AIMS Microbiology

http://www.aimspress.com/journal/microbiology

AIMS Microbiology, 10(3): 674–693.
DOI: 10.3934/microbiol.2024031
Received: 07 April 2024
Revised: 07 August 2024
Accepted: 09 August 2024
Published: 21 August 2024

Review

The reduction of abiotic stress in food crops through climate-smart mycorrhiza-enriched biofertilizer

Mohammad Zahangeer Alam[1,]* and Malancha Dey (Roy)[2]

[1] Department of Environmental Science, Faculty of Agriculture, Bangabandhu Sheikh Mujibur Rahman Agricultural University (BSMRAU), Gazipur-1706, Bangladesh
[2] Progyan Foundation for Research and Innovation (PFRI), Research Organ of the South Asian Forum for Environment (SAFE), India

* **Correspondence:** Email: mohammad.alam@wsu.edu.

Abstract: Climate change enhances stress in food crops. Recently, abiotic stress such as metalloid toxicity, salinity, and drought have increased in food crops. Mycorrhizal fungi can accumulate several nutrients within their hyphae through a symbiotic relationship and release them to cells in the root of the food crops under stress conditions. We have studied arbuscular mycorrhizal fungi (AMF)-enriched biofertilizers as a climate-smart technology option to increase safe and healthy food production under abiotic stress. AMF such as *Glomus sp.*, *Rhizophagus sp.*, *Acaulospora morrowiae*, *Paraglomus occultum*, *Funneliformis mosseae*, and *Claroideoglomus etunicatum* enhance growth and yield in food crops grown in soils under abiotic stress. AMF also works as a bioremediation material in food crops grown in soil. More precisely, the arsenic concentrations in grains decrease by 57% with AMF application. In addition, AMF increases mineral contents, and antioxidant activities under drought and salinity stress in food crops. Catalase (CAT) and ascorbate peroxidase (APX) increased by 45% and 70% in AMF-treated plants under drought stress. AMF-enriched biofertilizers are used in crop fields like precision agriculture to reduce the demand for chemical fertilizers. Subsequently, AMF-enriched climate-smart biofertilizers increase nutritional quality by reducing abiotic stress in food crops grown in soils. Consequently, a climate resilience environment might be developed using AMF-enriched biofertilizers for sustainable livelihood.

Keywords: arbuscular mycorrhizal fungi; biofertilizers; salinity; drought; heavy metals; crops

1. Introduction

Microbial biofertilizer is an essential part of climate-smart agriculture (CSA). It improves agricultural productivity, farmer incomes, and resilience to climate change, and reduces greenhouse gas emissions [1]. Microbial strains like arbuscular mycorrhizal fungi (AMF) can be used in biofertilizers that improve soil quality and reduce the demand for chemical fertilizers in food crops grown under abiotic stress. Consequently, AMF-enriched fertilizers can be considered climate-smart biofertilizers for increasing biomass growth in food crops grown under climate-change-induced stress conditions [1]. *Ectomycorrhiza*, *Ectendomycorrhiza*, and *Endomycorrhizal* fungi are available in the environment. Arbuscular mycorrhizal fungi (AMF) are known as Endomycorrhiza under the phylum *Glomeromycota* [2].

AMFs are vastly associated with over 80% of plant species through symbiotic relations [3–5]. Hyphae of AMF can easily penetrate smaller pores of root cells [6]. They can exchange carbohydrates and minerals between each other inside the roots. AMF hyphae form a branched structure in the root cortex known as arbuscules. These arbuscules work as the functional site of nutrient exchange for increasing plant growth [7–10]. AMF receives lipids from food crops for survival [11,12]. Several food crops (onions, leeks, garlic, carrots, lettuce, cucumbers, lentils, rice, mung beans, peas, tomatoes, and peppers) form symbiotic associations with AMF [13]. AMF increases the availability of nutrients through their hyphal network [3,14]. This increased nutrient content [15] improves yield and biomass growth under stress conditions in food crops [16–19]. For instance, leaves, roots, and shoots increased significantly under stress conditions in AMF-inoculated plants [20]. Consequently, productivity in food crops has increased remarkably under stress conditions [21].

In addition, mycorrhizae increase root surface area for water and nutrient uptake in crops. Plants with mycorrhizal association will have higher efficiency for nutrient absorption, such as nitrogen, potassium, calcium, magnesium, zinc, and copper; and also increase plant resistance to stress [22]. Mycorrhizal fungi can supply phosphate nutrients through hyphae to plant cells [23]. AMF grows widely in the soil to form a well-developed hyphal network that absorbs inorganic phosphorus (Pi) (via fungal high-affinity PiTs). AMF fungus forms arbuscules with coiled hyphae in the root cortex. This structure is enclosed with a plasma membrane and is potentially important to control nutrient transfers between the symbionts. This character of AMF increases phosphorus (P) uptake and plant biomass growth [24].

The extra-radical mycelium (ERM) of AMF can effectively improve nutrient uptake, thus improving plant growth and development [15]. Both macro- and micro-nutrients are increased significantly for plant growth in nutrient-deficient soils through symbiosis [25]. It is believed that AMF improves nutrients and decreases the uptake of Na and Cl, leading to growth stimulation [3,26]. In this regard, mycorrhizae can be used as a nutrient stimulator in the farmer’s field. Literature showed that crop yield improved by more than 50%, and the farmers’ income increased by 61% with the recommended doses of chemical fertilizer and mycorrhizal biofertilizer compared to chemical fertilizer alone [27]. Mycorrhizal association in plant roots resists root and collar rot diseases caused by other fungi. It can be used together with other agricultural chemicals. Mycorrhizae are tolerant to several chemical substances; for example, pesticides such as endrin, chlordane, methyl parathion, and methomyl carbofuran. In this regard, mycorrhizae containing biofertilizers are highly recommended in food crops grown under abiotic stress [22].

Environmental hazards like drought, salinity, metalloid toxicity, and disease epidemics have increased significantly. Climate-smart AMF-enriched biofertilizers can be used as an effective tool in reducing abiotic stress in food crops [20,21]. Research has shown that climate-smart biofertilizers using *Acaulospora morrowiae*, *Paraglomus occultum*, *Funneliformis mosseae*, *Rhizophagus clarus*, and *Rhizophagus intraradices* increase yield, chlorophyll, carotenoids, catalase (CAT), ascorbate peroxidase (APX), and minerals, and reduces hydrogen peroxide (H_2O_2) and malondialdehyde (MDA) in tomatoes (*Solanum lycopersicum* L.) grown in soil under drought stress [28–29]. However, drought reduction in plants using AMF is a complex process [30].

AMF is a dispersed fungus [31–34]. It expands the availability of water [35], increases the gas changes abilities in the host plant [30], changes root morphology [34], controls hormones [36], and decreases ROS [37]. Thus, reduces the hostile environments for food crops. Glomalin-related soil proteins (GRSP) are produced by AMF which work as a glue and improve water-holding capacity [38]. Also, AMF colonization significantly increases the accumulation of auxins (IAA), gibberellic acid (GA), and jasmonic acid (JA), which improves plant growth under drought stress [39–40]. AMF improves anti-oxidant activities, regulates osmolytes, and increases the photosynthetic performance under drought stress [41].

Salinity creates an antagonistic environment for crop production. Twenty-six percent of salinity has increased over the last three decades in the coastal region of Bangladesh [42]. Globally, more than 3 to 6% of soils are altered by salinity. These saline soils are extremely noticeable [43]. AMF can be recommended for decreasing salinity levels in food crops [44,45]. AMF provides numerous ways to alleviate salinity stress. For instance, AMF can improve nutrient uptake, osmotic balance, antioxidant activities, and hormonal balance in plants grown in saline soils [45]. AMF reduces reactive oxygen species (ROS) in food crops by alleviating salinity [46]. It also increased the activities of peroxidase (POD), superoxide dismutase (SOD), ascorbate peroxidase (APX), and catalase (CAT) in food crops [40,47]. It is strongly demonstrated that *Rhizophagus irregularis* SA and *Funneliformis mosseae* BEG95 (1:1) can alleviate salinity stress. In contrast, biofertilizers are prepared using alive cells of microbes that increase available nutrients for plants in saline soil [48]. AMF effectively enhances the salinity tolerance of plants by enhancing leaf gas exchanges, peroxidase, catalase, and superoxide dismutase activities, decreasing malondialdehyde contents, increasing the P/N ratio, and absorbing less Na^+ and more Ca^{2+} in their tissues [48].

In contrast, arsenic (As) is a deadly metalloid [49]. More than 60 million people are at risk of arsenic poisoning in Bangladesh [50]. A hundred million individuals are often in contact with As from potable water. The situation is overwhelming in South Asia [3]. Human and natural activities are responsible for the release of As into the environment. Groundwater, mineral ore, geothermal processes, and pesticides are the main sources of As [51–54]. Literature has shown that As could contribute to about 30% of the total As ingestion in food sources [54]. AMF remarkably reduces As in lentil plants grown at 8 and 45 mg kg^{-1} As soils [21]. The extended hyphal network of AMF reduces As toxicity in plants by modifying the metal acquisition [21].

