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Implications of abiotic stress tolerance in arbuscular mycorrhiza colonized plants: Importance in plant growth and regulation

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ABSTRACT

Arbuscular mycorrhizal fungi (AMF) are crucial for the growth and development of most terrestrial plants, enabling them to withstand abiotic stresses. Abiotic stress such as salinity, drought, extreme temperature, heavy metals, and carbon dioxide hampers plant growth. Abiotic stresses are being elevated because of abrupt climatic changes and agricultural malpractices such as excessive fertilizer and pesticide use, which is also hazardous for human consumption. To cope with the adverse effects, we need a reliable system that can monitor and control all these deleterious effects on plants, and AMF is one of the appropriate methods to create a sustainable platform for agriculture. Mycorrhizal symbionts grow together with the roots of higher plants, aiding them in the uptake of minerals and nutrients, which results in improved plant growth and yield even under stressed conditions. In return, these symbionts receive carbohydrates for the completion of their lifecycle. The role of AMF, as a bio-fertilizer, can strengthen the quality of crop plants, by elevating soil health and enhancing ecosystem stability. In this review, we will investigate how different abiotic stress factors can negatively affect plant growth, the role of AMF in controlling those stresses, its impact and effect on plant growth and yield, its use as a bio-fertilizer in agricultural fields, and its interaction with other organisms.

1. INTRODUCTION

Many abiotic stresses, such as salinity, drought, extreme temperatures, heavy metals, and excessive fertilizer and pesticide use, have contributed to soil degradation, and today, they pose a threat to agriculture, as they are responsible for most of the crop and yield losses globally [1]. Fortunately, several microorganisms, particularly bacteria and fungi, can counteract the negative effects of environmental stresses, thereby monitoring the plants' performance during stressful conditions [2].

One of them is AMF, a member of the subphylum Glomeromycota, which includes three classes (Glomeromycetes, Archaeosporomycetes, and Paraglomeromycetes) in the phylum Mucoromycota. So far, this subphylum has been classified into four orders and 25 genera, containing about 250 species [3]. Glomeromycota depends on plants for carbon substrate to survive. In return, the symbiont provides an abundance of minerals and nutrients to the host plants, such as nitrogen, phosphorus, and potassium through an intraradical network of hyphae and arbuscules, and the root apoplast interface. In addition, AMF improves the quality of the soil since fungal hyphae accelerate decomposition much earlier, thus improving soil quality [4].

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The AMF establishes symbiotic relationships with the roots of most of the terrestrial plants, including 80−90% of the vascular plants, and 90% of the agricultural plants [5], such as cereals, vegetables, and horticultural plants. The application of AMF has been found to increase plant growth and regulation by enhancing nutrient uptake and stress tolerance. Considering the research and development associated with AMF in agriculture, the present review aims to present an overview of the current knowledge on the relationship between AMF and host plants in regulation and development, improved nutrient uptake even under stress conditions, and the emergence of AMF as biofertilizers.

2. FEATURES OF AMF SYMBIOSIS

According to molecular data and fossil evidence, the symbiosis dates back to 400−450 million years ago [5] around the time land plants first appeared. Through the succession of biological processes, such links can result in a variety of beneficial effects in natural ecosystems. One of the examples of a mutualistic relationship is the symbiotic associations of mycorrhizal symbionts and the roots of higher terrestrial plants [Figure 1]. A hyphal network extends beneath the roots and enhances the uptake of nutrients and minerals by the host plants.

The mycelium of fungi colonizes the roots of a wide range of plants, even if they are from different species, producing a common mycorrhizal network (CMN). CMN is a critical component of the terrestrial ecosystem, affecting a wide range of plant communities,

Figure 1: An overview of some of the mycorrhizal functions that regulate plant growth and development during abiotic stress.

including invasive species [6], as well as the supply of nitrogen (N) and phosphorus (P) to plants through fungal symbionts [7]. It also increases the quality of the soil and its aggregation and allows host plants to grow even in the most stressed conditions.

