to stress [100]. Reports are also available regarding AMF enhancing plant tolerance to drought, which can occur most likely due to large volume of soil explored by roots and the extra-radical hyphae of fungi [101]. In 2001, a report was published which concluded that double inoculation of bacteria both wild and genetically modified *Sinorhizobium meliloti* and AMFs, *G. deserticole* and *G. intraradices* enhanced the drought tolerance in three different species of *Medicago*, *Medicago nolana*, *Medicago rigidula*, and *Medicago rotata*. Combination of genetically modified bacteria and AMFs showed much less detrimental effects of drought on plant [102].

In the following year, another report was published that also concluded that utilization of AMF *G. clarum* on tomato during drought condition alleviates stress by elongating the roots and enhancing water uptake [103]. In another report, lettuce plant was water stressed, and it was inoculated with different combination of bacterium, *Bacillus* sp. with AMF, *G. mosseae* and *G. intraradices.* The results showed that single inoculation of AMF has not much enhanced the stress tolerance, whereas combination of with bacteria increased root colonization and length especially in plant inoculated with *Bacillus* sp. and *G. intraradices.* The combination of bacterium and *G. intraradices* also enhanced water uptake capacity and lowered the water stress [104]. In wheat crop, AMF, *G. mosseae* and *G. etunicatum* was inoculated and plants were water stressed. The inoculation of both AMF in wheat reduced drought stress effects mainly in plant with *G. etunicatum* infection [105]. In different study, AMF *G. intraradices* was inoculated in rose (*Rosa hybrida* L.) plants subjected to drought regimens. Results of this study indicate that AMF enhanced tolerance to the stress as proline content in plants was high [106].

In 2006, also, study documented that utilization of AMF in plant increase drought tolerance when tested on soybean. In this study, dual inoculation of AMF, *G. etunicatum* and *Bradyrhizobium japonicum* was done in crop, soybean that results in higher relative water content of leafs; therefore, it was suggested this strains alleviate the water limiting stress in plant [107]. Another study have concluded that inoculation of *Glomus* species, *G. intraradices* and *G. mosseae* in lavender plant induce tolerance in plant by increasing root growth and decreasing the antioxidant compounds. According to this report, plant containing *G. mosseae* showed less detrimental effects of drought stress on plant then *G. intraradices* containing plant [108]. In a study, three species of *Glomus* (*G. mosseae*, *G. versiforme* and *Glomus diaphanum*) was inoculated in citrus (*Poncirus trifoliata*) seedlings. The results suggested that inoculation of *G. mosseae* was more effective to mitigate the drought stress followed by *G. versiforme* and *G. diaphanum.* The AMF were affecting the soil moisture retention through glomalin's effect that enhanced plant tolerance [109].

In another study, autochthonous AMFs, *G. coronatum*, *Glomus constrictum* or *G. claroideum* and effective drought tolerant bacteria *Bacillus megaterium* together was reported for enhancing the drought tolerance in plant [110]. Under glasshouse conditions, an experiment was conducted on *Casuarina equisetifolia* seedlings, in which different of *Glomus* species was inoculated and seedlings were water stressed. The results showed that plant inoculated with *G. caledonium* have more survival rate (36.6%) then, *G. versiforme* (23.3%) and *G. caledonium* (16.6%). *G. caledonium* also reported for enhancing plant biomass and drought tolerance in *C. equisetifolia* seedlings [111]. In similar study, *G. constrictum* was also reported for alleviating drought stress in marigold (*Tagetes erecta*) plant. This inoculation of this AMF also enhances photosynthetic pigments, that is, carotene and chlorophyll a and b), P content and flower quality [112]. Similarly, *G. deserticole* when inoculated in flower plant known as snapdragon (*Antirrhinum majus*) potted with water stress conditions. The result indicated that this AMF inoculation imposed significant increment of nutrients such as P, N, K, Mg, and Ca and chlorophyll content. This AM fungi also enhanced drought tolerance and mitigate stress in snapdragon ornamental plant [113].

