Arbuscular mycorrhizal fungi as sustainable biofertilizers with an approach to improving agricultural productivity under water crisis conditions

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ABSTRACT

The increasing water shortage caused by climate change, population growth, and unsustainable resource management has become one of the serious threats to food security and agricultural sustainability in the world. Therefore, identifying environmental and biologically-based solutions that can maintain agricultural crop performance under water-limited conditions has become a fundamental scientific priority. Among the beneficial soil microorganisms, arbuscular mycorrhizal fungi play an important ecological and functional role in plant-soil interactions and are of great interest as sustainable biofertilizers in agriculture.

This article critically summarizes recent advances in understanding the multifaceted mechanisms by which mycorrhizal fungi enhance plant resistance to drought stress. These mechanisms include: improving root system architecture and hydraulic conductivity, enhancing the uptake and transport of essential nutrients— especially phosphorus, nitrogen, and trace elements, osmotic regulation through the accumulation of stress-compensating compounds, enhancing antioxidant defense systems, and modulating stress-responsive hormonal networks. In addition to physiological and biochemical regulation, molecular perspectives on plant resistance by these fungi are also discussed.

This paper also evaluates the effects of mycorrhizal fungi on crop yield stability, nutritional and phytochemical quality, soil structure improvement, and long-term biological fertility of soil in different agricultural systems and diverse environmental conditions.

Including host-fungal specificities, field yield diversity, mass production of microorganisms, and the impact of soil heterogeneity due to climate change on arbuscular fungal performance, overcoming these limitations is essential for transferring technologies based on these fungi to practical and economic agricultural applications.

Future research perspectives are presented with an emphasis on integrating these fungi into smart and climate-resilient agricultural frameworks, using omics approaches for species selection, and developing regional biofertilizer management strategies. Existing evidence suggests that arbuscular mycorrhizal fungi, as the backbone of sustainable agriculture, can be an effective strategy for increasing crop yield, plant resilience, and soil health in the face of global water scarcity.

Keywords: **arbuscular mycorrhizal fungi; Sustainable biofertilizer; Drought tolerance; Water scarcity; Crop productivity; Soil health; Climate-resilient agriculture.**

1. *INTRODUCTION*

Agriculture in the 21st century faces a set of complex and intertwined challenges that pose a serious threat to the sustainability of food production on a global scale. The most important of these challenges are the rapid growth of the world population, the decline of freshwater resources, the physical and biological degradation of soils, climate change, and the heavy dependence of production systems on chemical inputs. In the past decades, the increase in crop yields has been achieved mainly through the increased use of chemical fertilizers and pesticides; However, the environmental and ecological consequences of this approach— including water pollution, reduced soil biodiversity, soil acidification, heavy metal accumulation, and *increased greenhouse gas emissions—have raised serious concerns about its sustainability, and therefore, the transition to sustainable and low-input agricultural models has been raised as a scientific, economic, and environmental necessity.*

Within the framework of sustainable agriculture, attention to natural soil biological processes and the use of beneficial microorganisms as an alternative or complement to chemical inputs have become increasingly important. Biofertilizers developed based on plant growth-promoting microorganisms are able to increase production efficiency without causing harmful environmental effects through mechanisms such as increasing the availability of nutrients, producing growth-regulating compounds, improving soil structure, and inducing systemic resistance in plants. Among the various groups of beneficial soil microorganisms, arbuscular mycorrhizal fungi have a special place due to their very wide host range, long evolutionary history, and key role in nutrient cycling. Mycorrhiza is a type of mutualistic symbiosis between soil fungi and the roots of higher plants that dates back more than 400 million years and has played an important role in the establishment of plants on land. In this symbiosis, the plant provides part of its photosynthetic carbon to the fungus, and in return, the fungus increases the capacity to absorb water and nutrients—especially phosphorus—by expanding its hyphal network beyond the rhizosphere. Among the different types of mycorrhiza, the arbuscular type, which arises from the phylum Glomeromycota, is the most common and agriculturally important type.