AMF is considered a bio-inoculant, and scientists are continually promoting its usage as a leading bio-fertilizer for long-term agricultural production and development [8]. The soil protein Glomalin-related soil protein (GRSP) is thought to maintain the water content of the soil during abiotic stress [9], which then regulates the total water frequency between soil and plants, resulting in higher plant growth and development. AMF inoculation had an effect on other parameters related to growth, including relative water content (RWC), leaf water potential, stomatal conductivity, PSII efficiency, and carbon dioxide uptake [10].

Studies have shown that AMF affects plant growth and physiological elements in a wide range of species, including *Solanum Lycopersicum* [11], *Sorghum bicolor* [12], *Cucurbita maxima* [13], and *Withania somnifera* [14]. It also contributes to 20% of total plant uptake [15], emphasizing the role of symbiosis in maintaining adequate water levels in the host plant. The inoculation of the fungus increases plant growth as well as the contents of various phytochemicals, such as flavonoids, tannins, phenols, and sugars.

3. DIFFERENT ROLES OF AMF

3.1. An AMF-based Bio-fertilizer

As bio-fertilizers, these materials contain a mixture of natural ingredients, called microorganisms, used to improve the fertility and quality of the soil. Besides being very useful for improving the soil's health, these fertilizers also help plants to grow and develop [16]. Numerous studies have shown the benefits of AMF on soil health and crop productivity. Thus, AMF is thought of as a biological tool that can be used to fight the problems regarding crop yield and productivity, hence, is a good substitute for inorganic fertilizers in the near future, fostering organic farming and sustainable agriculture [17]. Mycorrhizal symbionts are effective at reducing the quantitative use of chemical fertilizers, especially phosphorus.

Continuous use of inorganic fertilizers, pesticides, and fungicides has drastically caused havoc to the soil environment, leading to the infertility of soil and also associated with the risk of human health and life [18]. AMF is thought to reduce inorganic chemical use up to 50% for agricultural production; however, the reduced use depends on the species of plants and the stress regime.

3.2. AMF in Enhancing Mineral Nutrition

AMF transfers nutrients to plants, like inorganic carbon as sugars and lipids [19]. It is widely believed that AMF colonization stimulates plant nutrition uptake [Figure 2]. Increased biomass accumulation and photosynthate production are evident by inoculating AMF with host species, as it increases the concentration of various micronutrients and macronutrients [20]. Additionally, to macronutrients, the AMF association is reported to increase the phytoavailability of micronutrients copper and zinc. To obtain nutrients from the roots of host plants, AMF forms symbiotic relationships with them, providing minerals such as phosphorus, potassium, calcium, nitrogen, zinc,