AMF decreases As phytoavailability by stabilizing As through mycelium and glomalin [34,55]. Mycelium forms a network in the soil, effectively immobilizing and trapping As to prevent its uptake by plants. In addition, glomalin is a glycoprotein produced by AMF, which reduces the availability of arsenic [56]. These mechanisms, adopted by AMF to stabilize As, significantly contribute to lowering its potential impact on plants, enhancing agricultural sustainability, and mitigating the risks associated with As contamination. It can be well-defined that AMF is a significant element for nutrients and bioremediation of As in food crops [57].

AMF is an obligate biotroph that exchanges mutual benefits with plants. In this context, AMF can be considered as a natural biofertilizer. Although, naturally AMF richness can represent an effective substitute for conventional fertilization practices [58]. The production of AMF inoculum is highly laborious due to its obligate biotrophic nature. However, endomycorrhiza-enriched biofertilizers have already been explored in different countries. The mycorrhizae biofertilizer was used in economic crops such as fruit trees. Now, this biofertilizer can be used for food crops grown in stress soils. Therefore, AMF-enriched climate smart biofertilizers might be developed to increase the nutritional quality and antioxidants by reducing abiotic stress in food crops grown in soils.

2. AMF effectiveness differs with climatic and soil conditions

Arbuscular mycorrhizal fungi are widely characterized by geographical variability [59]. Soil type is a major factor in shaping AMF communities [60]. AMFs are variable in acidic and calcareous soils [61]. Literature shows that AMF communities can be affected by organic carbon and nitrogen contents in soils [62]. AMF with plants changes by edaphic factors such as nitrogen (N), phosphorus (P), magnesium (Mg), and potassium (K) contents and soil texture [36]. Still, comparatively little evidence is known about the impact of climate variables on AMF communities. The density and diversity of the AMF population were positively correlated with rainfall during the growing season [60]. Soil factors (especially pH, N, Zn, and Cu) mostly affected the variation in AMF communities associated with *Chenopodium ambrosioides*, while geographic and climate factors affected smaller variations [63]. Temperature, precipitation, N, and K strongly affected the abundance of AMF species associated with *Robinia pseudoacacia* [64]. AMF colonization was lower in sand than in gypsum or limestone soils and was largely explained by environmental factors. Soil physical stress also interrupted the variability of AMF with root colonization [64].

3. Inorganic fertilizers vs. biofertilizers

Inorganic fertilizers are classified based on the content of the nutrient element and their physical form can vary (solid or liquid) [65]. The most common traditional fertilizers include potassium (K), nitrogen (N), and phosphorus (P). Some fertilizers contain single nutrients that may be known as simple fertilizers. They have active ingredients that are easily soluble in water, rapidly decomposable, and easily absorbable by roots [65].

In contrast, biofertilizers are prepared using alive cells of microbes that increase nutrient solubility or plant access to nutrients. Biofertilizers are one of the vital components in integrated nutrient management in terms of cost-benefits and environmental friendliness. Several microorganisms are used for the production of biofertilizers. Table 1 shows the development of different types of biofertilizers using microorganisms such as algae, fungi, or bacteria [66]. Bacterial biofertilizers are used in crops as nitrogen fixers, symbiotic and non-symbiotic associative, and phosphate solubilizers (Table 1). Fungal biofertilizers might have different characteristics such as phosphate solubilizers, non-symbiotic, nutrient mobilizers, and symbiotic. Algal biofertilizers may have symbiotic, non-symbiotic, and nitrogen-fixing characteristics in food crops (Table 1).

Table 1. Biofertilizers and their character with examples are described below [66].

Types	Character	Example
Bacterial biofertilizer	Nitrogen Fixer	This type of biofertilizer contains bacteria that can fix nitrogen. The bacteria produce nodules in the roots of the leguminous crops and add nitrogen to the soil. Free-living bacteria also fix the nitrogen from the atmosphere.
	Symbiotic	*Mesorhizobium, Azorhizobium, Sinorhizobium, Allorhizobium, Bradyrhizobium, Rhizobium*, etc.
	Associative	*Herbaspirillum, Azospirillum*, etc.
	Non-symbiotic	*Azotobacter, Derxia, Rhodospirillum, Rhodopseudomonas, Chromatium, Beijerinckia, Acetobacter*, etc.
	Phosphate Solubilizer	This type of biofertilizer fixes phosphorous through phosphorus-solubilizing microorganisms. Phosphorus is converted into a soluble form by organic acids and enzymes.
	Non-symbiotic	*Pseudomonas striata, Bacillus pseudomonas, Bacillus circulans*, etc.
Fungal Biofertilizer	Phosphate Solubilizer	This biofertilizer comprises fungi. The mechanism is also the same as phosphate solubilizer biofertilizer.
	Non-symbiotic	*Penicillium, Aspergillus, Trichoderma*, etc.
	Nutrient Mobilizer	This biofertilizer transfers nutrients such as phosphorus from the soil to the cortical cells of the roots. They also perform as carriers of nutrients.
	Symbiotic	Arbuscular mycorrhizal fungi (AMF)
Algal Biofertilizer	Nitrogen Fixer	This type of biofertilizer contains algae that can fix nitrogen.
	Symbiotic	Blue-green algae or *cyanobacteria*
	Non-symbiotic	Azolla

However, arbuscular mycorrhizal fungi (AMF) can be applied as biofertilizers [58]. The tree-shaped structures, arbuscules, and fungal hyphae are used in AMF-enriched biofertilizers [3,5,6]. In addition, the extended extraradical mycelia and hyphae of AMF increase phosphorus, nitrogen, copper, and zinc under stress conditions [6]. Consequently, AMF might reduce the demand for chemical fertilizer in crop fields [58]. AMF is undoubtedly promising in sustainable farming for its various beneficial purposes such as augmented productivity, nutrient uptake, plant biomass, and yield. Consequently, AMF increases healthy foods for human beings [58]. Table 2 shows that AMF species of *Glomus mosseae*, *Rhizophagus irregularis*, *Glomus intraradices*, *Acaulospora morrowiae*, *Paraglomus occultum*, *Funneliformis mosseae*, *Rhizophagus clarus*, and *Rhizophagus intraradices* enhance biomass growth, yield, antioxidant activities, and mineral and bioactive compounds under abiotic stress in food crops [28,67–69]. *Glomus mosseae* reduces arsenic stress in lentils, mung bean, and pea crops [70]. AMF species of *Glomus etunicatum*, *Glomus intraradices*, *Glomus mosseae*, and *Claroideoglomus etunicatum* reduce salinity stress in rice and cucumber crops [40,71].

Table 2. AMF reduces abiotic stress in food crops grown in soils.

Abiotic Stress	Host	AMF	Benefits	References
Drought	*Glycine max* L.	AMF mixed	It boosted proline, photosynthesis, leaf area, growth, and biomass production	[67]
Drought	*Triticum aestivum*	*Glomus mosseae*	Reduced osmotic damage, increased chlorophyll, antioxidants, ascorbic acid, and nutrients	[68]
Drought	*Lactuca sativa*, *Solanum lycopersicum*	*Rhizophagus irregularis*, *Glomus intraradices*	Increased biomass and abscisic acid (ABA) accumulation	[69]
Metal-general	*Sesbania rostrata*	*Glomus mosseae*	Enhanced the formation of nodules with root, and increased N and P uptake	[72]
Arsenic	*Lens culinaris*, *Vigna radiata*, *Pisum sativum*	*Glomus mosseae*	Increased biomass and antioxidant	[19–21,49,70,73]
Drought	*Solanum lycopersicum*	*Acaulospora morrowiae*, *Paraglomus occultum*, *Funneliformis mosseae*, *Rhizophagus clarus*, *and Rhizophagus intraradices*	Increased biomass and antioxidant activities	[69]
Salinity	*Cucumis sativus*	*Glomus etunicatum*, *Glomus intraradices*, *Glomus mosseae*	Increased biomass, photosynthetic pigment, and antioxidant enzymes	[40]
Salinity	*Oryza sativa L.*	*Claroideoglomus etunicatum*	Improved yield, photosynthetic rate, and stomatal conductance	[71]

3.1. Comparative analysis between inorganic and mycorrhizae-enriched biofertilizer

The plant height, grain weight, and yield were 125.73 cm, 151.62 g, and 3536.83 kg ha^{-1} with the treatment of mycorrhiza and recommended doses of chemical fertilizers. In contrast, the application of mycorrhiza and rhizobium showed a thousand-grain weight, and yield was 167.19 g and 4321.41 kg ha^{-1}, respectively, in cowpea crops. Mycorrhizae-enriched biofertilizers increase yield by 23% compared to chemical fertilizers [74]. AMF and nitrogen-fixing bacteria have been widely used to improve soil fertility [75]. Also, this type of biofertilizer plays a crucial role in plant metabolism and nutrient availability, facilitating nutrient uptake from the soil [76]. The symbiotic association of rhizobium species with legumes promotes biological nitrogen fixation, phosphate solubilization, and Indole-3-acetic acid (IAA). AMF-containing biofertilizers enhance nutrient mineralization and the root area of crops [77]. In addition, AMF-enriched biofertilizer interacts with other microorganisms in the rhizosphere. It enhances Zn, Cu, Fe, Mn, and other nutrient uptake by expanding the network of hyphae in their cells. AMF improves the storage of carbon and nutrients and provides a favorable habitat for the survival and development of soil microorganisms. AMF also reduces soil-borne diseases, including *Aphanomyces*, *Cylindrocladium*, *Fusarium*, *Macrophomina*, *Phytophthora*, *Pythium*, *Rhizoctonia*, *Sclerotinium*, *Verticillium*, and *Thielaviopsis sp*. [78]. *G. intraradices* and *G. mosseae* improved K absorption in maize crops. This K-solubilizing AMF improves the growth of cotton, rape, pepper, cucumber, sorghum, wheat, tomato, chili, sudan grass, and tobacco [79]. Therefore, AMF-enriched biofertilizers are economically viable and environment friendly. Soil health and crop productivity also improved using AMF. It could be applied as a supplementary substance with chemical fertilizers [80]. AMF also reduces the demand for phosphorus fertilizers [81]. Incessant application of chemical fertilizers and pesticides creates environmental problems for soil, plants, and human health [82]. AMF enhances nutrients that augment photosynthate production [83,84]. For example, biomass growth and mineral contents were higher in AMF-inoculated plants [85].

