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# ROLE OF ARBUSCULAR MYCORRHIZAL FUNGI IN ENHANCING DROUGHT RESISTANCE OF *PANICUM TURGIDUM* IN ARID ECOSYSTEMS

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**Abstract**

Drought stress, salinity, nutrient deficiency and desertification are major factors that cause reduction in the productivity of ecosystems and plant growth in arid and semi-arid ecosystems. *Panicum turgidum* Forssk. is a perennial halophytic grass found essentially throughout the desert of the Arabian-peninsula and northern Africa which is ecologically important in desert rangelands for soil-stabilization, forage production and ecosystem resilience. AM fungi have an ecological relationship that is devoted to a mutualistic relationship on about 80-90% of the terrestrial flora with the capacity to benefit the plant significantly in nutrient uptake, water uptake, antioxidant defense and regulation of stress responsive physiological processes, and to increase the tolerance of the plants to abiotic stresses. This review aimed to summarize the knowledge about the ecological, physiological, biochemical and molecular mechanisms of how AM fungi can improve the drought resistance of *Panicum turgidum* in arid environments. Special emphasis on the AMF mediated increase in water use efficiency, root architecture, osmotic regulation, antioxidant defense systems, phytohormonal signaling and rhizosphere interaction. The importance of AMF in desert ecosystem stability, aggregation, nutrient cycling and desertification was also discussed. Further, some applications of AMF-based technologies for restoring rangelands sustainably and managing land for climate change resilience under the framework of AMF are put forward. Although significant advances have been made, there are still significant gaps in the knowledge concerning long-term studies on the desert AM fungi, molecular characterization of the desert AM community, and the effects of climate change on AM symbiosis. Overall, the use of *Panicum turgidum* together with native arbuscular mycorrhizal fungi seems to be a promising ecological approach for increasing the drought resistance of environments, establishing degraded rangelands, and optimizing their management in dry and arid lands.

**Key words:** *Panicum turgidum*; Arbuscular mycorrhizal fungi; Drought stress; Desert ecosystems; Water use efficiency; Rhizosphere; Arid rangelands; Abiotic stress tolerance.

**Abbreviation first definition:** AMF: Arbuscular mycorrhizal fungi; WUE: Water-use efficiency; ROS: Reactive oxygen species; PSII: Photosystem II; LWP: Leaf water potential; ABA: Abscisic acid; SOD: Superoxide dismutase; CAT: Catalase; POD: Peroxidase; APX: Ascorbate peroxidase; PEPC: Phosphoenolpyruvate carboxylase; PPDK: Pyruvate phosphate dikinase; NADP-ME: NADP-dependent malic enzyme; HKT: High-affinity potassium transporter; NHX: $Na^+/H^+$ exchanger; SOS: Salt overly sensitive pathway.

## Introduction

Arid and semi-arid regions constitute the largest terrestrial biomes on Earth and are characterized by low and irregular rainfall, high evapotranspiration, nutrient-poor soils, salinity, and extreme temperature fluctuations. These regions are ecologically important because they support unique biodiversity, livestock grazing, nutrient cycling, carbon sequestration, and the livelihoods of millions of people living in drylands. However, adverse environmental conditions, together with increasing anthropogenic pressures, have accelerated desertification and land degradation. In Saudi Arabia, rangelands cover approximately 170 million hectares, accounting for nearly 70% of the country's total land area, although large areas have been severely degraded by overgrazing, urbanization, and recurrent droughts (Madouh & Quoreshi, 2023). Consequently, drylands are among the most vulnerable ecosystems worldwide, highlighting the need for sustainable ecological management strategies to maintain their productivity and biodiversity (El-Sheikh *et al*., 2012; Assaeed *et al*., 2017; Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022).

Drought is the most severe abiotic stress limiting plant growth and productivity in these environments. Water scarcity adversely affects plant morphology, physiology, biochemistry, and molecular processes by restricting cell expansion, stomatal conductance, nutrient uptake, chlorophyll biosynthesis, and ultimately biomass accumulation (Jajoo & Mathur, 2021). It also disrupts cellular osmotic balance and promotes the accumulation of reactive oxygen species (ROS), including hydrogen peroxide, superoxide, and hydroxyl radicals, which damage cell membranes, proteins, nucleic acids, and chloroplasts. Consequently, photosystem II (PSII) is highly susceptible to drought-induced oxidative damage, resulting in reduced photosynthetic efficiency and carbon fixation (Jajoo & Mathur, 2021). Prolonged drought further suppresses soil microbial activity and nutrient mobility, thereby exacerbating nutrient deficiency and reducing ecosystem productivity (Hashem *et al*., 2015; Santander *et al*., 2017; Bahadur *et al*., 2019; Cheng *et al*., 2021; Tang *et al*., 2022).

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Desert ecosystems harbor native plant species with specialized adaptations that enable survival under prolonged drought and salinity. Among these, *Panicum turgidum* Forssk. is recognized as one of the most ecologically important perennial grasses of the Arabian Peninsula and North Africa. A member of the family Poaceae, it is naturally distributed throughout Saudi Arabia, Kuwait, Egypt, Sudan, and other desert regions (El-Sheikh *et al*., 2012). The species inhabits coastal dunes, inland sandy plains, wadis, gravel deserts, and saline habitats characterized by harsh environmental conditions (Heneidy & Halmy, 2009). Its broad ecological distribution and remarkable tolerance to water limitation and nutrient-poor soils make it a key component of desert vegetation (El-Sheikh *et al*., 2012; Assaeed *et al*., 2017; Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022). *P. turgidum* plays a vital ecological role in sand dune stabilization, soil conservation, fertility improvement, and rangeland productivity. Its deep and extensive root system enables efficient extraction of water from deeper soil horizons, allowing survival during prolonged drought. Furthermore, its $C_4$ photosynthetic pathway enhances photosynthetic efficiency and water-use efficiency under high temperatures and limited water availability, making it more drought tolerant than many other grasses (Van de Wouw *et al*., 2008). The species is also an important forage resource for desert livestock and contributes substantially to ecological resilience and biodiversity conservation (Heneidy & Halmy, 2009; El-Sheikh *et al*., 2012; Assaeed *et al*., 2017; Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022).

As a halophytic species, *P. turgidum* possesses several physiological and structural adaptations that facilitate survival under both drought and salinity stress. These include reduced transpiration, enhanced water-use efficiency, osmotic adjustment, salt compartmentalization, succulence, and efficient ion transport systems. Hameed *et al*., (2024) reported that halophytes maintain ion homeostasis by regulating the movement of $Na^+$ and $K^+$ through specialized membrane transporters and vacuolar sequestration, thereby reducing ionic toxicity and maintaining cellular stability. In addition, halophytes accumulate compatible osmolytes, including proline and soluble sugars, and possess efficient antioxidant defense systems that protect against environmental stress-induced cellular damage (Hashem *et al*., 2015; Santander *et al*., 2017; Bahadur *et al*., 2019; Cheng *et al*., 2021; Tang *et al*., 2022).

Despite these adaptive traits, vegetation stability and ecosystem functioning remain threatened by increasing climatic variability and prolonged drought. Consequently, recent research has focused on beneficial plant–microbe interactions, particularly those involving arbuscular mycorrhizal fungi (AMF). These obligate symbiotic fungi, belonging primarily to the phylum *Glomeromycota*, form mutualistic associations with approximately 80–90% of terrestrial plant species (Jha & Songachan, 2023). By colonizing root cortical tissues and forming specialized structures known as arbuscules and vesicles, AMF facilitate the exchange of nutrients and carbohydrates between the fungus and its host plant (Giovannetti & Gianinazzi-Pearson, 1994; Delian *et al*., 2011; Nadeem *et al*., 2017; Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022).

AMF are key components of soil microbial communities because they enhance plant growth, nutrient and water uptake, and tolerance to environmental stresses. Their extensive hyphal networks explore soil volumes beyond the rhizosphere, improving the acquisition of phosphorus, nitrogen, micronutrients, and water (Jha & Songachan, 2023). In addition, AMF promote soil aggregation through the production of glomalin-related proteins, thereby improving soil stability and water-holding capacity and contributing to soil fertility in drylands (Heneidy & Halmy, 2009; Powell & Rillig, 2018). Under drought stress, AMF enhance root biomass, water-use efficiency, leaf water potential, and photosynthetic performance. Begum *et al*., (2019) demonstrated that AMF improve nutrient uptake, metabolism, biomass production, chlorophyll biosynthesis, and antioxidant enzyme activities, including catalase, superoxide dismutase, peroxidase, and ascorbate peroxidase, thereby minimizing ROS-induced oxidative damage. In addition to regulating stomatal behavior under water deficit, AMF also modulate phytohormones such as abscisic acid, auxins, and jasmonic acid (Hashem *et al*., 2015; Santander *et al*., 2017; Bahadur *et al*., 2019; Cheng *et al*., 2021; Tang *et al*., 2022). Recent studies have reported approximately 90% AMF colonization in the roots of *P. turgidum*, demonstrating the strong compatibility between this desert grass and native AMF communities in the arid ecosystems of Kuwait (Madouh *et al*., 2025). These symbiotic associations promote plant establishment, drought tolerance, and ecological stability while supporting vegetation restoration and desertification control (El-Sheikh *et al*., 2012; Assaeed *et al*., 2017; Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022). Collectively, the physiological, biochemical, and ecological benefits conferred by AMF highlight their considerable potential for enhancing the drought resilience of *Panicum turgidum* and promoting sustainable management of arid landscapes. Although the role of arbuscular mycorrhizal fungi (AMF) in enhancing plant tolerance to drought and other abiotic stresses is well established across a wide range of plant species (Diagne *et al*., 2020), species-specific knowledge regarding the AMF *Panicum turgidum* symbiosis remains limited. As a dominant perennial grass of arid ecosystems, *P. turgidum* represents an excellent model for investigating how native AMF contribute to drought adaptation, soil stabilization, and ecosystem resilience under extreme desert conditions. Therefore, focusing on the AMF–*P. turgidum* interaction extends beyond the general AMF literature by integrating ecological, physiological, biochemical, and molecular evidence relevant to sustainable dryland restoration and climate-resilient rangeland management (Delavaux *et al*., 2017; Cheng *et al*., 2021). Hence, the objectives of this review are to summarize the available scientific evidence on the mechanisms of AMF-induced drought tolerance in *P. turgidum* and their perspectives for sustainable management in desert ecosystems and rangeland rehabilitation.