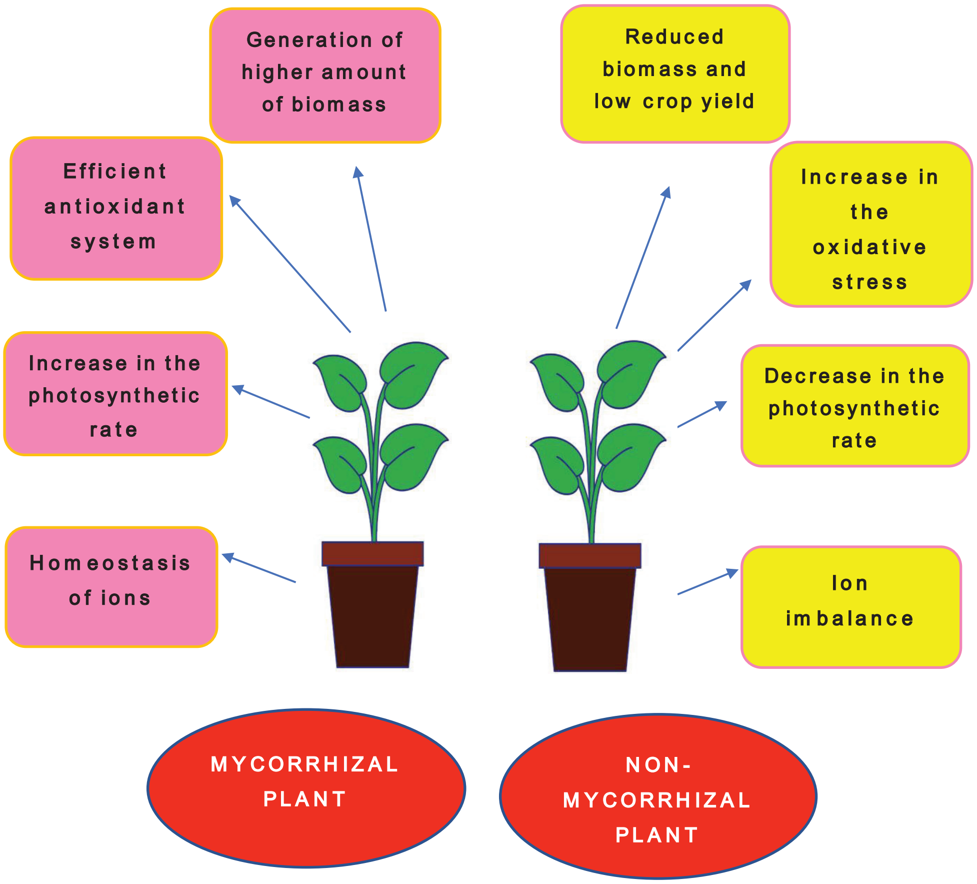

Figure 2: A diagrammatic representation contrasting the differences of the plants inoculated with mycorrhizal and non-mycorrhizal association.

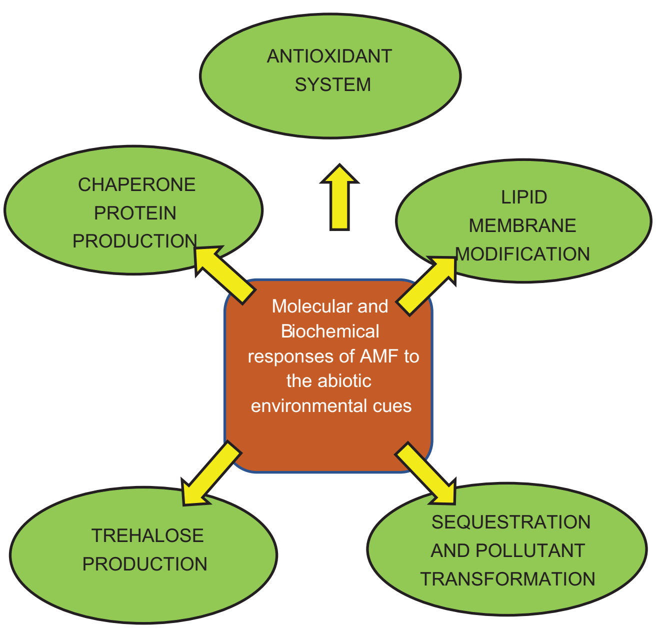

Figure 3: Summarized details have been provided in the diagram below, which shows list of various Molecular and Biochemical responses shown by AMF inoculated host plants, under various abiotic stresses.

and sulfur. AMF have structures called arbuscules, which aid in the exchange of inorganic minerals, carbon compounds, and phosphorous compounds, enhancing plant growth [21]. Thus, they improve the concentration of phosphorous in both root and shoot systems. Nitrogen is the major source of nutrients required by plants for growth and development, AMF inoculation helps in the absorption and transfer of nitrogen to nearby plants [21]. There is wide acceptance of the fact that decomposed and dead matter can supply fungi with a considerable amount of nitrogen which, in the future, can improve their ability to grow and live. Nitrogen is effectively trapped by chlorophyll molecules in plants colonized by AMF, which results in higher chlorophyll content [22]. AMF mediated improvement in N content of host plants have several pieces of evidence in the literature.

3.3. AMF in Increasing the Plant Yield with Inoculation

The nutrient status of the crops is not only improved by beneficial microorganisms, but they also contribute to the enhancement of the crop quality and yield. AMF also affects the production of carotenoids and other volatile compounds, associated with an enhancement in the dietary quality of crops [23]. Increased content of Vitamin C, other organic acids, sugars, minerals, and flavonoids occurs due to the AMF colonization resulting in the improved quality of citrus fruits [24]. Accumulation of carotenoids, anthocyanin, tocopherol, phenolic compounds, chlorophyll, and various other mineral nutrients [Figure 3] is enhanced by mycorrhizal symbiosis [25]. Large-scale field production of maize, yam, and potato has been done by the progressive use of AMF in the agricultural fields, confirming the potential value of AMF for increasing the plant yield. In addition, AMF increases the biosynthesis of beneficial phytochemicals. AMF inoculation maintains the pH of the soil, protecting the horticultural value [26].