Arbuscules of AMF are highly helpful for increasing nutrients, carbon, and phosphorus-containing compounds, finally improving the growth of host plants [86]. It is also detected that AMF maintains P and N uptake in plants for their development under stress conditions. AMF can reduce the demand for chemical fertilizers by up to 50% during crop production. Figure 1 shows that AMF increases biomass growth and microbial activities in soils compared to non-AMF plants [87,88].

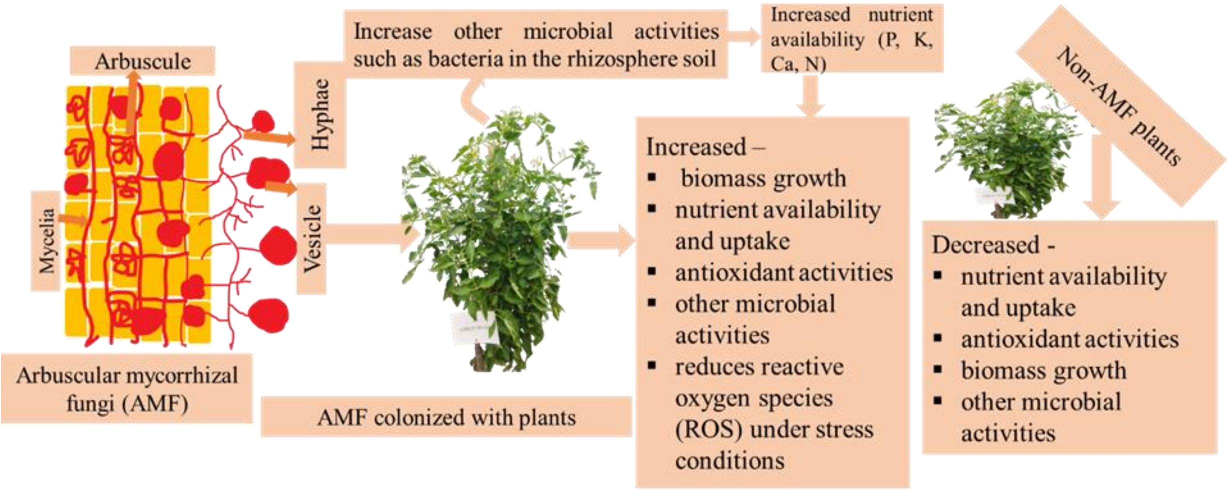

Figure 1. AMF increases other microbial activities and nutrient availability in the rhizosphere soil (adapted from [88]).

4. Development of AMF-enriched biofertilizers

AMF-enriched biofertilizers can be prepared using rhizosphere soils, and root-containing spores, hyphae, mycelium, vesicles, and arbuscules [58]. AMF production is easier than other methods through greenhouse experiments. The purity of the AMF strain is a major issue in developing mycorrhizae-enriched biofertilizers. *In vitro* is the more recognized method for pure culture of AMF [89]. Quite a lot of companies around the world are producing AMF spores. Accordingly, the production of mycorrhizal inoculants has been increasing globally for the last decades. Generally, the suppliers may have their AMF products mostly within their territories. Currently, ectomycorrhizal fungi are exported by a couple of multinational companies globally. This type of mycorrhizal inoculum is used in trees, shrubs, and precious fruit trees.

Also, AMFs are applied in vegetables, forests, and ornamental trees under abiotic stress [90]. AMF inoculation is highly used in food crops grown under drought stress. However, the production of AMF inocula with climate-smart technology is rarely visible; but, it is recognized that mycorrhizal fungi flourish crop yield under stress soils. However, quantity and genetic diversity may impact the colonization of AMF with host plants [91]. It is challenging to judge the cost-effectiveness of the AMF product and its rate [58]. However, inspection of the AMF inoculant is not easy due to its fundamentally multifaceted heritable structure [58]. So, molecular techniques are needed to characterize them [58]. Abiotic stress is focused on the crops' responses in the field crops [58]. Meta-analyses have been suggested for growth responses to AMF inoculations, based on the greenhouse and field conditions [91]. AMF has already been used in manufacturing biofertilizers for their constructive response in terms of stress. The collection of AMF spores, culturing them with host plants, identification, and use against stress in food crops are the main procedures for the preparation of AMF-enriched climate smart biofertilizer. The methods for the preparation of AMF-enriched biofertilizer are shown in Figure 2.

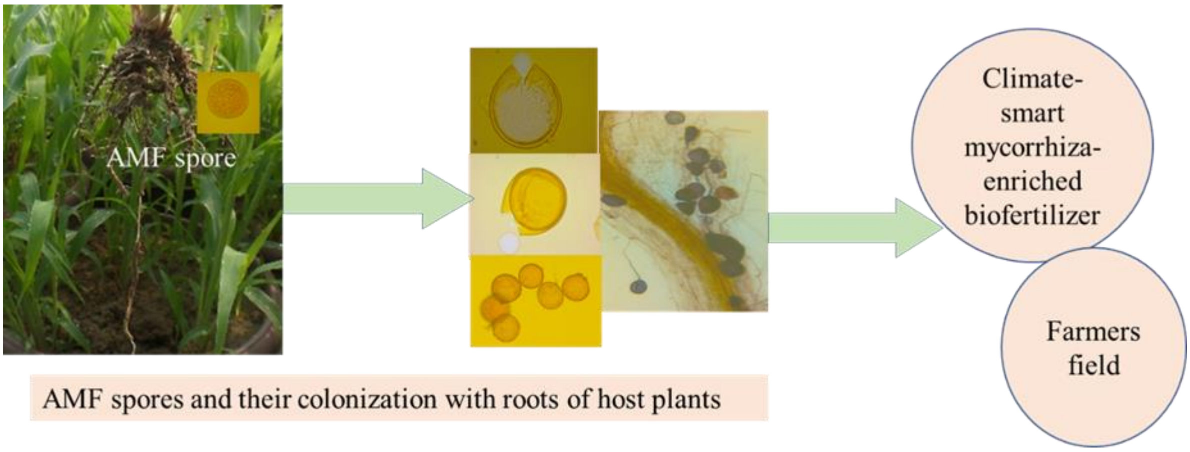

Figure 2. Climate-smart technology: Arbuscular mycorrhizal fungi (AMF)-enriched biofertilizer.

5. AMF-enriched biofertilizers reduce abiotic stress

Arsenic (As) stress has been a global problem in food crops for the last three decades [92]. Arsenic in soils is one of the most important abiotic stresses that reduce plant biomass growth and the quality of food production. Arsenic reduces growth, pigment, total chlorophyll, catalase (CAT), and ascorbic acid content in food crops [93]. For this reason, AMF is recommended to increase chlorophyll and CAT activity, and reduce oxidative stress in As-stressed crops (Figure 3). AMF enhances antioxidant defense mechanisms and the nutritional quality of food crops grown in As soils [20]. AMF has great potential in reducing As transfer in biomass and grains of food crops [21]. More precisely, the As in grains of food crops decreased by 57% with AMF application [70]. Arsenic (As) is stored in the vacuole through fungal hyphae [94,95]. This hypha of AMF improves the growth, yield, and nutrient status of food crops under As stress [96–99].

Under drought stress, AMF also increases nutritional quality and antioxidant activities in food crops grown in soil (Figure 4). Many studies show that AMF reduces drought stress in food crops [100]. The plant's tolerance to drought increased using the extra-radical hyphae of the AMF [101]. As a result, biomass production increased under drought stress [102,103]. Gas exchange, leaf water potential, stomatal conductance, and transpiration rate are increased through the symbiosis of AMF [104–106]. Photosynthesis in C3 (*Leymus chinensis*) and C4 (*Hemarthria altissima*) plants increased using AMF under stress conditions. The biomass growth with AMF-treated plants was significantly higher than that of the control in tomatoes (non-AMF). In AMF-treated tomatoes, CAT and APX increased by 42% and 66%, respectively, compared to non-AMF under drought conditions. MDA and H_2O_2 (ROS) in AMF-treated tomato plants were also reduced by 50% and 2% compared to the control. Minerals of tomato fruits improved by 36% with AMF treatment than that of the control [28]. AMF significantly enhanced drought tolerance and biomass production in plants over the activity of N metabolizing enzymes [107].