In a report, two AMF, *G. versiforme* and *Paraglomus occultum* was tested for alleviating drought stress in *Plukenetia volubilis*. The inoculation suggested that plant with *G. versiforme* infestation were more tolerant to this stress then *P. occultum.* Co-inoculation of both AMF showed greatest drought tolerance and development of plant [114]. Under greenhouse conditions, *Cyclobalanopsis glauca* seedlings were subjected to water limiting conditions. In the plant *G. mosseae* and *G. intraradice* was inoculated and result showed greater activity of superoxide dismutase (SOD), and peroxidase (POD), sugar content and lower proline content. Inoculation of AMF also improved nutrient uptake of P and K along with drought tolerance [115]. In maize plant, an AMF, *R. intraradices* was inoculated and result found to show improvement in drought resistance in plants. The inoculation of AMF also improves plant biomass, nutrient uptake (C, N and P) and plant growth [116]. Another report also concluded, indigenous

AMFs, *Rhizophagus manihotis*, *R. aggregatus*, *R. fasciculatus*, and *Acaulospora* sp. combined inoculation improves drought tolerance in plant *Cupressus atlantica* G [117].

In different report, combination of AMF and an endophyte, *R. intraradices* and *Piriformospora indica*, respectively, was inoculated in finger millet growing under water-fed conditions. The inoculation showed improvement in seedling growth under drought stress [118]. In 2018, a report was published that concluded inoculation of all the AMFs *G. etunicatum*, *Glomus microaggregatum*, *G. intraradices, G. claroideum, G. mosseae, and Glomus geosporum* in olive trees (*Olea europaea*) resulted in mitigation of drought stress as compare to non-mycorrhizal plant [119]. In the following year, different three AMF, known as *F. mosseae*, *Rhizo G. intraradices*, and *Diversispora versiformis* were inoculated in mixture on *Zenia insignis* seedling growing under drought stress. The result showed that AMF inoculation enhances plant biomass, P content, superoxide and catalase (CAT) activity. AMF also alleviates water limiting stress and restore degraded ecosystem in desertified regions [120]. Another study reported, *F. mosseae* alleviates drought stress in *Nicotiana tabacum* seedlings and helps in nutrient uptake [121]. Similarly, *F. mosseae* was also reported in another study to alleviate drought stress in citrus plant [122].

4.2.2.2. Salinity stress

Soil salinization is another serious abiotic stress that adversely affects the growth and production of plant. In a report by Wang *et al*. [123], it has estimated that by middle of 21st century up to 50% of land will be degrades as salt alters the basic texture of soil that leads to reduction of soil aeration, water conductance and soil porosity. Increasing salinity in soil also majorly affects plant metabolism processes, osmotic balance, ability to absorb water and nutrients hydraulic conductivity, stomatla conductance, photosynthetic rate and intercellular carbon dioxide concentration [124]. Since 1980s, AMF was being recognised for alleviating salt stress in plants and now considered as one of the excellent choice to alleviate the salt stress [125-127]. Mechanisms like uptake of nutrients, especially P [128] and water [129], keeping ionic balance by improving stimulating selective uptake [130], synthesis and effectiveness of some enzymes [131], increasing the plant capability to produce and accumulate proline in tissue [132] and adjusting osmotic status [133] are different mechanisms of salt stress alleviation in plants by AMF.

Various AMF species were being reported for ameliorating the salinity stress in plants. In 1996, a report concluded, inoculation of two different *Glomus* species (*G. mosseae* and *G. fasciculatum*) in lettuce plant enhanced salt resistivity. The results showed that inoculation of *G. fasciculatum* enhanced biomass of plant more; whereas *G. mosseae* inoculated plant have more proline production and accumulation. This study has also concluded that salinity alleviation was due to physiological process like transpiration, stomatal conductance, rather than nutrient uptake [134]. In another study, AMF (*G. mosseae*) and N fixing bacteria (*Rhizobium meliloti*) were co-inoculated in plant *Medicago sativa* with saline water having four concentrations of three salts (sodium chloride, Ca chloride and Mg chloride). The results showed that nodulation formation has been enhanced along with N and P concentration. This study also concluded that inoculation of mycorrhiza protected plant from highest salt level (43.5 dS m^{-1}) and decreases Ca and Mg level [135]. Two species of *Glomus* (*Glomus* sp. and *G. deserticole*) was tested on lettuce plant grown in soil with three salt concentrations (0.25, 0.50 and 0.75 g NaCl kg^{-1}) and result concluded that both the AMF protected host plant from salinity especially *G. deserticole* inoculated plants. *G. deserticole* inoculated plants also showed higher nutrient uptake and content and biomass than *Glomus* sp. inoculated plant and control [129].