3.4. AMF and Various Abiotic Stresses

3.4.1. Drought

Stresses such as drought affect plant life in a negative way. Plant development is drastically reduced as shortage of water provokes a reduction in the rate of transpiration, oxidative stress, the closure of stomata, with subsequent reduction in the influx of CO_2, causing a reduction in the overall rate of photosynthesis, plant productivity, carbon partitioning, and overall, a clear-cut reduction of the agricultural yield, dropping its core value.

A drought increases oxidative stress and reduces transpiration [27,28]. Drought stress causes deleterious effects on the overall plant growth and productivity, by affecting several functions, such as nutrient assimilation, uptake of ions, and enzymatic activity [29]. However, strong evidence shows that drought stress is minimized by AMF inoculation in several crops such as strawberry, barley, onion, wheat, and soybean [30-33]. The extra radical network of hyphae in fungi helps in tolerance against drought in plants, and another primary reason is that large volumes of soil are explored by the hyphal network [34-37].

Symbiotic association of mycorrhiza and plants is believed to control the variety of physio-biochemical processes like increase in the osmotic adjustment [38], ABA metabolism controls the stomatal regulation [39], increase in the accumulation of proline contents [40,41], and glutathione levels are also increased [42]. Furthermore, a symbiotic association of plants with AMF improves the leaf area index, size of the root, and its efficiency and biomass under an instant drought environment [43].

Moreover, AMF and its relationship with host plants are quite helpful and supportive in shielding against unfavorable conditions [31]. AMF association enhances gaseous exchange, transpiration, stomatal conductance, and enhanced leaf water relations [30]. In addition, it assists in regulating stomatal conductivity and other physiological processes [44].

AMF inoculation provides resistance against unfavorable conditions like drought, by increasing the radical hyphae-like structures in the soil and improving the performance of plants even under stressful conditions. Different effects of AMF inoculation with host plants, under drought conditions, ions have been mentioned in [Table 1] [45-48]. Mycorrhizal symbionts deal with water deficit through drought tolerance and drought mitigation mechanisms.

Table 1: Beneficial role of AMF inoculation in host plants, under drought conditions.

Host plants	Fungal species	AMF inoculations - responses	References
Olea europaea	AMF	Drought impact is mitigated, turgor potential and mineral uptake are maximized	[45]
Glycine max	AMF	Enhancement in a leaf area index, increased rate of photosynthesis, increased growth rate and dry weight of seeds	[46]
Digitaria eriantha	*Rhizophagus irregularis*	Enhanced stomatal conductivity, peroxidation of lipids and shoot dry matter	[47]
Triticum aestivum	*Glomus mossea*	Increase in the chlorophyll content, osmotic potential, rise in the enzymes linked to antioxidant activities and contents of N, *P* and K	[42]
Allium cepa	*Glomus etunicatus*	Higher fresh and dry biomass and phosphorus content	[48]

3.4.2. Salinity

Salinization of soils is a major alarming environmental concern, raising concerns for global food security. The growth of the plant is suppressed by the salinity stress, affecting the total vegetative development and assimilation. There is evidence that AMF is naturally present in saline conditions, and that it provides tolerance to salinity in plants that have been inoculated with it. The contribution of AMF resisting salinity stress involves several parameters such as physiological, biochemical, and nutritional effects. Salinity stress inhibits plant growth and productivity by affecting the number of parameters like assimilation rate is reduced resulting in the low yield productivity [28,49]. Reactive oxygen species are generated in high numbers [29,50] Various attempts are made to explore the methods used to enhance crop production even under stressful saline conditions. The use of AMF judiciously is one way we find to mitigate the damages caused by salinity [51]. Various studies have revealed that plant productivity is enhanced by AMF under stressful conditions [52,53].