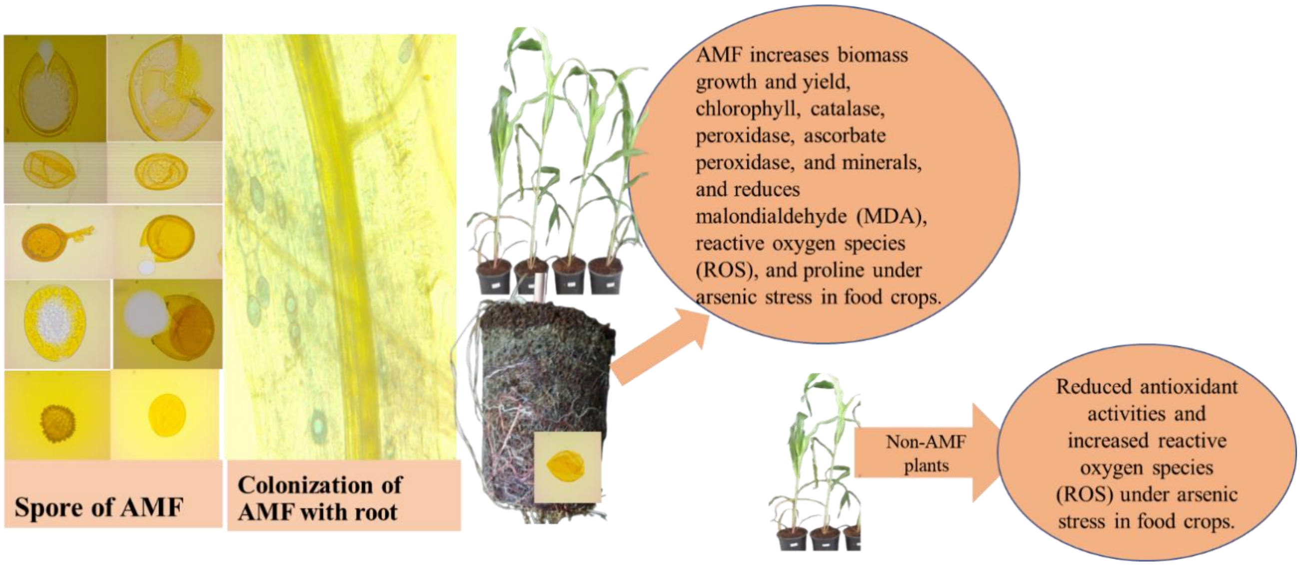

Figure 3. Arbuscular mycorrhizal fungi (AMF) improve photosynthetic pigments and antioxidant activity under arsenic stress in food crops (adapted from [19]).

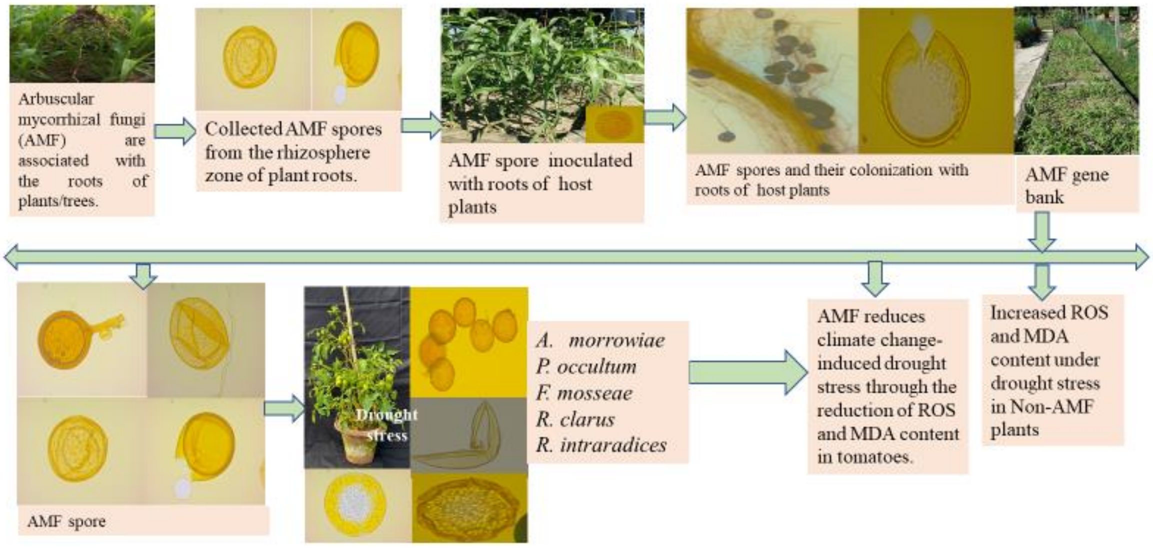

Figure 4. Arbuscular mycorrhizal fungi increase biomass growth and antioxidants and reduce climate change-induced drought in plants.

Global food security is affected due to soil salinity [108]. Reactive oxygen species (ROS) are enhanced in food crops grown in saline soils [109,110]. The biomass growth, photosynthetic rate, stomatal conductance, leaf water potential, and water use efficiency enhanced using AMF in plants grown under salinity stress [111,112]. AMF also enhanced gas exchange, leaf area index, fresh and dry biomass, and chlorophyll content in food crops under saline conditions [113–115]. In addition, P, N, Ca, and K were higher in the AMF-treated plants under salt-stress conditions [116–118]. Malondialdehyde (MDA), superoxide dismutase (SOD), proline, peroxidase (POD), superoxide dismutase (SOD), and catalase (CAT) are changed in plants through AMF under salinity stress. Therefore, the effect of AMF on plant growth and physiology is more notable under salinity stress [119]. The production of AMF inoculum is a bit tough due to its obligate symbiotic behavior with host plants. As a consequence, a methodology is needed for the production of AMF on a large scale. However, AMF-enriched climate-smart biofertilizers might be developed to improve the nutritional quality and antioxidants in food crops grown in soils under abiotic stress conditions (Figure 5).

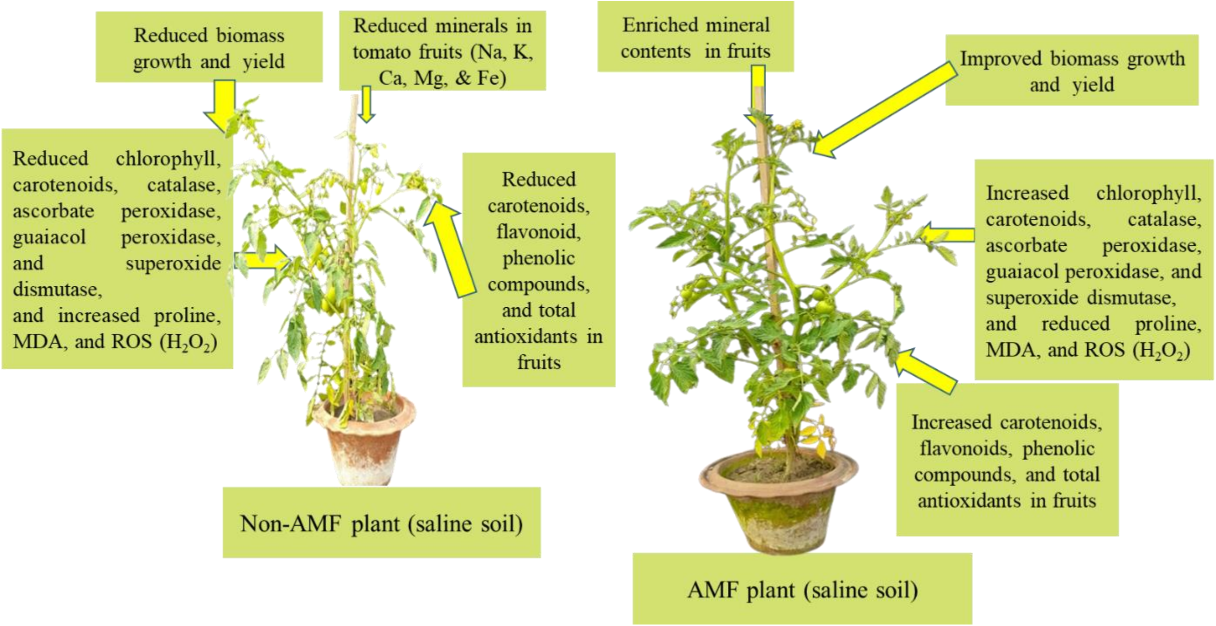

Figure 5. Differential response of an AMF and non-AMF plant under salinity stress (adapted from [119,121]).