## Ecological and biological characteristics of *Panicum turgidum*

**Geographic distribution in arid regions of Saudi Arabia:** *Panicum turgidum* Forssk. is a perennial halophytic desert grass widely distributed across the arid and semi-arid regions of Saudi Arabia, Kuwait, Egypt, Sudan, and other North African deserts. It naturally occurs in coastal dunes, inland sandy plains, wadis, gravel deserts, and other habitats characterized by low rainfall, high evapotranspiration, alkaline nutrient-poor soils, and

frequent drought (El-Sheikh *et al*., 2012). As a dominant component of the native desert flora and rangelands of the Arabian Peninsula, *P. turgidum* exhibits exceptional tolerance to prolonged drought and salinity, enabling it to persist under harsh environmental conditions (El-Sheikh *et al*., 2012; Assaeed *et al*., 2017; Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022). Van de Wouw *et al*., (2008) evaluated 74 perennial *Panicum* accessions using 49 agro-morphological traits and identified *P. turgidum*, *P. antidotale*, and *P. phragmitoides* among the most drought-tolerant species. Their evaluation under alkaline sandy soil conditions with approximately 600 mm annual rainfall further demonstrated the remarkable adaptability of *P. turgidum* to water-limited environments (Van de Wouw *et al*., 2008). Likewise, Heneidy & Halmy (2009) reported its occurrence across diverse desert habitats in Egypt, reflecting its broad ecological plasticity and adaptability. Owing to these characteristics, *P. turgidum* plays an important ecological role in sustaining ecosystem productivity and stability under extreme desert conditions (Fig. 1) (El-Sheikh *et al*., 2012; Assaeed *et al*., 2017; Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022; Hameed *et al*., 2024).

**Morphological and physiological adaptations to drought:** The ability of *Panicum turgidum* to tolerate drought and salinity stress is associated with several important morphological and physiological adaptations. One of the major adaptations is the development of deep and extensive root systems that enhance water absorption from deeper soil horizons. These extensive root networks enable efficient exploitation of scarce soil moisture resources under desert conditions (Heneidy & Halmy, 2009). Root proliferation also contributes significantly to soil binding and stabilization of mobile sand dunes (Hashem *et al*., 2015; Santander *et al*., 2017; Bahadur *et al*., 2019; Cheng *et al*., 2021; Tang *et al*., 2022).

The species exhibits C4 photosynthetic metabolism, which improves photosynthetic efficiency and water use efficiency under high temperatures and drought conditions. C4 plants generally possess lower photorespiration rates and higher carbon assimilation efficiency compared with C3 species, enabling continued biomass production under limited water availability (Van de Wouw *et al*., 2008). Reduced transpiration surfaces, thick cuticular layers, and narrow leaves further minimize water loss and improve drought survival (Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022).

Halophytic species including *P. turgidum* also possess specialized physiological mechanisms for ion regulation and osmotic adjustment. Hameed *et al*., (2024) explained that halophytes maintain cellular ion homeostasis through compartmentalization of toxic ions within vacuoles and regulation of ion transporters such as HKT, NHX, and SOS transport systems. Such mechanisms reduce ionic toxicity and maintain osmotic balance under saline conditions. Moreover, drought-adapted grasses frequently accumulate osmoprotectants including proline, soluble sugars, and compatible solutes that stabilize proteins and cellular membranes during dehydration stress (Hashem *et al*., 2015; Santander *et al*., 2017; Bahadur *et al*., 2019; Cheng *et al*., 2021; Tang *et al*., 2022). Several studies further demonstrated the importance of beneficial microbial associations in improving physiological adaptation of *P. turgidum*. Arbuscular mycorrhizal fungi (AMF) enhance nutrient uptake, water acquisition, antioxidant defense, and osmotic regulation under drought conditions. Madouh *et al*., (2025) reported approximately 90% vesicle colonization in *P. turgidum* roots collected from desert ecosystems of Kuwait, indicating strong compatibility between native AMF communities and the host plant. Such symbiotic relationships significantly improve plant adaptation and survival in water-deficient environments (Fig. 2) (Delian *et al*., 2011; Nadeem *et al*., 2017; Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022).

As a halophytic species, *Panicum turgidum* experiences not only water deficit caused by low precipitation but also physiological drought resulting from high soil salinity. Under saline conditions, elevated concentrations of soluble salts decrease the soil water potential, thereby restricting water uptake despite the presence of soil moisture (Munns & Tester, 2008). Consequently, *P. turgidum* must simultaneously cope with osmotic stress, ion toxicity, and dehydration. While its intrinsic halophytic adaptations, including $Na^+$ sequestration and $K^+$ homeostasis mediated by NHX, SOS, and HKT transport systems, help maintain cellular ion balance (Hameed *et al*., 2024), AMF provide complementary benefits by improving root hydraulic conductivity, water uptake, osmotic adjustment, nutrient acquisition, and antioxidant defense. Thus, AMF support *P. turgidum* under both hyper-arid drought, where soil water is scarce, and salt-induced physiological drought, where water availability is limited by osmotic constraints rather than the absence of water (Evelin *et al*., 2009; Porcel *et al*., 2012; Begum *et al*., 2019).

Compared with other halophytic grasses, *Panicum turgidum* is distinguished by its deep and extensive root system, which enhances water acquisition, stabilizes sand dunes, and reduces soil erosion under extreme arid conditions (Heneidy & Halmy, 2009; El-Sheikh *et al*., 2012). As a perennial $C_4$ grass, it exhibits high water-use efficiency and sustained productivity during prolonged drought (Van de Wouw *et al*., 2008). Moreover, its high forage value for desert livestock and strong association with native arbuscular mycorrhizal fungi make it an important species for rangeland restoration, biodiversity conservation, and desertification control in arid ecosystems (Assaeed *et al*., 2017; Madouh *et al*., 2025).

**Role in desert rangeland ecosystems and soil stabilization:** *Panicum turgidum* plays a critical ecological role in maintaining desert ecosystem stability and productivity (Table 1). The species contributes substantially to sand dune stabilization and prevention of soil erosion through its dense and extensive root systems. In arid ecosystems, wind erosion and desertification are major environmental concerns due to low vegetation cover and loose sandy soils. The root architecture of *P. turgidum* effectively binds soil particles, thereby reducing sand movement and improving soil stability (Heneidy & Halmy, 2009; El-Sheikh *et al*., 2012; Assaeed *et al*., 2017; Powell & Rillig, 2018).

The species also functions as an important forage resource for livestock in desert rangelands. Heneidy & Halmy (2009) reported that *P. turgidum* possesses significant nutritive value and contributes to sustaining grazing systems in Egyptian desert ecosystems. Due to its perennial growth habit and drought tolerance, the species maintains biomass production under severe environmental

conditions where many annual grasses fail to survive. Consequently, *P. turgidum* supports pastoral communities and contributes to food security in arid regions (Fernández-Lizarazo & Moreno-Fonseca, 2016; Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022; Abdalla *et al*., 2023). In addition to forage production, *P. turgidum* contributes to ecological resilience by improving soil fertility and facilitating establishment of associated vegetation. Desert grasses often act as nurse plants by reducing soil surface temperature, improving organic matter accumulation, and creating favorable microhabitats for other plant species. The species therefore contributes significantly to biodiversity conservation and restoration of degraded rangelands (El-Sheikh *et al*., 2012; Assaeed *et al*., 2017; Jian *et al*., 2024).

Beneficial interactions between *P. turgidum* and arbuscular mycorrhizal fungi further enhance ecosystem functioning. AMF improve soil aggregation and water retention through extensive fungal hyphal networks and production of glomalin-related proteins (Begum *et al*., 2019). Such interactions improve rhizosphere stability and nutrient cycling, thereby enhancing productivity and ecological sustainability of desert ecosystems. Consequently, *P. turgidum* and its associated microbial communities represent valuable ecological resources for combating desertification and promoting sustainable management of arid rangelands (Heneidy & Halmy, 2009; El-Sheikh *et al*., 2012; Assaeed *et al*., 2017; Powell & Rillig, 2018).

## Arbuscular Mycorrhizal Fungi: General Overview

**Definition and taxonomy of arbuscular mycorrhizal fungi:** Arbuscular mycorrhizal fungi (AMF) are obligate symbiotic fungi belonging primarily to the phylum *Glomeromycota* that form mutualistic associations with the roots of most terrestrial plants. By developing arbuscules and vesicles within root cortical tissues, AMF facilitate nutrient exchange, promote plant growth, and enhance tolerance to environmental stresses (Giovannetti & Gianinazzi-Pearson, 1994). Approximately 80–90% of terrestrial plant species establish symbiosis with AMF, underscoring their ecological importance in natural and agricultural ecosystems (Heneidy & Halmy, 2009; El-Sheikh *et al*., 2012; Assaeed *et al*., 2017; Powell & Rillig, 2018; Jha & Songachan, 2023). Taxonomically, AMF were previously classified under the order *Glomales*, with nearly 130 species identified based on spore and hyphal morphology (Giovannetti & Gianinazzi-Pearson, 1994). Their diversity is influenced by soil properties, salinity, moisture, vegetation, and climatic conditions (Madouh *et al*., 2025), while desert AMF communities exhibit specialized adaptations that enable persistence under high temperatures, salinity, and prolonged drought (Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022).