Nashar (2017) [54] has reported that leaf water potential, growth rate, and water-use efficiency are enhanced in great snapdragon plants. Under saline conditions, AMF increases stomatal conductance, leaf water relations, and photosynthetic rate [55]. AMF inoculation improves gaseous exchange, photosynthetic rate, chlorophyll contents, and efficient utilization of water in *Ocimum basilicum* during salinity stress [56]. Wang *et al*. (2018) [57] reported enhanced dry and fresh weights, N concentration in roots, and shoots during salt stress when inoculated with AMF. Furthermore, plants inoculated with AMF show much synthesis of hormones such as salicylic and jasmonic acid, and other inorganic minerals. Mycorrhizal inoculation with lettuce plant shows an increase in biomass production, increase in the uptake of N, high synthesis of proline, changes in ionic relations specifically decrease in the accumulation of Na+ with contrast to non-mycorrhizal plant, under-stressed environment [51]. In addition, plant growth mediated via AMF promotes the alteration in the pool of polyamine [58]. AMF inoculated lettuce plants showed an increase in strigolactone content mitigating effects of salt stress [59]. Among the mechanisms that contribute to salinity tolerance are ionic homeostasis, accumulation of osmoregulatory such as sugars, and reduction in the Na and Cl uptake. [Table 2] summarizes the tolerance of salt stress in different plant species when inoculated with AMF [60-64].

3.4.3. Extreme temperature

Loss of plant vigor, retardation in the growth rate, senescence, discoloration of fruit, yield reduction, and decreased biomass production are the causes of heat stress, fluctuations in the temperature, or extreme temperature. Temperature stress is among the most important factors, which negatively impact the productivity of the plants [65]. AMF improves the performance of plants to tolerate the vivid temperature by improving photosynthetic efficacy [Table 3], shields plants from severe oxidative stress, and increases the osmolytes content [66]. During salinity stress, shoot and dry root biomass inoculated with mycorrhiza showed higher numbers as compared with non-mycorrhizal association [67]. AMF develops the root system for water absorption in plants at higher temperatures to increase photosynthetic rate and prevention of photosynthetic units from damage [68]. The study of Hajiboland *et al*. (2019) [69] pointed out that *G. versiforme* was significantly better at minimizing the cold stress experienced during winter and spring than *R. irregularis*. The inoculation of the Barley (*Hordeum vulgare*) with AMF increased the number of parameters such as osmotic homeostasis, plant growth, photosynthesis, and potassium uptake [69].

AMF plays a very crucial role in tolerating a vivid range of temperatures (high and low), mitigation of climate change [70]. It also improves the N uptake and its assimilation by reducing the emission of N_2O. However, too many fluctuations in the temperature, climatic, and seasonal changes can affect the communities of AMF [71,72].

3.4.4. Heavy metals

In soil contaminated with heavy metals, AMF can establish a plant community because it enhances the defense system of inoculated plants, thereby promoting plant growth and development. Heavy metals are found in soils that are contaminated by mining or polluted sites, which contain AMF that are adapted to soil pollution. A number of studies have shown that around 80% of plants growing on or near mining sites are infested with AMF. Heavy metals can accumulate in various fruits, crop plants, vegetables, and soil posing a threat and causing a wide range of health problems [73,74]. In the soil where cadmium and zinc are quite abundant, suppresses root and shoot growth, results in leaf chlorosis, and even kills plants [75]. A fungal hypha of external and internal origin [76] can immobilize the heavy metals in the cell wall, storing some of them in vacuoles, or chelating them with substances in the cytoplasm [77] and reducing their toxicity significantly in plants. Chelation or enhanced growth in the soil of rhizospheric origin can cause the dilution of metals in plant cells and tissues [58,78]. AMF also binds to the Zn and Cd, in the cell walls of cortical cells and mantle hyphae, thereby, refraining from the excessive uptake of these minerals and improving the entire nutrient status of plants [79,80]. Uptake of several heavy metals by plants and subsequent movement from roots to the aerial parts are highly disturbed by mycorrhiza symbiosis [81,82]. Mycelia of many strains of AMF have a high cation exchange capacity and can absorb heavy metals [83]. AMF regulates the uptake of important inorganic minerals [Table 4], such as higher uptake of silicon has been reported in *Zea Mays* [84] and *Glycine max* [85]. Hammer *et al*. (2011) [86] has recorded that hyphae and spores of *Rhizophagus irregularis* have seen a considerable uptake in Si amounts. AMF inoculation increased cadmium tolerance in alfalfa species [87]. Bioremediation by AMF occurs by the dense hyphal network which binds heavy metals. Heavy metal toxicity is solely affected by the type of mycorrhizal association and the type of plant. Inoculation with AMF has been shown to enhance germination of seeds, plant growth, fresh, and dry weight [88-92].