It is already clear that AMF increases biomass growth, yield, and antioxidant activities under arsenic, drought, and salinity stress in food crops grown in soil [28]. Therefore, AMF-enriched biofertilizers might be recognized as climate-smart biofertilizers.

6. Future outlook and research gaps as an emerging technology

Global food production is required to double by 2050 to feed the increasing human population. Synthetic fertilizers in agriculture have lost soil quality due to many environmental consequences. Biofertilizers are recognized as an advanced approach to reducing environmental stress and maintaining sustainability in agriculture. There is much evidence that beneficial microbes improve soil productivity and quality. Of many microbial contestants, AMF has been shown potential to be used as a biofertilizer due to its numerous benefits. Plant growth and yield, nutrient availability, water-holding capacity, and disease resistance increased by the application of AMF-enriched biofertilizers. In addition, AMF could also play a role in controlling soil erosion, improving the initial growth of seedlings, remediating soil pollutants, and eradicating harmful organisms. In the future, a diverse pool of AMF species should be used in crop fields based on their host and environmental preferences. So, the selection of the best inoculum is highly recommended for crops. Technologies and protocols should be used to select the effective inocula. Maintaining quality control of products is also significantly important to commercializing AMF inoculants to meet the needs of the farmers. Once these challenges are addressed properly, AMF has more potential as a natural biofertilizer in future agriculture. This AMF-enriched biofertilizer will be used in crop fields like precision agriculture, which reduces the demand for chemical fertilizers and the impacts of climate change in crop fields. Finally, a climate resilience environment will be developed by AMF-enriched biofertilizers in the crop field [120,121].

Climate change induces an unexpected environment for crop cultivation. The symbiosis of microbial inoculants depends on the crop species, native microbial communities, soil type, and nutrient availability in soils. A study is needed on how the pathogen, temperature, rainfall, and antimicrobial activities affect the efficacy of AMF inoculant in mycorrhiza-enriched biofertilizers. Further field trials are essential to understand the factors hindering consistently positive plant responses to AMF inoculants and help farmers determine whether they are appropriate for their system. The viability of hyphae, mycelia, and spores in the mycorrhiza-enriched biofertilizers depends on the temperature. Further study is needed about the viability of AMF spores under specific temperatures.

7. Conclusions

A few researches have been done regarding the positive effect of AMF in increasing plant biomass under abiotic stress. Still, the role of AMF on plant growth is unknown in stressful environments. AMF has been mainly used as a valuable material for increasing nutrients in food crops. Recently, AMF can effectively reduce salinity, drought, and arsenic stress in food crops, thus increasing the yield of crops and vegetables. Therefore, AMF practice is tremendously important for its consistent sustainability in modern agricultural systems. AMFs must be explored at all levels to prepare as a natural climate-smart biofertilizer to reduce abiotic stress in sustainable agriculture. AMF-enriched biofertilizer may be applied to field crops. Thus, this type of fertilizer will be able to make a mutual relationship with food crops to supply them with nutrients under stressful conditions. A quality and regulation framework should be forwarded by an expanded list of authors to ensure that microbial products contain viable propagules, and an absence of pathogens, and are packaged with labels describing their contents and nutrient adjuncts. The benefits of introducing AMF into agricultural soils will be more predictable, which will turn them into more reliable and less environmentally damaging methods of improving crop productivity.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Acknowledgments

The authors are also immensely grateful to the Ministry of Science and Technology and BSMRAU for their funding.

Conflict of interest

The authors declare that the review paper was written in the absence of any commercial or financial relationship that could be construed as a potential conflict of interest.

Data availability

The data used to support the findings of this study are included in the article.

Authors' contributions

Mohammad Zahangeer Alam: Writing, original draft preparation, editing; Malancha Dey (Roy): Review. All authors have read and agreed to the published version of the manuscript.

References

1. Deepika S, Goswami V, Kothamasi D (2023) Arbuscular mycorrhizal fungi (AMF) and climate-smart agriculture: Prospects and challenges, *Global Climate Change and Plant Stress Management*, Hoboken: John Wiley & Sons Inc, 175–200. https://doi.org/10.1002/9781119858553.ch14
2. Johnson NC, Gehring CA (2007) Mycorrhizas: Symbiotic mediators of rhizosphere and ecosystem processes, *The Rhizosphere*, New York: Academic Press, 73–100. https://doi.org/10.1016/B978-012088775-0/50006-9
3. Smith FA, Jakobsen I, Smith SE (2000) Spatial differences in acquisition of soil phosphate between two arbuscular mycorrhizal fungi in symbiosis with *Medicago truncatula*. *New Phytol* 147: 357–366. https://doi.org/10.1046/j.1469-8137.2000.00695.x
4. Smith FA, Smith SE (2011) What is the significance of the arbuscular mycorrhizal colonisation of many economically important crop plants? *Plant Soil* 348: 63–79. https://doi.org/10.1007/s11104-011-0865-0
5. Smith SE, Read DJ (2008) *Mycorrhizal Symbiosis*, 3 Eds., New York: Academic Press.
6. Allen MF (2011) Linking water and nutrients through the vadose zone: A fungal interface between the soil and plant systems: linking water and nutrients through the vadose zone: a fungal interface between the soil and plant systems. *J Arid Land* 3: 155–163. https://doi.org/10.3724/SP.J.1227.2011.00155
7. Balestrini R, Lumini E, Borriello R, et al. (2015) Plant-soil biota interactions, *Soil Microbiology, Ecology and Biochemistry*, 4 Eds., New York: Academic Press, 311–338. https://doi.org/10.1016/B978-0-12-415955-6.00011-6

8. Nouri E, Breuillin-Sessoms F, Feller U, et al. (2014) Phosphorus and nitrogen regulate arbuscular mycorrhizal symbiosis in *petunia hybrida*. *PLoS One* 9: e90841. https://doi.org/10.1371/journal.pone.0090841
9. Smith SE, Smith FA (2012) Fresh perspectives on the roles of arbuscular mycorrhizal fungi in plant nutrition and growth. *Mycologia* 104: 1–13. https://doi.org/10.3852/11-229
10. Thirkell TJ, Charters MD, Elliott AJ, et al. (2017) Are mycorrhizal fungi our sustainable saviours? Considerations for achieving food security. *J Ecol* 105: 921–929. https://doi.org/10.1111/1365-2745.12788
11. Jiang Y, Wang W, Xie Q, et al. (2017) Plants transfer lipids to sustain colonization by mutualistic mycorrhizal and parasitic fungi. *Science* 356: 1172. https://doi.org/10.1126/science.aam9970
12. Parniske M (2008) Arbuscular mycorrhiza: The mother of plant root endosymbioses. *Nat Rev Microbiol* 6: 763–775. https://doi.org/10.1038/nrmicro1987
13. Baum C, El-Tohamy W, Gruda N (2015) Increasing the productivity and product quality of vegetable crops using arbuscular mycorrhizal fungi: A review. *Sci Hortic* 187: 131–141. https://doi.org/10.1016/j.scienta.2015.03.002
14. Govindarajulu M, Pfeffer PE, Jin HR, et al. (2005) Nitrogen transfer in the arbuscular mycorrhizal symbiosis. *Nature* 435: 819–823. https://doi.org/10.1038/nature03610
15. Lehmann A, Rillig MC (2015) Arbuscular mycorrhizal contribution to copper, manganese and iron nutrient concentrations in crops—A meta-analysis. *Soil Biol Biochem* 81: 147–158. https://doi.org/10.1016/j.soilbio.2014.11.013
16. Pellegrino E, Opik M, Bonari E, et al. (2015) Responses of wheat to arbuscular mycorrhizal fungi: A meta-analysis of field studies from 1975 to 2013. *Soil Biol Biochem* 84: 210–217. https://doi.org/10.1016/j.soilbio.2015.02.020
17. Veiga RSL, Jansa J, Frossard E, et al. (2011) Can arbuscular mycorrhizal fungi reduce the growth of agricultural weeds? *PLoS ONE* 6: e27825. https://doi.org/10.1371/journal.pone.0027825
18. Veresoglou SD, Rillig MC (2012) Suppression of fungal and nematode plant pathogens through arbuscular mycorrhizal fungi. *Biol Lett* 8: 214–217. https://doi.org/10.1098/rsbl.2011.0874
19. Alam MZ, Carpenter-Boggs L, Hoque MA, et al. (2020) Effect of soil amendments on antioxidant activity and photosynthetic pigments in pea crops grown in arsenic-contaminated soil. *Heliyon* 6: e05475. https://doi.org/10.1016/j.heliyon.2020.e05475
20. Alam MZ, Mcgee R, Hoque MA, et al. (2019) Effect of arbuscular mycorrhizal fungi, Selenium, and Biochar on photosynthetic pigments and antioxidant enzyme activity under arsenic stress in mung bean (Vigna radiata). *Front Physiol* 10: 193. https://doi.org/10.3389/fphys.2019.00193
21. Alam MZ, Hoque MA, Ahammed GJ, et al. (2019) Arbuscular mycorrhizal fungi reduce arsenic uptake and improve plant growth in Lens culinaris. *PLoS One* 14: e0211441. https://doi.org/10.1371/journal.pone.0211441
22. Fall AF, Nakabonge G, Ssekandi J, et al. (2022) Roles of arbuscular mycorrhizal fungi on soil fertility: Contribution in the improvement of physical, chemical, and biological properties of the soil. *Front Fungal Biol* 3: 723892. https://doi.org/10.3389/ffunb.2022.723892
23. Brundrett M, Bougher N, Dell B, et al. (1996) Working with mycorrhizas in forestry and agriculture. *Australian Centre for International Agricultural Research*.