**Life cycle and colonization process:** The life cycle of arbuscular mycorrhizal fungi (AMF) begins with spore germination in the rhizosphere, followed by hyphal growth toward host roots in response to root exudates. Upon root contact, fungal hyphae colonize the epidermal and cortical tissues, forming intracellular arbuscules and vesicles that facilitate nutrient exchange between the fungus and the host plant (Giovannetti & Gianinazzi-Pearson, 1994; Delian *et al*., 2011; Nadeem *et al*., 2017). Arbuscules serve as the primary sites for the transfer of phosphorus, nitrogen, micronutrients, and water to plants in exchange for photosynthetically derived carbohydrates and lipids, whereas vesicles function mainly in nutrient storage and survival. Extensive extraradical hyphal networks further enhance nutrient and water acquisition under drought conditions (Fig. 3) (Santander *et al*., 2017; Bahadur *et al*., 2019; Begum *et al*., 2019; Tang *et al*., 2022). AMF colonization is strongly influenced by soil moisture, salinity, temperature, and nutrient availability. In desert ecosystems, Madouh *et al*., (2025) reported approximately 90% vesicle colonization in *Panicum turgidum* roots, highlighting the strong compatibility between native AMF communities and this desert grass under arid conditions (Hashem *et al*., 2015; Boorboori & Lackóová, 2025).

**Symbiotic relationship with host plants:** The relationship between arbuscular mycorrhizal fungi (AMF) and host plants is a highly evolved mutualistic symbiosis in which plants provide carbohydrates and lipids for fungal metabolism, while AMF enhance the uptake of phosphorus, nitrogen, micronutrients, and water (Jha & Songachan, 2023). This association improves plant growth, nutrient use efficiency, and stress tolerance, making it particularly important in arid ecosystems (El-Sheikh *et al*., 2012; Assaeed *et al*., 2017). AMF further enhance drought adaptation by improving root architecture, photosynthetic performance, water uptake, osmotic adjustment, and antioxidant defense. Begum *et al*., (2019) demonstrated that AMF colonization increases chlorophyll biosynthesis, nutrient acquisition, and antioxidant enzyme activities under abiotic stress, thereby improving plant survival under prolonged drought (Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022). Moreover, extensive fungal hyphal networks and glomalin production improve soil aggregation, water retention, and rhizosphere stability, contributing to vegetation establishment, ecosystem restoration, and the resilience of desert rangelands under climate change (Hashem *et al*., 2015; Boorboori & Lackóová, 2025).

**Table 1. Ecological and Biological Characteristics of *Panicum turgidum*.**

| Parameter | Numerical value | Description | Reference |
|---|---|---|---|
| Number of perennial *Panicum* accessions studied | 74 | Accessions belonging to six perennial *Panicum* species | Van de Wouw *et al*., (2008) |
| Number of agro-morphological traits evaluated | 49 | Traits used for characterization analysis | Van de Wouw *et al*., (2008) |
| Annual rainfall at experimental site | 600 mm | Rainfall at ILRI Zwai site | Van de Wouw *et al*., (2008) |
| Soil pH($H_2O$) | 8.1 | Soil alkalinity at experimental field | Van de Wouw *et al*., (2008) |
| Nitrogen fertilizer application | 200 kg $ha^{-1}$ $yr^{-1}$ | Annual nitrogen application rate | Van de Wouw *et al*., (2008) |
| Phosphorus fertilizer application | 60 kg $ha^{-1}$ $yr^{-1}$ | Annual phosphorus application rate | Van de Wouw *et al*., (2008) |
| Moderate grazing pressure habitats | 26.3% | *P. turgidum* habitats under moderate grazing | Heneidy & Halmy (2009) |
| High grazing pressure habitats | 47.4% | *P. turgidum* habitats under heavy grazing | Heneidy & Halmy (2009) |
| AMF vesicle colonization in *P. turgidum* roots | 90% | Colonization observed in desert grass roots | Madouh *et al*., (2025) |
| Plant species associated with AMF | 80–90% | Terrestrial plant species forming AM symbiosis | Jha & Songachan (2023) |

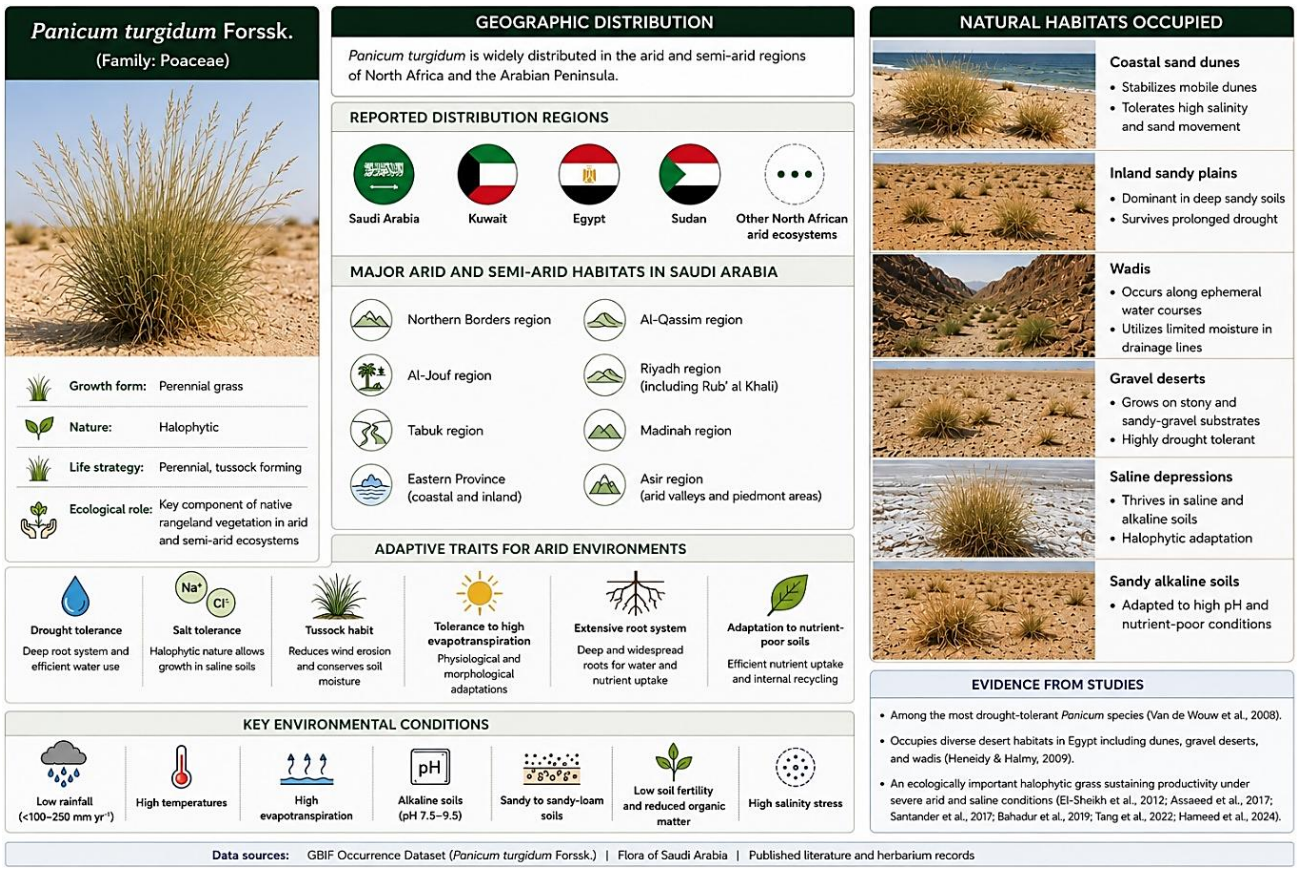


Fig. 1. Schematic illustration of the ecological distribution, natural habitats, environmental conditions, and adaptive traits of *Panicum turgidum* in arid and semi-arid ecosystems of Saudi Arabia and neighboring North African regions (created with https://gpai.app/ solver).