3.4.5. Flooding tolerance

AMF no matter is a wonder provides resistance to several abiotic stresses. Furthermore, some AMF is capable of facing and tolerating other constraints such as flood [93]. A high diversity of AMF is found in the wetland systems, beneficial against flooding stress [94]. AMF in such abrupt conditions improves plant growth through the absorption of various minerals and nutrients [95]. The authors listed in [Table 5] have found that under wetland conditions, some phosphorous was transported through the mycorrhizal pathway to the rice plants. Liang

Table 2: Salinity tolerance in plant inoculated with AMF.

Host plants	Fungal species	AMF inoculations - responses	References
Solanum lycopersicum	*Glomus intraradices*	Ion uptake, chlorophyll content, growth parameters and dry matter is improved	[60]
Solanum lycopersicum	*Rhizophagus irregularis*	Shoot, root, area of leaf, leaf number and the growth hormone content are enhanced	[61]
Aeluropus littoralis	*Claroideoglomus etunicatum*	Stomatal conductance, root and shoot dry biomass, free alpha amino acids, soluble sugars and Na and Cl uptake is increased	[62]
Acacia nilotica	*Glomus fasciculate*	Shoot and Root dry weight are improved along with Zn, Cu and *P* contents	[63]
Cucumis sativus	*Glomus mosseae, Glomus etunicatum, Glomus intraradices*	Biomass is increased, Biosynthesis of antioxidant enzymes and photosynthetic pigments	[64]

Table 3: Physiological response of plants related to AMF inoculation.

Host plants	Fungal species	AMF inoculations - responses	References
Hordeum vulgare	*R. irregularis G. versiforme*	Survival rate is increased and alleviation of low temperature stress	[69]
Zea mays	*Funneliformis (Glomus) species.*	Controlled photosystem (PS) II heterogeneity	[68]
Cucumis sativus	*R. irregularis*	Increased photosynthetic rate of cucumber seedlings subjected to cold stress	[71]
Elymus nutans	*F. mosseae*	Promotes the plant growth with less oxidative damage, the antioxidant and chlorophyll levels are enhanced.	[72]

Table 4: Responses of host plants related to AMF inoculation.

Host plants	Fungal species	AMF inoculations - responses	References
Zea mays	*Glomus isolates*	Enhanced production of Mg, P and K are increased, improved dry weight and distinction in the distribution of essential and heavy metals in cells	[88]
Trigonella foenum-graceum	*F. mosseae*	Improves the plant growth and yield	[89]
Lonicera japonica	*G. versiforme*	Cd content is reduced in roots and shoots	[90]
Populus alba Populus nigra	*R. irregularis or F. mosseae*	Alleviation in the Zn and Cu phytotoxicity	[91]
Trifolium pratense	*Glomus mosseae*	Root and Shoot concentrations are decreased along with reduction in Zn uptake	[92]

Table 5: Responses of host plants related to AMF inoculation.

Host plants	Fungal species	AMF inoculations - responses	References
Panicum hemitomon Leersia hexandra	*Acaulospora trappei, Glomus leptotichum, Scutellospora heterogama, A Acaulospora laevis, Glomus leptotichum, G. etunicatum* and *G. gerdemannii*	Enhanced phosphorus content in plants	[100]
Pterocarpus officinalis	*Glomus intraradices*	Higher plant growth and phosphorus content in leaves	[97]
Aster tripolium	*Glomus geosporum*	Higher sugars and proline content	[99]

et al. (2018) [96] reported that AMF may help *Phragmites australis* in resisting adverse changes. Fougnies *et al*. (2006) [97] reported that *Pterocarpus officinalis* contributes to resisting flood tolerance. The better growth of host plants with mycorrhizal inoculation with a condition like flooding stress can be combated with osmotic adjustment improvement [98]. Another study was conducted by Rodriguez *et al*. (2020) [99] which had indicated that AMF distributions in tropical low flooding forests are directly related to vegetation characteristics and soil parameters [100].