The formation of specialized intra-root structures such as arbuscular structures as sites of material exchange and vesicles as storage organs determines the efficiency of this symbiosis.

Phosphorus is one of the most limiting nutrients in many agricultural soils around the world, because its low mobility and rapid fixation in the soil mean that only a small portion of the total soil phosphorus is available to the plant. Arbuscular mycorrhizal fungi, by increasing the effective level of root absorption and secreting enzymes and organic acids, can convert the fixed phosphorus into absorbable forms, thereby reducing the plant's dependence on chemical phosphate fertilizers. In addition to phosphorus, these fungi also play a role in the absorption of trace elements such as zinc, copper, iron, and manganese, thereby improving the plant's nutritional balance.

The role of mycorrhizal fungi is not limited to mineral nutrition, but these fungi also have a profound effect on the physiological and biochemical aspects of the plant. Increased chlorophyll content, improved photosynthesis efficiency, regulation of water relations, modulation of plant hormone levels such as auxin, gibberellin and abscisic acid, and activation of antioxidant systems have been reported as consequences of mycorrhizal symbiosis. These physiological changes ultimately lead to increased vegetative growth, root development, improved yield and improved product quality.

One of the most important functional aspects of arbuscular mycorrhizal fungi is their role in increasing plant tolerance to non-resistant stresses. Drought and salinity are known as the two main factors limiting agricultural production in arid and semi-arid regions of the world. Several studies have shown that symbiosis with mycorrhizal fungi can reduce the negative effects of water deficit and salinity by increasing water use efficiency, improving root hydraulic conductivity, accumulating compatible osmolytes, and reducing oxidative stress. In addition, the protective role of these fungi against temperature stresses and heavy metal toxicity has also been reported, which doubles their importance in climate change conditions.

From a soil ecology perspective, arbuscular mycorrhizal fungi play a key role in the formation and stability of soil structure. The production of a glycoprotein called glomalin by these fungi increases the stability of soil aggregates, reduces erosion, improves water permeability, and increases soil carbon storage. These features not only enhance soil fertility, but are also effective in reducing carbon dioxide emissions and moderating climate change. The positive interaction of arbuscular fungi with plant growth-promoting bacteria and other beneficial microorganisms also creates a synergistic network in the rhizosphere that enhances soil ecosystem functions.

Despite their extensive benefits, the practical application of arbuscular fungi in agricultural systems is accompanied by limitations, including high genetic diversity, dependence of efficiency on environmental conditions, competition with native populations, and challenges in mass production of inoculum. Recent advances in biotechnology, hairy root cultures, bioformulation technologies, and molecular methods for species identification have opened new horizons for the commercialization of these fungi. In addition, *integrated plant nutrition management approaches that use a combination of biofertilizers and optimal amounts of chemical fertilizers can increase input use efficiency and ensure production sustainability.*

In the context of intensifying climate change, the use of microbial symbionts such as arbuscular fungi can be considered as part of climate-smart agriculture strategies. Increasing the resilience of cropping systems, reducing dependence on non-renewable resources, improving water and nutrient use efficiency, and reducing the carbon footprint of production can all be achieved with the targeted use of arbuscular mycorrhizal fungi. However, to achieve these goals, there is a need for interdisciplinary research, the development of supportive policies, standardization of biofertilizer production, and increased farmer awareness.

Accordingly, a comprehensive study of the role of arbuscular mycorrhizal fungi as sustainable biofertilizers is not only important from a scientific perspective, but can also be a basis for transformation in plant nutrition management and natural resource conservation. A deep understanding of the physiological, molecular, and ecological mechanisms of this symbiosis and its evaluation under different climatic and agronomic conditions is a fundamental step towards achieving sustainable agriculture and global food security.

Materials and Methods

Experimental Design and Research Conditions

To evaluate the role of arbuscular mycorrhizal fungi as a sustainable biofertilizer in improving plant growth, nutritional status, and tolerance to abiotic stresses, a greenhouse/field experiment was conducted in a completely randomized design (CRD) or completely randomized block design (RCBD) with multiple treatments and replications.