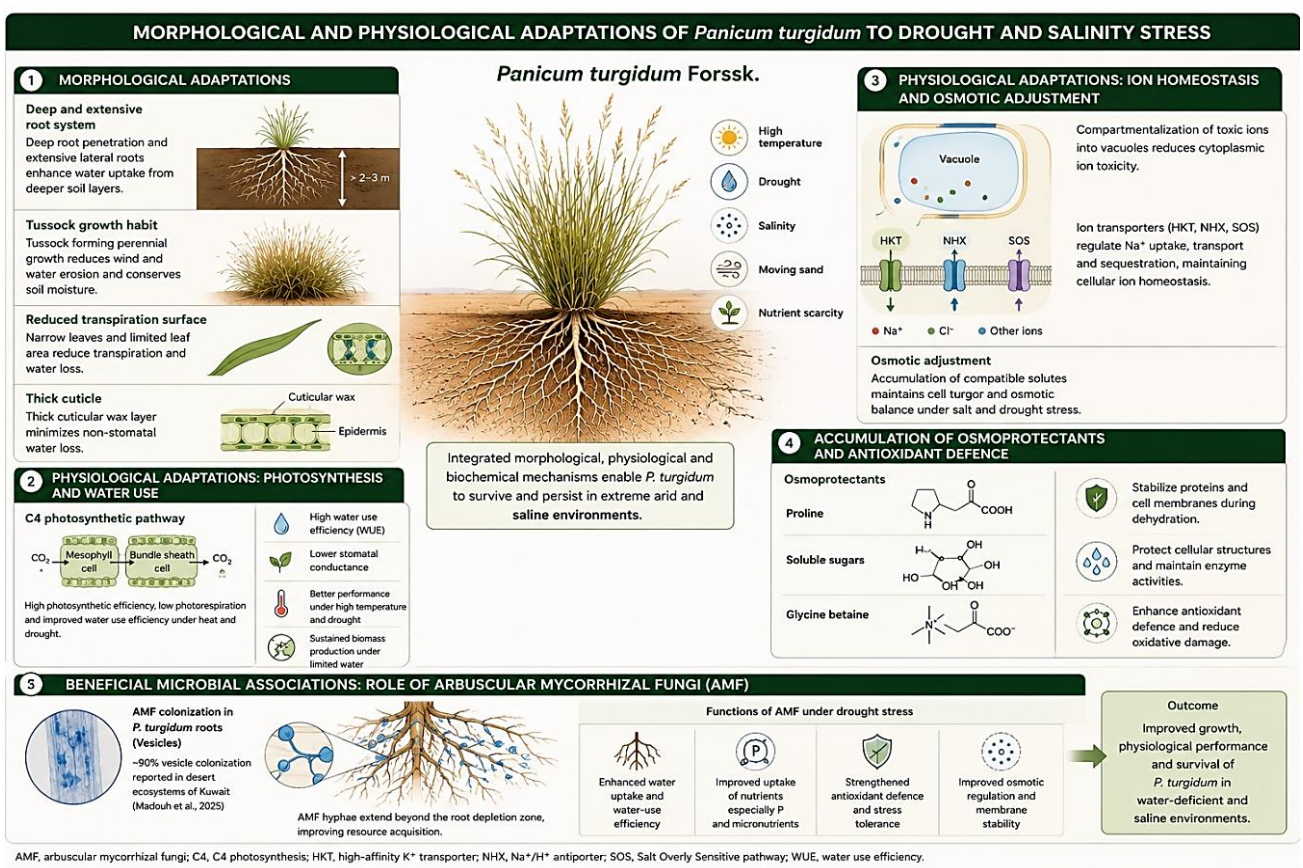


Fig. 2. Schematic representation of the morphological and physiological adaptations of *Panicum turgidum* to drought and salinity stress, highlighting root architecture, C4 photosynthesis, ion homeostasis, osmotic adjustment, osmoprotectant accumulation, and beneficial arbuscular mycorrhizal fungal associations in arid environments (created with BioRender.com).

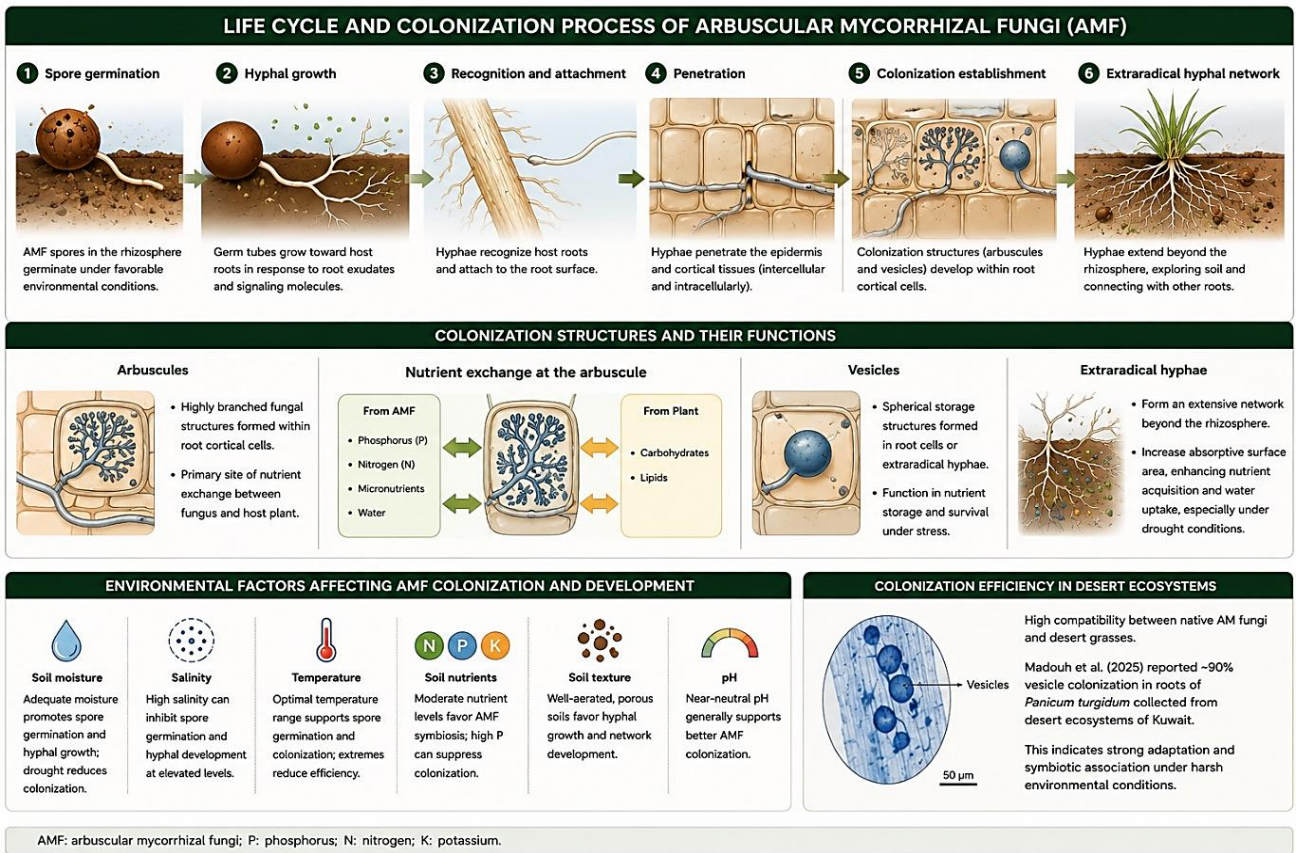


Fig. 3. Schematic representation of the life cycle, root colonization process, and functional structures of arbuscular mycorrhizal fungi (AMF), illustrating spore germination, hyphal growth, root penetration, arbuscule and vesicle formation, nutrient exchange, and environmental factors influencing AMF colonization in desert ecosystems (created with BioRender.com).

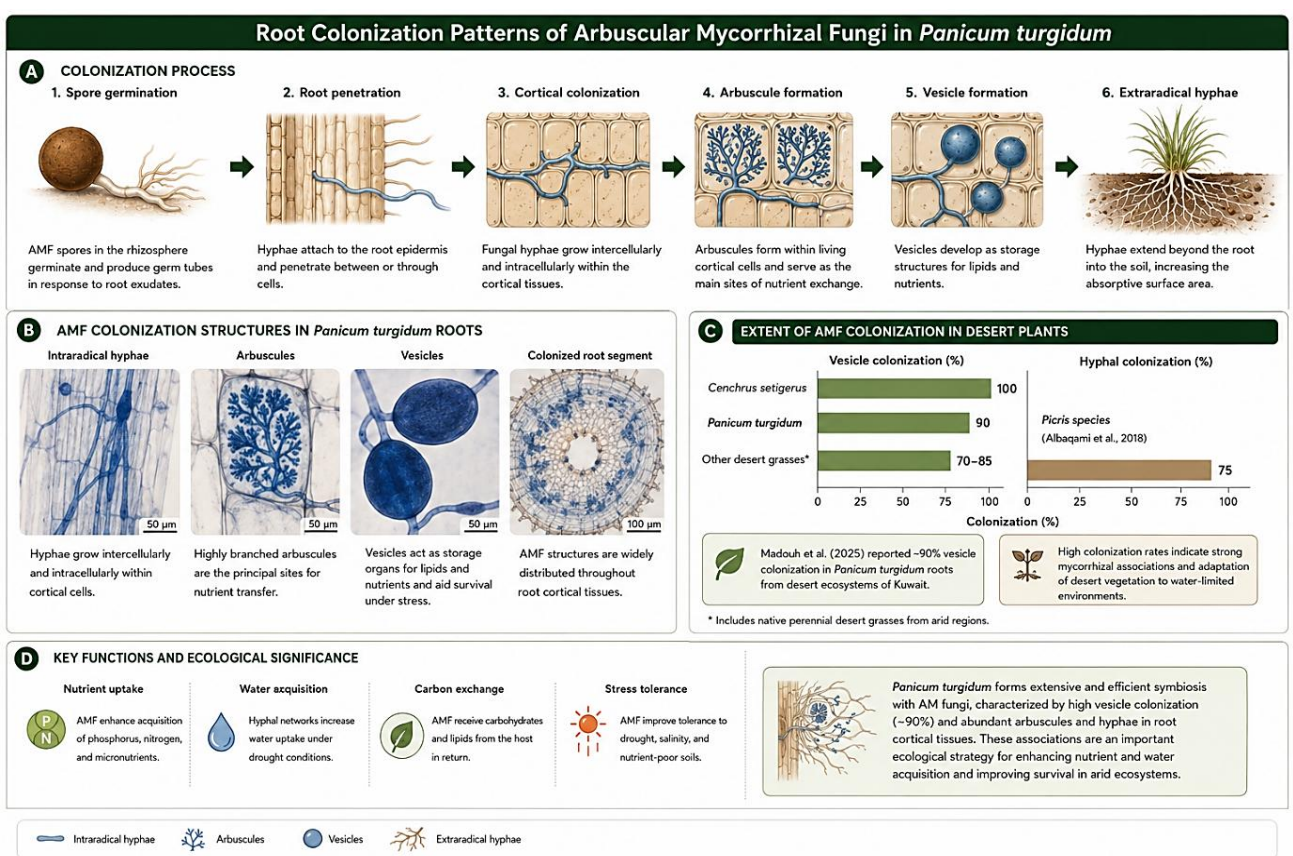


Fig. 4. Schematic representation of arbuscular mycorrhizal fungal (AMF) root colonization patterns in *Panicum turgidum*, illustrating spore germination, root penetration, arbuscule and vesicle formation, intraradical and extraradical hyphal development, and their ecological roles in nutrient uptake and drought adaptation in desert ecosystems (created with BioRender.com).