3.5. Role of AMF in Combined Abiotic Stresses

AMF is believed to be capable of alleviating various abiotic stresses as well as the combinations of similar stresses including drought, salinity, extreme heat, heavy metals, and flooding tolerance. Such as if plants are subjected to stressful environments like salinity and drought higher amounts of ROS are generated which are injurious for the plant life [101]. Enzymes such as peroxidase (POD), catalase (CAT), superoxide dismutase (SOD), and glutathione reductase (GR) help in the detoxification of a higher amount of ROS produced by plants subjected to stressful conditions [29]. Under stress conditions such as salinity and drought, tomato plants inoculated with *Scolecobasidium constrictum* show improved stomatal conductance, biomass production, leaf water relation, and Fv/Fm ratios than those without mycorrhizae. Thus, AMF helps in improving plant yield and growth [67]. Few research reports are found which tell about mitigation of combined effects of more than two stresses in AMF. AMF inoculation shields plants against several abiotic stresses using parameters such as accumulation and uptake of mineral nutrients, regulation of anti-oxidant enzymatic activity, changes in the ecosystem of the rhizosphere, and increased photosynthetic rate [102-104]. There have been a number of studies showing that AMF inoculated plants have improved in nutritional status even under stressful conditions [105-107] caused by the irrigation system or salinity levels. Similarities have been found in the tolerance mechanism which occurs in response due to the combined stress adaptations in the AMF mediated plants. Furthermore, nutrient uptake and assimilation, accumulation of osmolytes, and the anti-oxidant system are some of the common mechanisms that occur under different stressful cues. Specific mechanisms such as sequestration and compartmentation of toxic ions, excessive generation of phytochelatins, and protein can be species-specific, display changes during different stress conditions. The characteristics of roots like hydraulic conductivity may alleviate the osmotic stress to some levels [108]. Zhang *et al*. (2018) [109] have reported that castor bean is protected by AMF against salinity, by making changes in the gas exchange property and some specific metabolites. The above characteristics of AMF may lead to the enhancement of nutraceutical crop quality and could lead to its application in large-scale agricultural production. But still, a lot of research is required to unravel the AMF's role in combating the combined abiotic stresses.

3.6. Association of AMF with Important Soil Microbes

AMF plays an important role in laying establishment with a wide range of soil microorganisms [110,111]. Interactions between the associations can be either positive, negative, or neutral depending on the type of AMF strain and microbes in the rhizosphere [112-115]. In addition, it helps to acquire nutrients, control root pathogens, and improve plant resilience to stress [116].

3.6.1. AMF and rhizobia interaction

Rhizobia are the nitrogen-fixing bacteria that provide all essential minerals and nutrients to the plants, together with AMF inoculation, excellent synergistic effects are seen. A lot of experiments have been conducted in the past which shows positive effects in the interaction of AMF and nodulating Rhizobium [117]. Several reports have shown that interaction between rhizobia and AMF have beneficial effects in legume plants such as *Glycine max* [98,118], *Amorpha canescens, Lens culinaris* [119,120], *Pisum sativum* [121], *Lathyrus sativus* [122], and *Vicia faba* [123]. All these interactions modify the environment of microbes through secretions [124]. It was demonstrated by Chatarpaul *et al*. (1989) [124] that Faba beans grow very well in alkaline soil when AMF and rhizobium are inoculated concurrently.

3.6.2. AMF and Frankia interaction

Actinorhizal plant performance is improved by Frankia in the different environments [35,125-130]. In *Casuarina equisetifolia* and *Casuarina cunninghamiana,* dual inoculation with Frankia and mycorrhizal fungi, enhance the trees and seedlings height, depending on the availability of phosphorous contents. Dual inoculation of *Rhizophagus intraradices* and Frankia spp. with plants of Black alder, in highly anthropogenic alkaline sediment, increases the shoot length, P and N contents of leaf, overall biomass, and leaf area when compared with another control which was uninoculated the *Rhizophagus intraradices* and Frankia spp. treatments alone [126]. In addition to this, dual inoculation increased the symbiosis of AMF, indicating a synergistic effect demonstrated by a high number of nodules in dry weight and a high degree of root development. Although a lot of study and research says that not always a relationship between AMF and Frankia yields good results, sometimes it may be negative [125].