24. Smith SE, Jakobsen I, Grønlund M, et al. (2011) Roles of arbuscular mycorrhizas in plant phosphorus nutrition: Interactions between pathways of phosphorus uptake in arbuscular mycorrhizal roots have important implications for understanding and manipulating plant phosphorus acquisition. *Plant Physiol* 156: 1050–1057. https://doi.org/10.1104/pp.111.174581
25. Mitra D, Navendra U, Panneerselvam U, et al. (2019) Role of mycorrhiza and its associated bacteria on plant growth promotion and nutrient management in sustainable agriculture. *Int J Life Sci Appl Sci* 1: 1–10.
26. Evelin H, Giri B, Kapoor R (2012) Contribution of Glomus intraradices inoculation to nutrient acquisition and mitigation of ionic imbalance in NaCl-stressed *Trigonella foenum-graecum*. *Mycorrhiza* 22: 203–217. https://doi.org/10.1007/s00572-011-0392-0
27. Smith SE, Read DJ (1997) *Mycorrhizal Symbiosis*, 2Eds., New York: Academic Press.
28. Alam MZ, Choudhury TR, Mridha MAU (2023) Arbuscular mycorrhizal fungi enhance biomass growth, mineral content, and antioxidant activity in tomato plants under drought stress. *J Food Qual*. https://doi.org/10.1155/2023/2581608
29. Palacios YM, Winfrey BK (2021) Three mechanisms of mycorrhizae that may improve stormwater biofilter performance. *Ecol Eng* 159: 106085. https://doi.org/10.1016/j.ecoleng.2020.106085
30. Huang D, Ma M, Wang Q, et al. (2020). Arbuscular mycorrhizal fungi enhanced drought resistance in apple by regulating genes in the MAPK pathway. *Plant Physiol Biochem* 149: 245–255. https://doi.org/10.1016/j.plaphy.2020.02.020
31. Behrooz A, Vahdati K, Rejali F, et al. (2019) Arbuscular mycorrhiza and plant growth-promoting bacteria alleviate drought stress in walnut. *Hortscience* 54: 1087–1092. https://doi.org/10.21273/HORTSCI13961-19
32. Ahmed A, Abdelmalik A, Alsharani T, et al. (2020) Response of growth and drought tolerance of Acacia seyal Del. seedlings to arbuscular mycorrhizal fungi. *Plant Soil Environ* 66: 264–271. https://doi.org/10.17221/206/2020-PSE
33. Hu Y, Pandey AK, Wu X, et al. (2022) The role of arbuscular mycorrhiza fungi in drought tolerance in legume crops: A review. *Legume Res Intern J* 1: 9. https://doi.org/10.18805/LRF-660
34. Zhang Z, Zhang J, Xu G, et al. (2019) Arbuscular mycorrhizal fungi improve the growth and drought tolerance of Zenia insignis seedlings under drought stress. *New For* 50: 593–604. https://doi.org/10.1007/s11056-018-9681-1
35. Ortas I, Rafique M, Çekiç FÖ (2021) Do Mycorrhizal Fungi enable plants to cope with abiotic stresses by overcoming the detrimental effects of salinity and improving drought tolerance, *Symbiotic Soil Microorganisms*, Berlin: Springer, 391–428. https://doi.org/10.1007/978-3-030-51916-2_23
36. Begum N, Ahanger MA, Zhang L (2020) AMF inoculation and phosphorus supplementation alleviates drought induced growth and photosynthetic decline in Nicotiana tabacum by up-regulating antioxidant metabolism and osmolyte accumulation. *Environ Exp Bot* 176:104088. https://doi.org/10.1016/j.envexpbot.2020.104088
37. Amiri R, Nikbakht A, Etemadi N (2015) Alleviation of drought stress on rose geranium [Pelargonium graveolens (L.) Herit.] in terms of antioxidant activity and secondary metabolites by mycorrhizal inoculation. *Sci Hortic* 197: 373–380. https://doi.org/10.1016/j.scienta.2015.09.062

38. Gupta MM (2020) Arbuscular mycorrhizal fungi: the potential soil health indicators, *Soil Health*, Berlin: Springer, 183–195. https://doi.org/10.1007/978-3-030-44364-1_11
39. Egamberdieva D, Wirth S, Abd-Allah EF (2018) Plant hormones as key regulators in plant-microbe interactions under salt stress, *Plant Microbiome*: *Stress Response*, Berlin: Springer, 165–182. https://doi.org/10.1007/978-981-10-5514-0_7
40. Hashem A, Alqarawi AA, Radhakrishnan R, et al. (2018) Arbuscular mycorrhizal fungi regulate the oxidative system, hormones and ionic equilibrium to trigger salt stress tolerance in Cucumis sativus L. *Saudi J Biol Sci* 25: 1102–1114. https://doi.org/10.1016/j.sjbs.2018.03.009
41. Wang Y, Lin J, Yang F, et al. (2022) Arbuscular mycorrhizal fungi improve the growth and performance in the seedlings of Leymus chinensis under alkali and drought stresses. *PeerJ* 10: 12890. https://doi.org/10.7717/peerj.12890
42. Alam MZ, Carpenter-Boggs L, Mitra S, et al. (2017) Effect of salinity intrusion on food crops, livestock, and fish species at Kalapara coastal belt in Bangladesh. *J Food Qual*. https://doi.org/10.1155/2017/2045157
43. Food and Agriculture Organization of the United Nations (2023) Global map of salt-affected soils. Available from: https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/global-map-of-salt-affected-soils/en.
44. Li Z, Wu N, Meng S, et al. (2020). Arbuscular mycorrhizal fungi (AMF) enhance the tolerance of Euonymus maackii Rupr. at a moderate level of salinity. *PLoS One* 15: e0231497. https://doi.org/10.1371/journal.pone.0231497
45. Evelin H, Devi TS, Gupta S, et al. (2019) Mitigation of salinity stress in plants by arbuscular mycorrhizal symbiosis: Current understanding and new challenges. *Front Plant Sci* 10: 470. https://doi.org/10.3389/fpls.2019.00470
46. Evelin H, Kapoor R (2014) Arbuscular mycorrhizal symbiosis modulates antioxidant response in salt-stressed *Trigonella foenum-graecum* plants. *Mycorrhiza* 24: 197–208. https://doi.org/10.1007/s00572-013-0529-4
47. Chen J, Zhang H, Zhang X, et al. (2017) Arbuscular mycorrhizal symbiosis alleviates salt stress in black locust through improved photosynthesis, water status, and K^+/Na^+ homeostasis. *Front Plant Sci* 8: 1739. https://doi.org/10.3389/fpls.2017.01739
48. Qin W, Yan H, Zou B, et al. (2021) Arbuscular mycorrhizal fungi alleviate salinity stress in peanut: Evidence from pot-grown and field experiments. *Food Energy Secur* 10: e314. https://doi.org/10.1002/fes3.314
49. Alam MZ, Hoque MA, Ahammed GJ, et al. (2019a) Arsenic accumulation in lentil (Lens culinaris) genotypes and risk associated with the consumption of grains. *Sci Rep* 9: 9431. https://doi.org/10.1038/s41598-019-45855-z
50. Li J, Dong F, Lu Y, et al. (2014) Mechanisms controlling arsenic uptake in rice grown in mining impacted regions in South China. *PLoS One* 9: e108300. https://doi.org/10.1371/journal.pone.0108300
51. ATSDR: Agency for Toxic Substances & Disease Registry (2016) Environmental health and medicine education. Available from: https://www.atsdr.cdc.gov/.
52. Chung JY, Yu SD, Hong YS (2014) Environmental source of arsenic exposure. *J Prev Med Public Health* 47: 253–257. https://doi.org/10.3961/jpmph.14.036
53. Huq SMI, Joardar JC, Parvin S, et al. (2006) Arsenic contamination in food-chain: Transfer of arsenic into food materials through groundwater irrigation. *J Health Popul Nutr* 24: 305–316.