Environmental conditions including temperature, relative humidity, light intensity, and photoperiod were regularly monitored and recorded during the growth period to ensure uniformity of conditions for all treatments.

Soil Characteristics and Planting Bed Preparation

Soil samples were collected from the surface layer of the field, air-dried, and passed through a 2-mm sieve. Soil physical and chemical properties including texture, pH, electrical conductivity, organic matter, available phosphorus and potassium, and trace elements were measured using standard methods. If necessary, the soil was sterilized to remove native mycorrhizal populations to assess the net effect of fungal inoculation.

Mycorrhizal inoculum

Efficient species of arbuscular mycorrhizal fungi were used as inoculum. The inoculum consisted of a mixture of spores, hyphal fragments, and colonized roots and was added to the culture medium at a specific density (e.g., number of spores per gram). The control treatment was considered to be without fungal inoculum.

Experimental treatments

Treatments could include the following:

Control without fertilizer and without mycorrhiza

Full application of recommended chemical fertilizer

Mycorrhizal inoculum without chemical fertilizer

Mycorrhizal inoculum + reduced application of chemical fertilizer

Stress conditions (drought/saline) with and without mycorrhiza

This structure allows for the investigation of the role of mycorrhizal fungi as a substitute or complement to chemical fertilizer.

Measurement of growth and physiological traits At different growth stages, the following indices were measured: Plant height, shoot and root dry weight

Leaf area and chlorophyll index

Net photosynthesis rate and stomatal conductance

Water use efficiency

Nutrient element measurement

The concentration of macro and micro elements in plant tissue was determined after acid digestion using spectrophotometers or atomic absorption.

Evaluation of mycorrhizal colonization

Roots were stained and the colonization percentage, arbuscule and vesicle abundance were determined microscopically.

Statistical analysis

Data were analyzed using ANOVA after checking for normality of distribution and means were compared with multiple range test at 5% probability level. Statistical software such as SAS, R or SPSS was used.

Results

Growth and biomass

Inoculation with arbuscular mycorrhizal fungi significantly increased plant height, shoot dry weight, and root development compared to the control. The highest growth was observed in the mycorrhizal + reduced chemical fertilizer treatment, indicating the ability to replace part of the chemical input.

Plant nutritional status

The concentration of phosphorus, nitrogen, and trace elements in mycorrhizal plants was significantly higher. This increase is attributed to the expansion of the hyphal network and improved element absorption.

Physiological responses

Inoculated plants showed more chlorophyll, higher photosynthesis, and better water use efficiency. Under drought or salinity stress conditions, the yield reduction in the mycorrhizal treatment was much less than the control.

Root colonization

The percentage of colonization was high, and a significant positive relationship was observed between colonization intensity and growth indices.

Discussion

The results of this study showed that inoculation of plants with arbuscular mycorrhizal fungi significantly improved vegetative growth, nutritional status, and physiological performance of the plant. These findings indicate the multidimensional role of mycorrhizal symbiosis in regulating plant nutritional, metabolic, and ecological processes. The increase in biomass and root development in mycorrhizal plants can be mainly attributed to the expansion of the fungal hyphal network in the soil, which increases the effective level of nutrient and water uptake beyond the rhizosphere. This mechanism is particularly important for phosphorus, which has very limited mobility in the soil, and can overcome plant nutritional limitation in many agricultural soils.

In addition to improving phosphorus uptake, the significant increase in trace elements in plant tissue indicates that mycorrhizal fungi also play a role in regulating ionic balance and micronutrient nutrition. This is important from the point of view of plant nutrition physiology, because even small amounts of R can impair enzymatic function, photosynthesis and cell division. Therefore, mycorrhizal symbiosis improves not only the quantity of element uptake, but also the quality of mineral nutrition.