## Mycorrhizal colonization in *Panicum turgidum*

**Root colonization patterns:** Arbuscular Mycorrhizal Fungi (AMF) establish extensive symbiotic associations with the roots of *Panicum turgidum* in arid and semi-arid ecosystems. Colonization occurs through fungal penetration of root epidermal tissues followed by development of intracellular and intercellular hyphal structures within cortical cells. The most characteristic colonization structures include arbuscules, vesicles, and intraradical hyphae, which collectively facilitate nutrient and water exchange between the fungal symbiont and host plant roots (Giovannetti & Gianinazzi-Pearson, 1994; Heneidy & Halmy, 2009; Delian *et al*., 2011; Nadeem *et al*., 2017; Powell & Rillig, 2018). Studies conducted in desert ecosystems of Kuwait demonstrated substantial AMF colonization in roots of native perennial grasses including *P. turgidum*. Madouh *et al*., (2025) reported approximately 90% vesicle colonization in roots of *P. turgidum*, indicating strong mycorrhizal associations under natural desert conditions. The study further demonstrated that AM fungal structures were widely distributed throughout root cortical tissues, reflecting efficient colonization and adaptation of AMF communities in arid ecosystems. Vesicles formed by AM fungi function primarily as storage organs for lipids and nutrients, while arbuscules serve as the principal sites for nutrient transfer between fungal hyphae and host roots (Fig. 4) (Heneidy & Halmy, 2009; Powell & Rillig, 2018). The extent of AMF colonization in desert grasses varies among plant species and environmental conditions. Madouh *et al*., (2025) observed the highest vesicle colonization (100%) in Cenchrus setigerus, whereas *P. turgidum* exhibited 90% colonization, confirming that perennial desert grasses generally maintain strong mycorrhizal relationships. Similarly, Albaqami *et al*., (2018) reported high hyphal colonization rates in desert plant species from Saudi Arabia, with Picris species exhibiting approximately 75% hyphal colonization. Such findings indicate that AM fungal colonization is a common ecological strategy among desert vegetation for improving adaptation to water-limited environments (El-Sheikh *et al*., 2012; Assaeed *et al*., 2017; Tang *et al*., 2022; Shen & Duan, 2024).

**Host specificity and compatibility:** Although AM fungi are generally considered broad host-range symbionts, variations in host specificity and compatibility have been reported among different plant species and fungal taxa. The compatibility between *P. turgidum* and native AM fungal communities appears particularly strong in desert ecosystems. Madouh *et al*., (2025) identified Rhizophagus iranicus associated with roots of *P. turgidum*, demonstrating species-specific associations between desert grasses and AM fungi under arid environmental conditions (Heneidy & Halmy, 2009; Powell & Rillig, 2018). Host specificity is influenced by several biological factors including root morphology, rhizosphere chemistry, plant genotype, and fungal species diversity. Root exudates released by host plants play an important role in attracting fungal propagules and stimulating spore germination and hyphal growth. Successful colonization depends on compatibility between fungal signaling molecules and plant receptors that regulate root penetration and arbuscule formation (Jha & Songachan, 2023). The strong compatibility observed between *P. turgidum* and native AMF communities is ecologically important because such associations significantly improve nutrient acquisition, water uptake, and drought resistance. Begum *et al*., (2019) reported that AMF associations enhance plant adaptation under environmental stress through improved root architecture, antioxidant defense, and osmotic regulation. In arid ecosystems, highly compatible AMF-host associations therefore contribute substantially to survival and persistence of desert grasses under extreme environmental stress (El-Sheikh *et al*., 2012; Assaeed *et al*., 2017; Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022).

**Environmental factors influencing colonization:** Several environmental factors influence AM fungal colonization and diversity in desert ecosystems. Soil moisture availability is one of the most important factors regulating AMF spore germination, hyphal growth, and colonization efficiency. Under drought conditions, AM fungi improve plant water uptake; however, extremely low soil moisture may reduce fungal metabolic activity and colonization intensity (Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022; Madouh & Quoreshi, 2023). Soil salinity also strongly affects AMF distribution and colonization patterns. Desert halophytic plants such as *P. turgidum* inhabit saline soils where AM fungal communities exhibit specialized tolerance to osmotic and ionic stress. Hameed *et al*., (2024) explained that halophytic ecosystems possess unique microbial communities adapted to high salinity and water-deficit conditions. Soil pH, temperature, nutrient availability, and vegetation composition further influence AMF colonization dynamics (Hashem *et al*., 2015; Boorboori & Lackóová, 2025). Albaqami *et al*., (2018) demonstrated that AMF diversity differed between arid regions of Saudi Arabia due to variations in climatic conditions, soil properties, and host plant distribution. High temperatures and alkaline sandy soils characteristic of desert ecosystems impose substantial environmental stress on fungal communities, thereby influencing colonization efficiency and fungal diversity. Nevertheless, desert-adapted AMF communities maintain functional symbiosis with perennial grasses such as *P. turgidum*, contributing significantly to ecosystem resilience and vegetation stability in arid landscapes (Jian *et al*., 2024).

## Role of AM fungi in drought tolerance

**Improvement of plant water uptake:** Arbuscular mycorrhizal fungi (AMF) play a critical role in improving plant adaptation to drought stress through enhancement of water uptake and maintenance of plant water status. In arid and semi-arid ecosystems, water availability is the primary limiting factor affecting plant growth and productivity. AMF improve water acquisition through the development of extensive extraradical hyphal networks that extend beyond the rhizosphere into soil regions inaccessible to plant roots (Abdalla *et al*., 2023). These hyphal structures function as extensions of the root system and facilitate absorption and transport of water from microsites containing residual soil moisture (Delian *et al*., 2011; Nadeem *et al*., 2017; Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022). The efficiency of AMF-mediated water uptake is particularly important in desert-adapted species such as *Panicum turgidum*, which naturally inhabit water-deficient environments. AMF colonization enhances root hydraulic conductivity and maintains leaf water potential under drought conditions, thereby reducing

dehydration stress and maintaining cellular turgor (Santander *et al*., 2017). Mycorrhizal plants generally exhibit delayed wilting and improved physiological performance compared with non-mycorrhizal plants under water deficit conditions (Hashem *et al*., 2015; Santander *et al*., 2017; Bahadur *et al*., 2019; Cheng *et al*., 2021; Tang *et al*., 2022). Begum *et al*., (2019) reported that AM fungi significantly improve nutrient and water acquisition under abiotic stress by increasing the absorptive surface area of plant roots. Additionally, AMF associations contribute to enhanced osmotic adjustment and stomatal regulation, which collectively improve water retention and drought resistance in host plants (Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022).

**Enhancement of root system architecture:** AM fungi significantly influence root morphology and architecture, thereby improving plant adaptation to drought stress. Colonization by AMF stimulates root branching, root hair development, root elongation, and overall root biomass production. Enhanced root architecture increases soil exploration capacity and facilitates efficient uptake of water and nutrients under drought conditions (Santander *et al*., 2017; Bahadur *et al*., 2019; Begum *et al*., 2019; Tang *et al*., 2022). In desert ecosystems, development of extensive root systems is essential for survival because water resources are highly limited and unevenly distributed. AMF-associated plants often exhibit larger root surface areas and greater root density compared with non-mycorrhizal plants. Abd_Allah *et al*., (2019) demonstrated that AMF inoculation improved growth performance and physiological characteristics of *Panicum turgidum* under drought stress conditions. Improved root development enabled enhanced water absorption and nutrient uptake, thereby contributing to increased drought tolerance (Fernández-Lizarazo & Moreno-Fonseca, 2016; Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022; Abdalla *et al*., 2023). AM fungal hyphae also establish close interactions with soil particles and create efficient pathways for movement of water and nutrients toward plant roots. Such interactions are particularly important in sandy desert soils where water retention capacity is inherently low.

**Increase in water use efficiency (WUE):** Water Use Efficiency (WUE) is a critical physiological parameter that reflects the ability of plants to produce biomass under limited water availability. AM fungi substantially improve WUE by enhancing photosynthetic efficiency, maintaining stomatal regulation, and reducing excessive transpiration under drought conditions (Hashem *et al*., 2015; Santander *et al*., 2017; Bahadur *et al*., 2019; Cheng *et al*., 2021; Tang *et al*., 2022; Abdalla *et al*., 2023).