G. mosseae was also reported in another report for enhancing salt tolerance in plant *Lycopersicon esculentum* (tomato) [124]. Similarly, *G. mosseae* was inoculated in maize plant growing in salt amended soil, and the result showed that AMF enhances resistivity to salt-induced osmatic stress, along with soluble sugar accumulation. Furthermore, chlorophyll, dry weight of plants and electrolyte concentration in roots was also enhanced in host plant with the inoculation of AMF [136]. In another report, *Acacia auriculiformis* plant growing under different salinity level (0.3, 0.5, 1.0 Sm^{-1}) was inoculated with two different AMF fungi *G. fasciculatum* and *G. macrocarpum.* The study concluded that both AM fungi protected host plant against salinity, and co-inoculation of both AMF showed higher resistivity along with higher roots and shoot weight, nutrient uptake and electrical conductivity [137]. In another study, two species of *G. mosseae* from saline and non-saline soil was isolated, and it inoculated in cotton growing in four levels of sodium chloride concentration. The results showed that, *G. mosseae* from saline shows significant improvement of plant under 3 g kg^{-1} Nacl concentration and increase P concentration at 0 and 1 g kg^{-1} NaCl. On the other hand *G. mosseae* from non-saline soil showed no significant enhancement in salt resistivity at any salt level, but increases the biomass and P concentration in cotton [138].

In greenhouse, combination of a bacterium (*Bradyrhizobium*), an arbuscular mycorrhizal (*G. intraradices*) and an ectomycorrhizal fungus (*Pisolithus albus*) was inoculated in two different species of *Acacia* (*A. auriculiformis* and *A. mangium*) grown in soil containing saline nutrient solution (0, 50 and 100 mM NaCl). The result concluded that host plant have higher proline accumulation and have better tolerance to salt stress in both the plant species [139]. In another report, horticulture crop, tomato growing under salt condition was inoculated with AMF, *G. mosseae* and it was found that nutrient content of P, K, Zn, Cu and Fe were higher and Na concentration was lower in AM containing plant. Furthermore, AMF inoculation in plants also increases yield and alleviate the deleterious effects of salinity [140]. In similar report, *G. mosseae* was inoculated in tomato crop grown under salt and salt-less condition. This treatment resulted that AMF enhanced salt tolerance as SOD, ascorbate POD (APX), POD and CAT activity was suppressed [141]. In greenhouse experiment, zucchini plant was grown at low and high P concentration and they were salt stressed. The plants grown host plant was inoculated with *G. intraradices* and the results have showed that zucchini plant under saline and high P concentration were more resistant to salt stress as compare to low P concentrated plant and control. Inoculation of AMF also improves the water uptake and nutritional (K) status in host plant and lowers Na accumulation [142].

In another report, pepper grown at high salinity concentration in glasshouse conditions and it was inoculated with AMF, *G. clarum*. The results showed that inoculation of mycorrhizal colonization resorted leaf nutrients level and also reduced salt stress [143]. In pot experiment, citrus (*Citrus tangerine*) were inoculated with AMFs *G. mosseae* and *P. occultum* and when seedlings were 85 days old they were stressed with sodium chloride salt. The colonization of *P. occultum* in citrus showed that more tolerance to salt stress as compare to plant inoculated with *G. mosseae.* Along with tolerance plants were also taller, stem diameter, plant biomass, photosynthetic and transpiration rate and stomatal conductance was also higher in case of *P. occultum.* On the other hand plant infected with *G. mosseae* was having higher root volume. Furthermore, concentration of Na^+ was decreased and concentration of K^+ and Mg^{2+} were increased in both the treatments [144]. In similar report, G. mosseae was inoculated in salt stressed tomato plant and treatment resulted in enhancement of activities like SOD, CAT, POD and APX in host leaves. In addition, AMF inoculation also reduced salinity induced oxidative stress [145].