3.6.3. Tripartite symbiosis and its beneficiaries

A lot of benefits have been known about tripartite symbiosis (nitrogen fixers, plant growth-promoting rhizobacteria or mycorrhizal fungi, and AMF) by a lot of researchers [131-133]. Rajendran and Devaraj (2004) [131] found that inoculating *C. equisetifolia* plants with AMF, Azospirillum, Frankia, and Phosphobacterium increased the overall height and biomass.

AMF also co-exists with EMF which is Ectomycorrhizal fungi that enhance plant growth [131,134]. There is no simultaneous colonization of AMF and EMF. In general, the colonization of AMF is first, followed by the EMF, but it is much less, as EMF establishes itself first, further reducing the colonization of AMF by forming a mantle that prevents infection. However, if AMF establishes itself first, it shows no deleterious effects on infection by EMF [134]. According to Emumalai and Raaman (2009) [135], inoculating *C. equisetifolia* plants with both AMF and EMF increases the phosphorous content and biomass compared to inoculating them with either one of them.

3.6.4. Mycorrhization helper bacteria and its interaction with AMF

Interaction of AMF with Mycorrhization Helper Bacteria (MHB) is positive [136-138]. Due to bacterial effects that are beneficial to mycorrhizal associations, Mycorrhization Helper Bacteria (MHB) concept was developed. MHB and its five possible actions were proposed by [138] on the mycorrhizal association like proper receptivity between root and its mycobiont, recognition of root and fungus, modifications in the soil of rhizospheric nature, growth and germination of propagules of fungus. MHB is fungus-specific and not plant-specific; the study was shown by the authors mentioned above.

4. CONCLUSION AND FUTURE PERSPECTIVES

Numerous research reports have demonstrated that AMF inoculation improves many plant attributes, including the growth and development of the plant under the most stressful conditions. Consequently, this review highlights current information about AMF in a coherent manner to gain a better understanding of how AMF interacts with a large number of plants in unfavorable conditions. The AMF is known to act as one of the beneficial elements in mineral uptake from the soil. Furthermore, AMF plays an important role in the alleviation of a number of different environmental stress factors on plants such as drought, salinity, temperature extremes, heavy metals, and flooding. These factors thereby provide an increase in the yield per hectare of many vegetables and crops. AMF is a potential tool to restore the degraded ecosystem. It is considered one of the key indicators for detecting soil pollution. They play a crucial role in increasing the yield and plant growth, tolerance against hazardous compounds, which can be toxic and lethal for human life, and subsequent growth. An alternative approach of switching to AMF inoculation can provide an environment-friendly solution to reduce the excessive use of pesticides and industrial fertilizers. The application of this knowledge should be implemented on a wide scale, to boost organic farming and sustainable development. Industrial production of AMF is to be done at a large scale to ensure that there is no lack of food availability and food scarcity. Isolation of indigenous AMF which are adapted to stressful conditions can be proved as one of the potential biotechnological tools to combat the problems of stresses in plants and for the excellent restoration of the degraded ecosystems. Screening of such indigenous and pollution tolerant isolates should be done effectively to provide beneficiaries of the mycorrhizal symbiotic association, for the restoration of the contaminated soils. In addition, combining selected plants with particular AMF which are adaptable to the various stress cues is the subject of research in agricultural farming in order to increase the use of organic manures. New methods and mechanisms should be followed and encouraged to boost up this entire process which is quite a good subject to combat the problems of environmental stress. People should be encouraged to adopt this method, which is quite affordable and accessible. Consistent sustainability can occur only by much encouragement given to the AMF usage throughout at global level. The exploitation of AMF will lower the dependence on inorganic chemicals, fertilizers, and pesticides, promoting healthy sustainable development and the environment. Environment-friendly technologies should be given a chance to represent and address the critical issues, and thereby coming up with a solution, is one of the healthy approaches to address this issue and solve it. Future research should primarily focus on some objective of identifying genes and gene products that directly control AMF symbiosis and regulate plant growth under stressful cues.

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

9. DATA AVAILABILITY

All data generated and analyzed are included within this research article.

10. PUBLISHER'S NOTE

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