54. Das DK, Sur P, Das K (2008) Mobilisation of arsenic in soils and in rice (*Oryza sativa* L.) plants affected by organic matter and zinc application in irrigation water contaminated with arsenic. *Plant Soil Environ* 54: 30–37. https://doi.org/10.17221/2778-PSE
55. Riaz M, Kamran M, Fang Y, et al. (2021) Arbuscular mycorrhizal fungi-induced mitigation of heavy metal phytotoxicity in metal contaminated soils: A critical review. *J Hazard Mater* 402: 123919. https://doi.org/10.1016/j.jhazmat.2020.123919
56. Maldonado-Mendoza IE, Harrison MJ (2018) RiArsB and RiMT-11: Two novel genes induced by arsenate in arbuscular mycorrhiza. *Fungal Biol* 122: 121–130. https://doi.org/10.1016/j.funbio.2017.11.003
57. Ferrol N, Tamayo E, Vargas P (2016) The heavy metal paradox in arbuscular mycorrhizas: From mechanisms to biotechnological applications. *J Exp Bot* 67: 6253–6265. https://doi.org/10.1093/jxb/erw403
58. Berruti A, Lumini E, Balestrini R, et al. (2016) Arbuscular mycorrhizal fungi as natural biofertilizers: Let’s benefit from past successes. *Front Microbiol* 19: 1559. https://doi.org/10.3389/fmicb.2015.01559
59. Davison J, Moora M, Öpik M, et al. (2015) Global assessment of arbuscular mycorrhizal fungus diversity reveals very low endemism. *Science* 80: 349. https://doi.org/10.1126/science.aab1161
60. Torrecillas E, del Mar Alguacil M, Roldán A, et al. (2014) Modularity reveals a tendency of arbuscular mycorrhizal fungi to interact differently with generalist and specialist plant species in gypsum soils. *Appl Environ Microbiol* 80: 5457–5466. https://doi.org/10.1128/AEM.01358-14
61. Van Geel M, Jacquemyn H, Plue J, et al. (2018) Abiotic rather than biotic filtering shapes the arbuscular mycorrhizal fungal communities of European seminatural grasslands. *New Phytol* 220: 1262–1272. https://doi.org/10.1111/nph.14947
62. Lekberg Y, Koide RT, Rohr JR, et al. (2007) Role of niche restrictions and dispersal in the composition of arbuscular mycorrhizal fungal communities. *J Ecol* 95: 95–105. https://doi.org/10.1111/j.1365-2745.2006.01193.x
63. Xu X, Chen C, Zhang Z, et al. (2017) The influence of environmental factors on communities of arbuscular mycorrhizal fungi associated with Chenopodium ambrosioides revealed by MiSeq sequencing investigation. *Sci Rep* 7: 45134. https://doi.org/10.1038/srep45134
64. Klichowska E, Nobis M, Piszczek P (2019) Soil properties rather than topography, climatic conditions, and vegetation type shape AMF–feathergrass relationship in semi-natural European grasslands. *Appl Soil Ecol* 144: 22–30. https://doi.org/10.1016/j.apsoil.2019.07.001
65. Raul IC, Alma RSP (2017) Mineral nutrition and fertilization management, *Reference Module in Life Sciences*, Amsterdam: Elsevier. https://doi.org/10.1016/B978-0-12-809633-8.05087-1
66. Ikbal, Minakshi P, Brar B, et al. (2017) Promiscuous rhizobia: A potential tool to enhance agricultural crops productivity, *Biotechnology for Sustainability Achievements, Challenges and Perspectives*, Malaysia: AIMST University, 358–375.
67. Pavithra D, Yapa N (2018) Arbuscular mycorrhizal fungi inoculation enhances drought stress tolerance of plants. *Ground Water Sust Dev* 7: 490–494. https://doi.org/10.1016/j.gsd.2018.03.005
68. Rani B (2016) Effect of arbuscular mycorrhiza fungi on biochemical parameters in wheat Triticum aestivum L. under drought conditions. Doctoral dissertation, CCSHAU, Hisar.

69. Ruiz-Lozano JM, Aroca R, Zamarreño ÁM, et al. (2015) Arbuscular mycorrhizal symbiosis induces strigolactone biosynthesis under drought and improves drought tolerance in lettuce and tomato. *Plant Cell Environ* 39: 441–452. https://doi.org/10.1111/pce.12631
70. Alam MZ, Hoque MA, Carpenter-Boggs L (2022) Mycorrhizal fungi, biochar, and selenium increase biomass of Vigna radiata and reduce arsenic uptake. *Toxicol Environ Chem* 104: 84–102. https://doi.org/10.1080/02772248.2022.2028790
71. Porcel R, Redondogómez S, Mateosnaranjo E, et al. (2015) Arbuscular mycorrhizal symbiosis ameliorates the optimum quantum yield of photosystem II and reduces non-photochemical quenching in rice plants subjected to salt stress. *J Plant Physiol* 185: 75–83. https://doi.org/10.1080/02772248.2022.2028790
72. Lin AJ, Zhang XH, Wong MH, et al. (2007) Increase of multi-metal tolerance of three leguminous plants by arbuscular mycorrhizal fungi colonization. *Environ Geochem Health* 29: 473–481. https://doi.org/10.1007/s10653-007-9116-y
73. Alam MZ, Hoque MA, Ahammed GJ, et al. (2020b) Effects of arbuscular mycorrhizal fungi, biochar, selenium, silica gel, and sulfur on arsenic uptake and biomass growth in Pisum sativum L. *Emerging Contam* 6: 312–322. https://doi.org/10.1016/j.emcon.2020.08.001
74. Gautam N, Ghimire S, Kafle S, et al. (2024) Efficacy of bio-fertilizers and chemical fertilizers on growth and yield of cowpea varieties. *Technol Agron* 4: e007. https://doi.org/10.48130/tia-0024-0004
75. Zeng Q, Ding X, Wang J, et al. (2022) Insight into soil nitrogen and phosphorus availability and agricultural sustainability by plant growth-promoting rhizobacteria. *Environ Sci Pollut Res* 29: 45089−45106. https://doi.org/10.1007/s11356-022-20399-4
76. Kumar S, Diksha, Sindhu SS, et al. (2022) Biofertilizers: An eco-friendly technology for nutrient recycling and environmental sustainability. *Curr Res Microb Sci* 3: 100094. https://doi.org/10.1016/j.crmicr.2021.100094
77. Javaid A (2009) Arbuscular mycorrhizal mediated nutrition in plants. *J Plant Nutr* 32: 1595−1618. https://doi.org/10.1080/01904160903150875
78. Dubey M, Verma V, Barpete R, et al. (2019) Effect of biofertilizers on growth of different crops: A review. *Plant Arch* 19: 1083–1086.
79. Mącik M, Gryta A, Frąc M (2020) Biofertilizers in agriculture: an overview on concepts, strategies and effects on soil microorganisms. *Adv Agron* 162: 31–87. https://doi.org/10.1016/BS.AGRON.2020.02.001
80. Sadhana B (2014) Arbuscular mycorrhizal fungi (AMF) as a biofertilizers—A review. *Int J Curr Microbiol App Sci* 3: 384–400.
81. Ortas I (2012) The effect of mycorrhizal fungal inoculation on plant yield, nutrient uptake and inoculation effectiveness under long-term field conditions. *Field Crops Res* 125: 35–48. https://doi.org/10.1016/j.fcr.2011.08.005
82. Yang S, Li F, Malhi SS, et al. (2004) Long term fertilization effects on crop yield and nitrate nitrogen accumulation in soil in Northwestern China. *Agron J* 96: 1039–1049. https://doi.org/10.2134/agronj2004.1039
83. Nell M, Wawrosch C, Steinkellner S, et al. (2010) Root colonization by symbiotic arbuscular mycorrhizal fungi increases sesquiterpenic acid concentrations in Valeriana officinalis L. *Planta Med* 76: 393–398. https://doi.org/10.1055/s-0029-1186180