Mycorrhizal plants generally maintain higher chlorophyll content and photosynthetic activity during drought stress compared with non-colonized plants. Improved nutrient uptake, particularly phosphorus acquisition, supports ATP synthesis, energy metabolism, and photosynthetic carbon fixation under stress conditions. Furthermore, AMF enhance stomatal regulation through modulation of phytohormones such as abscisic acid (ABA), which contributes to reduced transpiration and improved water conservation (Santander *et al*., 2017; Bahadur *et al*., 2019; Begum *et al*., 2019; Tang *et al*., 2022).

Jajoo & Mathur (2021) reported that AMF improve photosynthetic performance and photochemical efficiency by protecting photosystem II against oxidative damage during abiotic stress. Consequently, AMF-colonized plants utilize available water resources more efficiently and sustain higher productivity under drought conditions (Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022).

**Contribution to soil–plant–water relationships:** AM fungi contribute significantly to soil–plant–water relationships through improvement of soil structure, aggregation, and rhizosphere stability. Extensive fungal hyphal networks bind soil particles together and enhance soil aggregation through production of glomalin-related soil proteins (Powell & Rillig, 2018). Improved soil aggregation increases soil porosity, water infiltration, and water-holding capacity, which are particularly important in sandy desert soils characterized by rapid drainage and low moisture retention. AMF-mediated improvements in rhizosphere structure facilitate efficient movement of water and nutrients between soil and plant roots. Such interactions maintain soil moisture availability and reduce drought-induced stress in host plants. In arid ecosystems, AMF therefore function as critical biological mediators that integrate soil physical properties with plant physiological processes (Hashem *et al*., 2015; Santander *et al*., 2017; Bahadur *et al*., 2019; Cheng *et al*., 2021; Tang *et al*., 2022). Furthermore, AM fungi contribute to stabilization of degraded soils and enhancement of ecosystem resilience under drought conditions. In desert rangelands dominated by *Panicum turgidum*, AMF associations improve vegetation establishment, soil fertility, and nutrient cycling, thereby promoting sustainable ecosystem functioning under extreme environmental conditions (Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022; Madouh & Quoreshi, 2023).

## Physiological mechanisms under drought stress

**Regulation of stomatal conductance:** Drought stress significantly affects stomatal behavior and gas exchange processes in plants. Under water-deficit conditions, stomatal closure is one of the earliest physiological responses that minimizes transpiration and prevents excessive water loss. However, prolonged stomatal closure also restricts carbon dioxide uptake and reduces photosynthetic efficiency. Arbuscular mycorrhizal fungi (AMF) play an important role in regulating stomatal conductance and improving plant water relations during drought stress (Delian *et al*., 2011; Nadeem *et al*., 2017; Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022). AMF-associated plants generally maintain better stomatal regulation compared with non-mycorrhizal plants due to improved water uptake and enhanced root hydraulic conductivity. Enhanced acquisition of water and nutrients allows plants to sustain stomatal function under moderate drought conditions while minimizing excessive transpiration losses. Begum *et al*., (2019) reported that AMF improve physiological adaptation under abiotic stress through enhanced water relations, nutrient uptake, and hormonal regulation. In addition, AMF influence the production and signaling of phytohormones such as abscisic acid (ABA), which plays a central role in controlling stomatal movement during water deficit conditions (Hashem *et al*., 2015; Santander *et al*., 2017; Bahadur *et al*., 2019; Cheng *et al*., 2021; Tang *et al*., 2022).

In desert-adapted grasses such as *Panicum turgidum*, AMF-mediated regulation of stomatal conductance contributes substantially to drought resistance by maintaining a balance between carbon assimilation and water conservation. Such regulation improves water use efficiency and enhances plant survival under prolonged drought stress (Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022).

**Maintenance of cell turgor and water status:** Maintenance of cellular water balance and turgor pressure is essential for plant growth and survival under drought conditions. Water deficit reduces cell hydration, leading to loss of turgor, membrane instability, and inhibition of metabolic processes. AMF significantly contribute to maintenance of plant water status by improving root water uptake and facilitating efficient transport of water from soil to plant tissues (Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022; Abdalla *et al*., 2023). The extensive extraradical hyphal networks formed by AM fungi enhance the absorptive surface area of roots and improve access to microsites containing residual soil moisture. Mycorrhizal plants therefore exhibit higher leaf water potential, improved relative water content, and reduced wilting under drought stress compared with non-mycorrhizal plants (Santander *et al*., 2017). Improved water relations also maintain cell expansion, enzymatic activity, and membrane integrity during dehydration stress (Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022). In *Panicum turgidum*, AMF colonization has been associated with improved physiological performance and enhanced drought tolerance. Abd_Allah *et al*., (2019) demonstrated that AMF inoculation mitigated drought-induced physiological stress by improving plant water status and reducing oxidative damage. Such responses are particularly important in arid ecosystems where prolonged drought periods severely limit plant growth and ecosystem productivity (Fernández-Lizarazo & Moreno-Fonseca, 2016; Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022; Abdalla *et al*., 2023).

**Photosynthetic performance under water deficit:** Photosynthesis is highly sensitive to drought stress because water deficit restricts stomatal opening, reduces chlorophyll content, and impairs photochemical activity. Under severe drought conditions, oxidative stress damages chloroplast membranes and photosystem II (PSII), leading to reduced carbon assimilation and growth inhibition (Santander *et al*., 2017; Bahadur *et al*., 2019; Jajoo & Mathur, 2021; Tang *et al*., 2022). AM fungi significantly improve photosynthetic performance under water-deficit conditions through enhancement of nutrient uptake, chlorophyll biosynthesis, and antioxidant defense systems. Mycorrhizal plants generally maintain higher chlorophyll concentrations and photochemical efficiency than non-colonized plants. Begum *et al*., (2019) reported that AMF improve photosynthetic activity by enhancing phosphorus acquisition and energy metabolism, which are essential for ATP synthesis and carbon fixation (Tang *et al*., 2022; Shen & Duan, 2024). Jajoo & Mathur (2021) further explained that AMF protect photosynthetic machinery against oxidative damage by stimulating antioxidant enzyme activities and reducing reactive oxygen species accumulation. Consequently, AMF-colonized plants sustain higher photosynthetic rates and biomass production under drought stress conditions. Such physiological benefits are particularly advantageous for desert grasses such as *P. turgidum*, which rely on efficient photosynthetic performance for survival under high temperature and limited water availability (Hashem *et al*., 2015; Santander *et al*., 2017; Bahadur *et al*., 2019; Cheng *et al*., 2021; Tang *et al*., 2022).

*Panicum turgidum* possesses an inherently efficient $C_4$ photosynthetic system that confers high water-use efficiency under arid conditions. Current evidence indicates that AMF improve plant water status, photosynthetic performance, and antioxidant capacity under drought in $C_4$ species, including maize and *Hemarthria altissima*, thereby complementing the intrinsic drought-adaptive traits of $C_4$ metabolism rather than replacing them. However, whether AMF directly regulate $C_4$-specific enzymes (e.g., PEPC, PPDK, NADP-ME) or preserve bundle sheath structure in *P. turgidum* remains unknown and warrants further investigation.

**Osmotic adjustment mechanisms:** Osmotic adjustment is an important physiological mechanism that enables plants to maintain cellular hydration and metabolic activity during drought stress. Under dehydration conditions, plants accumulate compatible solutes such as proline, soluble sugars, glycine betaine, and amino acids that reduce cellular osmotic potential and stabilize proteins and membranes (Hashem *et al*., 2015; Santander *et al*., 2017; Bahadur *et al*., 2019; Begum *et al*., 2019; Cheng *et al*., 2021; Tang *et al*., 2022). AM fungi contribute substantially to osmotic adjustment through enhancement of osmolyte accumulation and regulation of cellular water balance. Mycorrhizal plants generally exhibit increased concentrations of proline and soluble carbohydrates under drought stress compared with non-mycorrhizal plants. These osmoprotectants improve membrane stability, maintain enzyme function, and protect cellular structures from dehydration-induced damage (Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022). Furthermore, AMF-mediated osmotic adjustment contributes to maintenance of turgor pressure and continued physiological activity under severe water limitation. Improved osmotic regulation also enhances nutrient transport, photosynthetic efficiency, and antioxidant defense responses during drought stress. Consequently, AM fungi play a vital role in improving physiological resilience of *Panicum turgidum* and other desert plants inhabiting arid ecosystems (Hashem *et al*., 2015; Santander *et al*., 2017; Bahadur *et al*., 2019; Cheng *et al*., 2021; Tang *et al*., 2022).

## Biochemical and molecular responses

**Antioxidant defense system activation:** Drought stress induces excessive production of reactive oxygen species (ROS) such as hydrogen peroxide, superoxide radicals, and hydroxyl radicals, which cause oxidative damage to cellular membranes, proteins, chloroplasts, and nucleic acids. In arid ecosystems, oxidative stress represents one of the major biochemical constraints limiting plant growth and survival under prolonged water deficit conditions. Arbuscular mycorrhizal fungi (AMF) significantly improve plant tolerance to oxidative stress through activation of antioxidant defense systems (Delian *et al*., 2011; Nadeem *et al*., 2017; Santander *et al*., 2017; Bahadur *et al*., 2019; Begum *et al*., 2019; Tang *et al*., 2022). AMF-colonized

plants generally exhibit enhanced activities of antioxidant enzymes including superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), and ascorbate peroxidase (APX), which collectively detoxify reactive oxygen species and reduce membrane lipid peroxidation. Abd_Allah *et al*., (2019) demonstrated that AMF inoculation mitigated drought-induced oxidative stress in *Panicum turgidum* by improving physiological performance and reducing cellular damage under water-deficit conditions. Similarly, Jajoo and Mathur (2021) reported that AMF protect photosynthetic machinery from oxidative injury by enhancing antioxidant enzyme activities and stabilizing chloroplast membranes under abiotic stress conditions (Hashem *et al*., 2015; Santander *et al*., 2017; Bahadur *et al*., 2019; Cheng *et al*., 2021; Tang *et al*., 2022).