Under salinization, an experiment was designed, where wheat plant was inoculated with three different AMF namely, *G. mosseae*, *G. deserticole* and *Gigaspora gergaria*. The results showed that under saline conditions AMF significantly enhanced growth response, nutrient content (P, N, K and Mg), acid and alkaline phosphatase, proline and soluble protein content in the host plant. In addition, the results also showed lower Na concentration and salt stress was alleviated in mycorrhizal infected wheat plant [146]. In another study, *G. intraradices* isolated from saline and desertification affected soil was tested *in vitro* on salt stressed maize plant. It was concluded that AMF isolate stimulates plant growth and increases salt tolerance in maize plant by expressing *GintBIP, Gint14-3-3* and *GintAQP1* genes and lowering the expression of *GintSOD1* gene [147]. AMF (*G. versiforme*) effect was tested in apple seedlings under saline conditions and this study concluded that roots were longer as well as percent of salinity stress were reduced and Na^{+} and Cl^{-} concentration was lowered as compare to control [148]. In another study, greenhouse experiment was conducted, in which saline soil AMF inoculums, *F. mossseae* and *R. irregularis* were tested individually and in dual mix on *Cajanus cajan* under salt stress. The results showed that *R. irregularis* individually reduce the negative effect of salinization and enhances plant biomass, yield, nutrient uptake and membrane stability as compare to *F. mosseae.* On the other hand combination of both the inoculum also enhanced salt tolerance in plants [149].

In another report, rice plant selected as a host which is known as salt-sensitive crop. The host plant was grown and subjected to toxicity of sodium ions and it was inoculated with AMF inoculum identified as *Claroideo G. etunicatum*. This treatment in salt stress rice resulted in lowering the negative effect of salinity. The study also found that genes like *OsNHX3, OsSOS1, OsHKT2;1,* and *OsHKT1;5* were involved in the upregulation of AMF plant in saline soil [150]. *Glomus desrticola* in another report were inoculated in sweet basil (*Ocimum basilicum* L.), and results were revealed, the significant enhancement of chlorophyll content, water uptake under saline conditions. Moreover, photosynthetic efficiency and gas exchange were higher as compare to control [126]. Salinity mitigation was also reported by the co-inoculation of AMFs identified as *Claroideo G. etunicatum*, *R. intraradices* and *F. mosseae* in cucumber (*C. sativus* L.) plants. Combination of AMF also increases the accumulation of proline and phenols, jasmonic acid, salicylic acid, and elements such as K, Ca, Mg, Z, Fe, Mn, and Cu and also decline the Na^{+} concentration [151].

AMF species such as *Glomus* sp., *Sclerocystis* sp., and *Acaulospora* sp. were also reported for enhancing the salt stress tolerance, photosynthetic pigment, and protein content. Moreover, antioxidant enzymes such as SOD, CAT, POD, and APX were enhanced in the plant date palm (*Phoenix dactylifera* L.) [152]. In another report, *F. mosseae* was inoculated in plant *Zelkova serrata* grown in saline soil. After inoculation, it was examined that AMF increases CAT and reduced glutathione content. Moreover, AMF also enhanced the plant growth, vitality of roots, photosynthetic pigments, net biomass of the seedlings and helps in mitigating the salt stress in plants [153]. In a similar report, *F. mosseae* were inoculated in salt treated plant *Suaeda salsa*. The results showed promoted growth of host plant and nutrient content of Mg and Ca were also enhanced. Further the inoculum reduced the ration of K^{+}/Na^{+} ratio and the expression of *SsNHX1* and *SsSOS1* in shoot and roots, respectively downregulated at 400 mM NaCl. At 100mM NaCl, *SsSOS1* in shoots were upregulated and expression of *SsSOS1* and *SsNHX1* in roots was downregulated. This study also suggested that this AMF can be play significant role phytoremediation of salinized ecosystems [154].