84. Kayama M, Yamanaka T (2014) Growth characteristics of ectomycorrhizal seedlings of Quercus glauca, *Quercus salicina*, and *Castanopsis cuspidata* planted on acidic soil. *Trees* 28: 569–583. https://doi.org/10.1007/s00468-013-0973-y
85. Balliu A, Sallaku G, Rewald B (2015) AMF Inoculation enhances growth and improves the nutrient uptake rates of transplanted, salt-stressed tomato seedlings. *Sustainability* 7: 15967–15981. https://doi.org/10.3390/su71215799
86. Prasad R, Bhola D, Akdi K, et al. (2017) Introduction to mycorrhiza: Historical development, *Mycorrhiza*, Berlin: Springer, 1–7. https://doi.org/10.1007/978-3-319-53064-2_1
87. Liu C, Ravnskov S, Liu F, et al. (2018) Arbuscular mycorrhizal fungi alleviate abiotic stresses in potato plants caused by low phosphorus and deficit irrigation/partial root-zone drying. *J Agric Sci* 156: 46–58. https://doi.org/10.1017/S0021859618000023
88. Khan Y, Shah S, Hui T (2022) The roles of arbuscular mycorrhizal fungi in influencing plant nutrients, photosynthesis, and metabolites of cereal crops—A review. *Agronomy* 12: 2191. https://doi.org/10.3390/agronomy12092191
89. Vosátka M, Látr A, Gianinazzi S, et al. (2012) Development of arbuscular mycorrhizal biotechnology and industry: Current achievements and bottlenecks. *Symbiosis* 58: 29–37. https://doi.org/10.1007/s13199-012-0208-9
90. Igiehon ON (2015) Bioremediation potentials of Heterobasidion annosum 13.12 B and Resinicium bicolor in diesel oil contaminated soil microcosms. *J Appl Sci Environ Manage* 19: 513–519. https://doi.org/10.4314/jasem.v19i3.22
91. Hart MM, Antunes PM, Chaudhary VB, et al. (2018) Fungal inoculants in the field: Is the reward greater than the risk? *Funct Ecol* 32: 126–135. https://doi.org/10.1111/1365-2435.12976
92. Alam MZ, Ali MP, Al-Harbi NA, et al. (2011) Contamination status of arsenic, lead, and cadmium of different wetland waters. *Toxicol Environ Chem* 93: 1934–1945. https://doi.org/10.1080/02772248.2011.622073
93. Srivastava S, Sharma Y (2013) Impact of arsenic toxicity on black gram and its amelioration using phosphate. *Int Scholarly Res Not*. https://doi.org/10.1155/2013/340925
94. Punamiya P, Datta R, Sarkar D, et al. (2010) Symbiotic role of Glomus mosseae in phytoextraction of lead in vetiver grass Chrysopogon zizanioides L. *J Hazard Mater* 177: 465–474. https://doi.org/10.1016/j.jhazmat.2009.12.056
95. Audet P (2014) Arbuscular mycorrhizal fungi and metal phytoremediation: Ecophysiological complementarity in relation to environmental stress, *Emerging Technologies and Management of Crop Stress Tolerance*, New York: Academic Press, 133–160. https://doi.org/10.1016/B978-0-12-800875-1.00006-5
96. Garg N, Chandel S (2012) Role of arbuscular mycorrhizal (AM) fungi on growth, cadmium uptake, osmolyte, and phytochelatin synthesis in Cajanus cajan (L.) Millsp. under NaCl and Cd stresses. *J Plant Growth Regul* 31: 292–308. https://doi.org/10.1007/s00344-011-9239-3
97. Li H, Chen XW, Wong MH (2015) Arbuscular mycorrhizal fungi reduced the ratios of inorganic/organic arsenic in rice grains. *Chemosphere* 145: 224–230. https://doi.org/10.1016/j.chemosphere.2015.10.067
98. Wang Y, Wang M, Li Y, et al. (2018) Effects of arbuscular mycorrhizal fungi on growth and nitrogen uptake of Chrysanthemum morifolium under salt stress. *PLoS One* 13: e0196408. https://doi.org/10.1371/journal.pone.0196408

99. Souza LA, Andrade SAL, Souza SCR, et al. (2012) Evaluation of mycorrhizal influence on the development and phytoremediation potential of *Canavalia gladiata* in Pb contaminated soils. *Int J Phytorem* 15: 465–476. https://doi.org/10.1080/15226514.2012.716099
100. Moradtalab N, Roghieh H, Nasser A, et al. (2019) Silicon and the association with an arbuscular-mycorrhizal fungus *(Rhizophagus clarus*) mitigate the adverse effects of drought stress on strawberry. *Agronomy* 9: 41. https://doi.org/10.3390/agronomy9010041
101. Zhang X, Li W, Fang M, et al. (2016) Effects of arbuscular mycorrhizal fungi inoculation on carbon and nitrogen distribution and grain yield and nutritional quality in rice (*Oryza sativa* L.). *J Sci Food Agric* 97: 2919–2925. https://doi.org/10.1002/jsfa.8129
102. Gholamhoseini M, Ghalavand A, Dolatabadian A, et al. (2013) Effects of arbuscular mycorrhizal inoculation on growth, yield, nutrient uptake and irrigation water productivity of sunflowers grown under drought stress. *Agric Water Manag* 117: 106–114. https://doi.org/10.1016/j.agwat.2012.11.007
103. Ruiz-Lozano JM (2003) Arbuscular mycorrhizal symbiosis and alleviation of osmotic stress. *Mycorrhiza* 13: 309–317. https://doi.org/10.1007/s00572-003-0237-6
104. Mena-Violante HG, Ocampo-Jimenez O, Dendooven L, et al. (2006) Arbuscular mycorrhizal fungi enhance fruit growth and quality of chile ancho *Capsicum annuum* L. cv San Luis plants exposed to drought. *Mycorrhiza* 16: 261–267. https://doi.org/10.1007/s00572-006-0043-z
105. Ludwig-Müller J (2010) Hormonal responses in host plants triggered by arbuscular mycorrhizal fungi, *Arbuscular mycorrhizas: Physiology and function*, Berlin: Springer, 169–190. https://doi.org/10.1007/978-90-481-9489-6_8
106. Li J, Meng B, Chai H, et al. (2019) Arbuscular mycorrhizal fungi alleviate drought stress in C3 (*Leymus chinensis*) and C (*Hemarthria altissima*) grasses via altering antioxidant enzyme activities and photosynthesis. *Front Plant Sci* 10: 499. https://doi.org/10.3389/fpls.2019.00499
107. Ouledali S, Ennajeh M, Zrig A, et al. (2018) Estimating the contribution of arbuscular mycorrhizal fungi to drought tolerance of potted olive trees (*Olea europaea*). *Acta Physiol Plant* 40: 81. https://doi.org/10.1007/s11738-018-2656-1
108. Ahanger MA, Alyemeni MN, Wijaya L, et al. (2018) Potential of exogenously sourced kinetin in protecting Solanum lycopersicum from NaCl-induced oxidative stress through up-regulation of the antioxidant system, ascorbate–glutathione cycle and glyoxalase system. *PLoS One* 13: e0202–e0175. https://doi.org/10.1371/journal.pone.0202175
109. Ahanger MA, Tittal M, Mir RA, et al. (2017) Alleviation of water and osmotic stress-induced changes in nitrogen metabolizing enzymes in *Triticum aestivum* L. cultivars by potassium. *Protoplasma* 254: 1953–1963. https://doi.org/10.1007/s00709-017-1086-z
110. Santander C, Sanhueza M, Olave J, et al. (2019) Arbuscular mycorrhizal colonization promotes the tolerance to salt stress in lettuce plants through an efficient modification of ionic balance. *J Soil Sci Plant Nutr* 19: 321–331. https://doi.org/10.1007/s42729-019-00032-z
111. EL-Nashar YI (2017) Response of snapdragon *Antirrhinum majus* L. to blended water irrigation and arbuscular mycorrhizal fungi inoculation: uptake of minerals and leaf water relations. *Photosynthetica* 55: 201–209. https://doi.org/10.1007/s11099-016-0650-7
112. Ait-El-Mokhtar M, Laouane RB, Anli M, et al. (2019) Use of mycorrhizal fungi in improving tolerance of the date palm (*Phoenix dactylifera* L.) seedlings to salt stress. *Sci Horti* 253: 429–438. https://doi.org/10.1016/j.scienta.2019.04.066

113. Elhindi KM, El-Din SA, Elgorban AM (2017) The impact of arbuscular mycorrhizal fungi in mitigating salt-induced adverse effects in sweet basil (*Ocimum basilicum* L.). *Saudi J Biol Sci* 24: 170–179. https://doi.org/10.1016/j.sjbs.2016.02.010
114. Borde M, Dudhane M, Jite PK (2010) AM fungi influences the photosynthetic activity, growth and antioxidant enzymes in Allium sativum L. under salinity condition. *Not Sci Biol* 2: 64–71. https://doi.org/10.15835/nsb245434
115. Wang Y, Jing H, Gao Y (2012) Arbuscular mycorrhizal colonization alters subcellular distribution and chemical forms of cadmium in Medicago sativa L. and resists cadmium toxicity. *PLoS One* 7: 3161–3164. https://doi.org/10.1371/journal.pone.0048669
116. Cameron DD, Neal AL, Van wees SC, et al. (2013) Mycorrhiza induced resistance: more than the sum of its parts? *Trends Plant Sci* 18: 539–545. https://doi.org/10.1016/j.tplants.2013.06.004
117. Poveda J, Abril-Urias P, Escobar C (2020) Biological control of plant-parasitic nematodes by filamentous fungi inducers of resistance: trichoderma, mycorrhizal and endophytic fungi. *Front Microbiol* 11: 992. https://doi.org/10.3389/fmicb.2020.00992
118. Santoyo G, Guzmán-Guzmán P, Parra-Cota FI, et al. (2021) Glick Plant growth stimulation by microbial consortia. *Agronomy* 11: 219. https://doi.org/10.3390/agronomy11020219
119. Dastogeer KMG, Zahan MI, Tahjib-Ul-Arif M, et al. (2020) Plant salinity tolerance conferred by arbuscular mycorrhizal fungi and associated mechanisms: A meta-analysis. *Front Plant Sci* 11: 588550. https://doi.org/10.3389/fpls.2020.588550
120. Madawala HMSP (2021) Arbuscular mycorrhizal fungi as biofertilizers: Current trends, challenges, and future prospects, *Biofertilizers*, Cambridge: Woodhead Publishing, 83–93. https://doi.org/10.1016/B978-0-12-821667-5.00029-4
121. Li Z, Wu N, Meng S, et al. (2020) Arbuscular mycorrhizal fungi (AMF) enhance the tolerance of Euonymus maackii Rupr. at a moderate level of salinity. *PLoS One* 15: e0231497. https://doi.org/10.1371/journal.pone.0231497