**Regulation of phytohormones:** Phytohormones play a crucial role in plant adaptation to drought stress through regulation of stomatal movement, root growth, osmotic balance, and stress-responsive signaling pathways. AM fungi significantly influence the biosynthesis and regulation of important phytohormones including abscisic acid (ABA), auxins, jasmonic acid, gibberellins, and cytokinins (Santander *et al*., 2017; Bahadur *et al*., 2019; Bahadur *et al*., 2019; Tang *et al*., 2022). Among these hormones, ABA is particularly important in drought tolerance because it regulates stomatal closure and reduces water loss through transpiration. AMF-mediated enhancement of ABA signaling improves stomatal regulation and water conservation under drought stress conditions. Auxins and cytokinins further contribute to enhanced root development and maintenance of plant growth during environmental stress. Bahadur *et al*., (2019) explained that AMF-associated hormonal regulation contributes substantially to improved stress signaling and physiological adaptation under drought conditions (Fernández-Lizarazo & Moreno-Fonseca, 2016; Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022; Abdalla *et al*., 2023).

Recent molecular and transcriptomic studies indicate that AMF-mediated drought tolerance is not limited to improved nutrition, but also involves coordinated regulation of stress-signaling genes, phytohormone pathways, aquaporins, calcium signaling, antioxidant defense, and osmotic adjustment. Transcriptomic evidence shows that AMF can regulate drought-responsive genes associated with ABA signaling, jasmonic acid pathways, water transport, ion homeostasis, and ROS detoxification, thereby improving plant adaptation under water deficit conditions (Cheng *et al*., 2021; Wang *et al*., 2023). Recent transcriptome analyses in AMF-colonized maize further demonstrated that mycorrhizal symbiosis enhances drought tolerance by modulating $Ca^{2+}$ signaling and stress-response pathways (Zhang *et al*., 2025). Although transcriptomic data specifically for AMF-colonized *Panicum turgidum* remain limited, these molecular findings provide strong mechanistic support for interpreting AMF-mediated phytohormonal regulation and stress signaling in desert grasses.

**Expression of drought-responsive genes:** At the molecular level, AM fungi influence the expression of several drought-responsive genes associated with water transport, ion regulation, antioxidant defense, and osmotic adjustment. AMF colonization activates genes encoding aquaporins, ion transporters, dehydrins, and stress-responsive transcription factors, thereby improving plant adaptation to water-deficit environments (Santander *et al*., 2017; Bahadur *et al*., 2019; Cheng *et al*., 2021; Tang *et al*., 2022). Aquaporin-related genes play a major role in facilitating water movement across cellular membranes and maintaining plant water balance under drought conditions. In addition, AMF-mediated regulation of ion transport genes improves ionic homeostasis and membrane stability during dehydration stress. Cheng *et al*., (2021) further reported that AMF stimulate molecular signaling pathways involved in antioxidant defense and osmotic regulation, thereby enhancing stress tolerance in host plants (Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022).

The strong mycorrhizal association observed in *Panicum turgidum* roots suggests that AMF-mediated molecular responses contribute substantially to adaptation of desert grasses under extreme arid conditions (Heneidy & Halmy, 2009; Abd_Allah *et al*., 2019; Madouh *et al*., 2025).

**Role of compatible solutes (Proline and Sugars):** Compatible solutes such as proline, soluble sugars, amino acids, and glycine betaine play an essential role in osmotic adjustment and cellular protection during drought stress. These osmolytes reduce cellular osmotic potential, maintain turgor pressure, stabilize proteins and membranes, and protect enzymatic activities under dehydration conditions (Santander *et al*., 2017; Bahadur *et al*., 2019; Begum *et al*., 2019; Tang *et al*., 2022). AMF significantly enhance accumulation of compatible solutes in host plants exposed to drought stress. Mycorrhizal plants generally exhibit higher concentrations of proline and soluble carbohydrates compared with non-mycorrhizal plants. Such osmotic adjustment mechanisms improve membrane integrity and reduce oxidative damage during water deficit conditions (Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022). Furthermore, compatible solutes contribute to stabilization of photosynthetic structures and maintenance of metabolic activity during drought stress. In arid ecosystems, accumulation of osmoprotectants therefore represents an important biochemical adaptation mechanism enhancing survival of *Panicum turgidum* and other desert plants under prolonged drought conditions (Santander *et al*., 2017; Bahadur *et al*., 2019; Begum *et al*., 2019; Cheng *et al*., 2021; Tang *et al*., 2022).

**Soil and rhizosphere interactions**

**AM Fungi effects on soil structure and aggregation:** Arbuscular mycorrhizal fungi (AMF) play a fundamental role in improving soil structure and maintaining rhizosphere stability in arid and semi-arid ecosystems. In desert environments, sandy soils are generally characterized by poor aggregation, low organic matter content, weak water-holding capacity, and high susceptibility to wind erosion. AM fungi contribute significantly to soil stabilization through the development of extensive extraradical hyphal networks that physically bind soil particles and promote formation of stable soil aggregates (Heneidy & Halmy, 2009; Delian *et al*., 2011; Nadeem *et al*., 2017; Powell & Rillig, 2018). AM fungal hyphae also produce glomalin-related soil proteins, which enhance soil aggregation and

improve soil structural integrity. Improved aggregation increases soil porosity, aeration, water infiltration, and water retention capacity, all of which are essential for plant survival under drought conditions. In desert grasses such as *Panicum turgidum*, AMF-mediated improvements in soil structure contribute substantially to stabilization of sandy soils and reduction of desertification processes. Powell and Rillig (2018) emphasized that AM fungal biodiversity is strongly associated with ecosystem functioning and maintenance of soil health under environmental stress conditions (Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022).

**Nutrient mobilization under drought conditions:** Drought stress significantly restricts nutrient mobility and nutrient uptake because low soil moisture reduces diffusion and transport of essential elements toward plant roots. AM fungi improve nutrient mobilization through extensive fungal hyphal systems that explore larger soil volumes inaccessible to roots (Begum *et al*., 2019). These hyphae effectively absorb phosphorus, nitrogen, potassium, and micronutrients and transfer them to host plants through arbuscules formed within root cortical cells (Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022). Phosphorus acquisition is particularly important under drought conditions because phosphorus availability in arid soils is generally low due to reduced solubility and mobility. Jha & Songachan (2023) reported that AMF function as effective biofertilizers by improving nutrient acquisition efficiency and supporting plant growth under stressful environmental conditions. Enhanced nutrient uptake contributes to improved photosynthesis, osmotic adjustment, antioxidant defense, and drought tolerance in mycorrhizal plants (Fernández-Lizarazo & Moreno-Fonseca, 2016; Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022; Abdalla *et al*., 2023).

**Microbial interactions in the rhizosphere:** The rhizosphere is a biologically active zone where plant roots interact with diverse microbial communities including bacteria, fungi, and actinomycetes. AM fungi are important components of rhizosphere microbial communities and interact synergistically with other beneficial microorganisms to improve plant growth and ecosystem functioning. These interactions contribute to nutrient cycling, organic matter decomposition, soil fertility enhancement, and stress tolerance under arid conditions (Heneidy & Halmy, 2009; Powell & Rillig, 2018; Madouh & Quoreshi, 2023). Studies conducted in desert ecosystems of Saudi Arabia and Kuwait demonstrated considerable diversity of AM fungal communities associated with native grasses and halophytic vegetation. Albaqami *et al*., (2018) reported high hyphal colonization rates in desert plant species from Saudi Arabian arid regions, while Madouh *et al*., (2025) observed approximately 90% vesicle colonization in *Panicum turgidum* roots. Such findings indicate the ecological importance of AMF-rhizosphere interactions in maintaining vegetation productivity and ecosystem stability under drought stress conditions (El-Sheikh *et al*., 2012; Assaeed *et al*., 2017; Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022).

**Ecological and environmental implications**

**Contribution to desert ecosystem stability:** Arbuscular mycorrhizal fungi (AMF) and *Panicum turgidum* play a significant role in maintaining ecological stability and productivity in arid and semi-arid ecosystems. Desert ecosystems are highly vulnerable to environmental degradation because of low rainfall, poor soil fertility, salinity, and high evapotranspiration rates. Under such stressful environmental conditions, the symbiotic association between AM fungi and desert grasses contributes substantially to vegetation persistence, nutrient cycling, soil stabilization, and ecosystem resilience (El-Sheikh *et al*., 2012; Hashem *et al*., 2015; Assaeed *et al*., 2017; Madouh & Quoreshi, 2023; Boorboori & Lackóová, 2025). *Panicum turgidum* is considered one of the most ecologically important perennial grasses in desert rangelands because of its ability to survive prolonged drought and stabilize sandy soils through its extensive root system. Heneidy & Halmy (2009) reported that the species contributes significantly to desert ecosystem functioning through forage production and stabilization of mobile sand dunes. AM fungi further enhance ecological stability by improving nutrient acquisition, water uptake, and physiological adaptation of host plants under drought stress conditions (El-Sheikh *et al*., 2012; Assaeed *et al*., 2017; Santander *et al*., 2017; Bahadur *et al*., 2019; Begum *et al*., 2019; Tang *et al*., 2022). The fungal hyphal network also improves soil aggregation and water retention through production of glomalin-related proteins and binding of soil particles. Powell & Rillig (2018) emphasized that AM fungal biodiversity is strongly associated with ecosystem functioning and soil health maintenance under stressful environmental conditions. Consequently, AMF-host interactions contribute substantially to maintenance of vegetation cover and prevention of soil erosion in desert ecosystems (Heneidy & Halmy, 2009; Powell & Rillig, 2018).