4.2.2.3. Extreme temperature stress

Extreme temperature weather high or low is one of the environmental perturbations that encounter the plant health. Global climate change makes this abiotic stress more frequent in the world. Plant exposed to such stress leads to many physiological, biochemical functional and changes in the plants. Temperature injuries may damages membrane structure, lipid composition, cellular leakage of electrolytes and amino acid, peroxidation of membrane lipids in plants. Moreover, protein aggregation and inactivation, intercellular Ca ions were redistributed, inactivation of chloroplast and mitochondria enzymes, toxic compound production and reactive oxygen species (ROS) production are also different types of injuries that harm plant because of temperature [155,156]. To overcome the stress and harm, plants used to adapt and induce modification in biochemical and physiology such as cytosolic Ca ion accumulation, photosynthesis acclimation, ROS scavenger system activation, and accumulation of compatible solutes like proline and sugars and induction of related genes expression [155,157]. Several reports have confirmed that, AMF symbiosis increases their tolerability against extreme temperature stress by supporting such modification in plant [158].

In a study, maize was sown in pots and it was exposed to five different temperatures (5°C, 15°C, 25°C, 35°C and 40°C) for 1 week. AMF (*G. etunicatum*) was also inoculated and it was concluded that content of soluble protein and proteins were higher in roots. Moreover, SOD, CAT, POD, was also increased in both leaves and roots with the inoculation of *G. etunicatum.* This study also concluded that AMF were capable of alleviating temperature stress and their damage in maize plant [159]. Another study by Latef, Chaoxing [160], concluded that AMF, *G. mosseae* inoculation is tomato (*L. esculentum*) grown in pot under low temperature stress (8°C for 1 week) enhances the sugars, proline and photosynthetic pigment in the leaves. AMF also enhances the SOD, CAT, POD, and APX in leaves, and it was also indicated that fungi alleviates the damage caused by low temperature. In another study, combination of *G. versiforme* and paclobutrazol was examined on the low temperature stressed teak seedlings. The results showed that the combination significantly increases leaf chlorophyll content, soluble protein content, SOD and POD activity and also alleviates the damage caused by cold temperature in teak seedlings [161].

G. fasciculatum was also tested positive for alleviating heat stress when inoculated in plant, cyclamen (*Cyclamen persicum* Mill.) grown under heated soil (30°C). The study concluded that AMF plant was having higher antioxidant enzymes activity such as SOD and APX. Furthermore, content of ascorbic and polyphenols were enhanced and ultimately alleviates heat stress damage [162]. In different study, low temperature stressed cucumber plant were inoculated with *F. mosseae* AMF. The investigation concluded that plants were having more fresh and dry mass and NADPH oxidase and H_2O_2 accumulation was lowered by 42.44% (as compare to control). Moreover, activities of P-type H^{+}-ATPase, P-$Ca2^{+}$-ATPase, V-type H^{+}-ATPase, total ATPase activity, ATP concentration and plasma membrane protein content were remarkably increased in the host plant roots under low temperature. The study also concluded NADPH oxidase and ATPase might play an important role in AMF mediated tolerance to low temperature stress [163].

In another investigation, cold (4±1°C) stressed plant *Jatropha curcas* was inoculated with *R. intraradices.* The treatment resulted in increment of enzyme activity of CAT and concluded that it also protect the plant from the damage of cold stress [164]. Chilling stress damage in plant, tomato was reported to be alleviated by *F. mosseae*. The inoculation of culture reduced remarkable level of malondialdehyde (MAD), H_2O_2 and O_2^- and increases precipitates of Ca in apoplast and vacuole of root cells. Furthermore, inoculum of AMF also induces antioxidant enzymes and transcripts of related genes [165]. In investigation, plants, *Vaccinium ashei* and *Vaccinium corymbosum*, exposed to low temperature (10°C) were inoculated with *G. mosseae.* The results showed that inoculation of culture enhances the activities of SOD, APX, guaiacol POD, ascorbate, and glutathione. Furthermore, MAD, H_2O_2, and O_2^- were declined with AMF inoculation and resistivity against low temperature stress was enhanced [166].