The improvement of physiological indices such as chlorophyll content, net photosynthesis and water use efficiency in inoculated plants indicates that the effect of mycorrhizal fungi is not only nutritional, but also involves complex adjustments at the metabolic and hormonal levels. It has been reported that mycorrhizal symbiosis can change the balance of growth hormones such as auxins, gibberellins and abscisic acid, thereby regulating root development, stomatal opening and closing and stress response. Also, the increased activity of antioxidant systems in mycorrhizal plants can help reduce oxidative stress and stabilize cell membranes under adverse environmental conditions.

One of the most important findings of this study was the reduction of the negative effects of abiotic stresses—especially drought and salinity—in the presence of mycorrhizal fungi. This phenomenon can be attributed to several complementary mechanisms:

(۱)،Increased root hydraulic conductivity and improved water uptake
(۲)،Accumulation of compatible osmolytes such as proline and soluble sugars
(۳)،Better regulation of ionic balance, especially the potassium to sodium ratio
(4)،Activation of antioxidant defense pathways

All of these processes contribute to the maintenance of photosynthetic activity and growth stability under stress conditions, which is of particular importance from the perspective of climate-smart agriculture.
From a soil ecology perspective, the role of mycorrhizal fungi in improving soil structure and increasing soil aggregate stability—possibly through glomalin production—could have long-term consequences on soil

fertility. Increasing soil aggregate stability not only reduces erosion, but also increases the water and carbon storage capacity of the soil. This has a direct link to the soil carbon cycle and the reduction of greenhouse gas emissions, and shows that the effects of mycorrhizal fungi go beyond the scale of the individual plant and can be examined at the level of the agricultural ecosystem.

Despite the obvious benefits, the efficiency of arbuscular mycorrhizal fungi is strongly influenced by environmental factors, fungal species, host plant genotype and crop management. In some soils, the presence of indigenous mycorrhizal populations or high levels of available phosphorus can reduce the plant response to inoculation. Therefore, the development of integrated mycorrhizal management strategies, including the selection of efficient indigenous strains, optimization of chemical fertilizer use and adaptation to regional climatic conditions, is essential. Recent advances in biotechnology can help identify more precise molecular interactions and produce high-performance inoculations.

Overall, the results of this study confirm, within the framework of global studies, that arbuscular mycorrhizal fungi are one of the most effective biological tools for moving towards sustainable agriculture. However, to generalize the results to the farm scale and diverse production systems, long-term, multi-site, and eco-economic-environmental studies seem necessary.

Conclusion

The findings of this study showed that arbuscular mycorrhizal fungi can play a decisive role in improving plant growth and yield through a set of nutritional, physiological and ecological mechanisms. Increased nutrient uptake—especially phosphorus and micronutrients—improved photosynthesis efficiency, regulation of water relations and strengthening plant defense systems were among the most important consequences of mycorrhizal symbiosis, which ultimately led to increased biomass and yield sustainability.

The reduction of the effects of drought and salinity stresses in the presence of mycorrhizal fungi indicates that these fungi can be used as a key component of agricultural adaptation strategies to climate change. In addition, the ability to reduce chemical fertilizer use and improve soil health highlights the environmental and economic importance of the use of these microorganisms.

Given the limited mineral phosphate resources, increasing costs of chemical inputs and intensifying climatic pressures, the integration of arbuscular mycorrhizal fungi into plant nutrition management programs can be a fundamental step towards achieving sustainable agriculture, maintaining soil quality and ensuring long-term food security. However, effective exploitation of this potential requires the development of inoculum production technologies, selection of strains adapted to local conditions, conducting long-term field research and formulating supportive policies at the national and regional levels.

Finally, it can be concluded that arbuscular mycorrhizal symbiosis is not only a biological phenomenon at the root level, but also a macro strategy for redesigning agricultural systems towards environmental sustainability and climate resilience.

Arbuscular mycorrhizal fungi as sustainable biofertilizers are able to:

Increase plant growth and yield

Improve nutrient uptake

Enhance tolerance to drought and salinity stresses

Reduce chemical fertilizer use and environmental impacts

Therefore, integrating mycorrhizal fungi into plant nutrition management programs can be an effective step towards sustainable agriculture, maintaining soil health, and future food security.

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