In an investigation, mixed starter culture of AMFs, *R. intraradices*, *F. mosseae,* and *F. geosporum* were inoculated maize plant that were exposed to high temperature range of 44°C. The investigation concluded that AMFs inoculation increased the net photosynthetic rate in the host plant along with that cob number and Cl content of maize also increased. Combination of AMF in maize also alleviates the damage caused by the high temperature stress [167]. On the other hand, combination of *G. versiforme* and *R. irregularis* in barley grown in the freezing conditions (58C day, 38C night) alleviates the damage the caused by the freezing conditions. It was concluded that inoculation increased photosynthesis, K uptake, osmotic and water homeostasis in maize plant [168]. In another report, *G. intraradices* was reported for alleviating chilling stress of watermelon. It the inoculum was reported for decreasing the H_2O_2 and MDA accumulation in the plant [169]. Recently, *R. irregularis* was reported for alleviating cold stress in plants in maize plant. This AMF was also reported for enhancing the photosynthetic rate and metabolic process of the plant [170].

4.2.2.4. Heavy metals stress

Heavy metals accumulation in soil is a serious pollutant, which are caused by the anthropogenic sources like industries. HM like arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), Ni, mercury (Hg), Fe, lead (Pb), and Zn are some of the accumulated soil metals from which few are essential micronutrient for the plants responsible for regular life processes However, high level concentration of such metals can adversely affect the plant and becomes an abiotic stress [171]. In plants, high level of heavy metals exerts a negative effect on the biomass, growth and photosynthesis of plant [171]. Some heavy metals also decline the net stomatal conductance, cellular carbon dioxide concentration, transpiration rate, photochemical efficiency [172]. To the date, AMF roles have been recognized for alleviating stress caused by heavy metals [173]. In a study, AMF, *G. mosseae* was inoculated in *Populus alba* grown in Cu and Zn polluted soil under greenhouse conditions and the results concluded that AMF restores plant biomass and alleviates present metal stress [174].

Cu toxicity in pseudometallophyte *Oenothera picensis* alleviation was reported by the inoculation of Glomeromycotan fungi, *G. claroideum*. The inoculation of AMF resulted in the hike of SOD and APX antioxidant enzyme, glutathione reductase and CAT activities [82]. Similarly, NaCl and Cd stressed *Cajanus cajan*, grown under greenhouse conditions was inoculated with *G. mosseae*. The study concluded the decrease of negative effect of salt and Cd metal in plant. The AMF inoculation also improved the growth of plant by increasing the content of sugars, proteins, free amino acids, proline, and glycine betaine content [175]. In another report, sunflower grown in trace metal polluted soil (Cd, and Zn), was inoculated with two AMF isolates namely, *R. irregularis* and *F. mosseae*. The inoculation of *F. mosseae* resulted in alleviation of Cd and Zn stress more in comparison with *R. irregularis* [176].

Combination of *G. mosseae* and composted olive waste was inoculated in Cr and As stressed *Tetraclinis articulata* plant. Inoculation resulted in improved quality of soil, nutrient uptake (P) and Cr and As stress attenuation [177]. In another study, inoculation of *F. mosseae* and *R. intraradices* on a leguminous tress, *Robinia pseudoacacia* L. grown with Pb stress resulted in plant growth promotion and alleviation of Pb stress. Moreover, both AMF enhanced photosynthesis and antioxidant enzyme activities (SOD, APX, and glutathione POD) [178]. In another investigation, Marigold flower (*Calendula officinalis* L.) grown in pots and was stressed with Cd and Pb metals. The plant was inoculated with *F. mosseae* and resulted in lower level in Cd and Pb in plant. Further, AMF inoculated plant was recoreded higher β-carotene and lycopene content [179].

Similarly, inoculation of *F. mosseae* on pepper plants (*C. annuum* L.) stressed with Cu metals also resulted in the stress alleviation. The pepper plants inoculated with AMF has higher dry weight, leaf area, electrolyte leakage, photosynthetic, and transpiration rate [180]. In another study, maize plant was grown in heavy metal polluted soil and it was inoculated with AMF, *F. mosseae* and *Diversispora spurcum*. Both the AMF, alleviates plant stress but *F. mosseae* inoculation also enhanced chlorophyll, height, biomass and antioxidant activities (SOD, MDA, and CAT) [181]. In a report, combination of AMF namely, *G. intraradices, G. mosseae*, and *G. fasciculatum* was used in Cd stressed Russian Knapweed (*Acroptilon repens* L.) plant. The study concluded that AMF declined the negative effect of Cd, as lower concentration was found in the shoot [182]. *R. irregularis*, an AMF was also reported for alleviating the Cu stress in plant *Phragmites australis* [183]. In another study, *F. mosseae* was inoculated in Pb and Zn stressed soybean plant. The results showed, the plant was more tolerant to metal toxicity and overall productivity and growth of plants improves [184].

5. DEVELOPMENT OF AM FUNGI AS BIOFERTILIZERS

AMF, the one of the beneficial and plant growth promoter plays an important role in the sustainable agriculture. It has been reported for mobilizing different minerals mainly P and N and alleviating abiotic stress in plants. To use this organism in agriculture fields their development as biofertilizer is important [185]. There are several factors for the selection of potent strain of AMF for the development of biofertilizer. AMF is an organism that is not capable of living solely or as one species of host and lives in a combination that can vary with distinct endophytes. The potential AMF should have a high light tolerance which is required for rapid production of fungi. It should also have a capability of producing abundant roots quickly, present in majority of soils and large quantity of inoculum can be produced in less time [186]. Selected potent AMF strain can be mass produced by three well known systems that are widely used, that is, production system, substrate free production and *in-vitro* production system [187].

6. ISOLATION, CHARACTERIZATION OF AMF

Wet sieving method can be used for the collection of AMF spores, in which 50 g rhizospheric soil is decanted in 1–2 l of water and its suspension is sieved with fine mesh (500 μm and 250 μm are preferabaly) after the siol particles have settled down. The filtrate is sonicated firstly stronger and then weak. The separated spores (50–500 μm in diameter) can be recognized under dissecting microscope [188].

7. CONCLUSION AND FUTURE PROSPECT

Chemical fertilization has been used in agriculture over the past 50 years to increase the crop yield, which have created serious issues like pollution and degradation of environmental health. At present, environmentalist and researchers are spreading awareness regarding the environment health and dreamt of sustainable agriculture and environment. One of the sustainable alternatives to chemical fertilizers was found to be use of biofertilizer. Biofertilizers have now become an important input in agricultural fields and their demand is growing. Biofertilizer consisting vesicular AMF are also well know. On AMF tremendous work have been conducted that concluded that it have potencial application in mobilizing nutrients to plant and alleviating stresses such as drought, salinity, heavy metals, and temperature extremes by enhancing the root length. Moreover, it also helps in controlling the pest on the plants that enhances plant growth. Undoubtly, tremendous work has already been done across the globe in the field of mycorrhizal technology. There is also an urgent need to enhance further the regional collaboration so that benefits of technology advancements could reach those presently left behind.

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9. AUTHORS’ CONTRIBUTIONS

All authors made substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published; and agreed to be accountable for all aspects of the work. All the authors are eligible to be an author as per the International Committee of Medical Journal Editors (ICMJE) requirements/guidelines.

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11. CONFLICTS OF INTEREST

The authors report no financial or any other conflicts of interest in this work.

12. ETHICAL APPROVALS

This study does not involve experiments on animals or human subjects.

13. DATA AVAILABILITY

Not Applicable.

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