**Role in combating desertification:** Desertification represents one of the major environmental challenges affecting arid and semi-arid regions worldwide. Loss of vegetation cover, soil erosion, salinity, and reduced soil fertility collectively contribute to degradation of rangelands and ecosystem productivity. The symbiotic relationship between AM fungi and desert-adapted plants such as *Panicum turgidum* provides an important biological mechanism for combating desertification (Hashem *et al*., 2015; Boorboori & Lackóová, 2025). AM fungi improve plant establishment and survival under degraded soil conditions through enhancement of root development, nutrient uptake, and drought tolerance. Madouh & Quoreshi (2023) highlighted that AMF-mediated stress tolerance significantly improves the adaptability of native desert plants under extreme environmental conditions. Furthermore, AM fungi contribute to restoration of degraded soils through enhancement of soil aggregation and stabilization of loose sandy substrates (Fernández-Lizarazo & Moreno-Fonseca, 2016; Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022; Abdalla *et al*., 2023). The extensive root systems of *P. turgidum* reduce wind erosion and bind soil particles, thereby minimizing sand movement and desert expansion.

Such ecological functions are particularly important in regions exposed to severe grazing pressure and climatic variability. Heneidy & Halmy (2009) reported that *P. turgidum* habitats experience varying grazing pressures, including 26.3% moderate grazing and 47.4% high grazing intensity, indicating the ecological resilience of the species under disturbed environmental conditions (El-Sheikh *et al*., 2012; Assaeed *et al*., 2017).

**Potential applications in rangeland restoration:** The ecological characteristics of *Panicum turgidum* and its association with AM fungi make this symbiotic system highly valuable for restoration and sustainable management of degraded rangelands. AMF-based restoration strategies are increasingly recognized as environmentally sustainable approaches for improving vegetation establishment and ecosystem rehabilitation in arid regions (Heneidy & Halmy, 2009; El-Sheikh *et al*., 2012; Assaeed *et al*., 2017; Powell & Rillig, 2018; Jha & Songachan, 2023). AM fungi function as natural biofertilizers that improve nutrient availability, water uptake, and soil fertility under harsh environmental conditions. Such characteristics are particularly important in desert restoration programs where soil nutrient deficiency and water scarcity limit plant establishment. The strong AMF colonization observed in *P. turgidum* roots, reaching approximately 90% vesicle colonization in desert ecosystems of Kuwait, demonstrates the suitability of this species for ecological restoration programs (Heneidy & Halmy, 2009; El-Sheikh *et al*., 2012; Assaeed *et al*., 2017; Powell & Rillig, 2018; Madouh *et al*., 2025). Furthermore, perennial desert grasses such as *P. turgidum* contribute to long-term stabilization of restored ecosystems by improving soil structure, enhancing biodiversity, and supporting sustainable grazing systems. Consequently, integration of native desert grasses and AM fungi represents a promising ecological strategy for restoration of degraded rangelands and mitigation of climate change impacts in arid ecosystems (Heneidy & Halmy, 2009; El-Sheikh *et al*., 2012; Assaeed *et al*., 2017; Powell & Rillig, 2018).

## Research gaps and future perspectives

**Lack of long-term field studies:** Despite significant advances in understanding the role of arbuscular mycorrhizal fungi (AMF) in drought tolerance, several important research gaps remain unresolved, particularly under natural desert ecosystem conditions. Most available studies concerning AMF-mediated drought resistance have been conducted under greenhouse or short-term experimental conditions, whereas long-term field investigations in arid ecosystems remain limited (Madouh & Quoreshi, 2023). Desert environments are characterized by highly variable climatic conditions, including fluctuations in temperature, precipitation, salinity, and soil nutrient availability, which may significantly influence AM fungal colonization and plant responses over time (Delian *et al*., 2011; Nadeem *et al*., 2017; Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022). Long-term ecological studies are therefore necessary to evaluate the sustainability and stability of AMF-host interactions under natural environmental conditions. In particular, field-based investigations focusing on *Panicum turgidum* and native desert AMF communities could provide valuable information regarding seasonal colonization dynamics, ecosystem resilience, and restoration potential in degraded rangelands (Heneidy & Halmy, 2009; El-Sheikh *et al*., 2012; Assaeed *et al*., 2017; Powell & Rillig, 2018).

**Need for molecular-level investigations:** Current knowledge regarding molecular interactions between AM fungi and desert-adapted plants remains insufficient. Although several studies have demonstrated physiological and biochemical improvements associated with AMF colonization, limited information is available concerning drought-responsive genes, signaling pathways, and transcriptional regulation involved in AMF-mediated stress tolerance (Hashem *et al*., 2015; Santander *et al*., 2017; Bahadur *et al*., 2019; Cheng *et al*., 2021; Tang *et al*., 2022). Molecular investigations focusing on aquaporins, ion transporters, stress-responsive transcription factors, and phytohormonal signaling pathways are essential for understanding the mechanisms underlying drought adaptation in *Panicum turgidum*. In addition, identification of AM fungal species through molecular characterization techniques remains limited in desert ecosystems. Madouh *et al*., (2025) identified Rhizophagus iranicus associated with *P. turgidum* roots in Kuwait; however, comprehensive molecular diversity analyses of AM fungal communities in Saudi Arabian deserts are still lacking (Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022).

**Climate change impacts on AM symbiosis:** Climate change represents a major challenge for arid and semi-arid ecosystems because increasing temperatures, prolonged drought periods, and irregular rainfall patterns are expected to intensify desertification processes and ecosystem degradation. Such environmental changes may significantly alter AM fungal diversity, colonization efficiency, and plant–microbe interactions (Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022; Hameed *et al*., 2024). AM fungi are highly sensitive to soil moisture and temperature variations, and prolonged climatic stress may reduce fungal survival and functionality in desert soils. Consequently, future studies should evaluate the resilience of AMF-host associations under predicted climate change scenarios. Understanding how climate variability influences the symbiotic relationship between *Panicum turgidum* and AM fungi is essential for developing adaptive ecosystem management strategies in arid regions (Jian *et al*., 2024).

**Potential for sustainable land management strategies:** The ecological and physiological benefits associated with AMF-mediated symbiosis indicate substantial potential for sustainable land management and restoration programs in arid ecosystems. AM fungi improve nutrient uptake, soil aggregation, water retention, and drought tolerance, making them valuable biological tools for rehabilitation of degraded rangelands (El-Sheikh *et al*., 2012; Assaeed *et al*., 2017; Santander *et al*., 2017; Bahadur *et al*., 2019; Tang *et al*., 2022; Jha & Songachan, 2023). Integration of native desert grasses such as *Panicum turgidum* with AM fungal inoculation may improve vegetation establishment and ecosystem recovery under harsh environmental conditions.

Furthermore, AMF-based biofertilization strategies could reduce dependence on chemical fertilizers and enhance sustainability of desert agriculture and rangeland management. Future research should therefore focus on development of climate-resilient AMF inoculants, large-scale field applications, and ecosystem-based restoration strategies suitable for arid and semi-arid environments (Heneidy & Halmy, 2009; Powell & Rillig, 2018).

Successful restoration of arid rangelands should prioritize the conservation, characterization, and utilization of indigenous arbuscular mycorrhizal fungal (AMF) consortia, as native isolates are better adapted to the harsh environmental conditions of desert ecosystems than generalized inocula. Locally adapted AMF communities exhibit greater compatibility with native host plants and are more likely to persist under extreme drought, high temperatures, alkaline soils, and low phosphorus availability, thereby improving revegetation success and ecosystem resilience (Al-Yahya'ei *et al*., 2021; Delavaux *et al*., 2025). Recent molecular characterization of desert AMF associated with *Panicum turgidum* identified *Rhizophagus iranicus* as a dominant indigenous species, highlighting its potential as a candidate bioinoculant for restoration of degraded rangelands in hyper-arid environments (Madouh *et al*., 2025). Therefore, future restoration programs should focus on the isolation, molecular characterization, propagation, and large-scale production of native AMF strains, particularly *R. iranicus*, for nursery inoculation and field restoration. Such strategies are expected to improve inoculum persistence, symbiotic efficiency, and long-term restoration success while supporting sustainable land management in arid ecosystems (Al-Yahya'ei *et al*., 2021).

The integration of native arbuscular mycorrhizal fungi (AMF) with *Panicum turgidum* offers considerable potential for sustainable rangeland restoration and climate-smart land management in arid regions. Owing to its deep root system, high drought tolerance, and strong association with native AMF, *P. turgidum* can facilitate revegetation of degraded rangelands, improve forage availability, and stabilize mobile sand dunes. Inoculation with native AMF may further enhance plant establishment, nutrient cycling, soil aggregation through glomalin production, and vegetation resilience under drought and salinity stress, thereby increasing restoration success (Smith & Read, 2008; Powell & Rillig, 2018; Cheng *et al*., 2021). Integrating AMF-inoculated *P. turgidum* into rotational or moderate grazing systems could improve pasture productivity while minimizing soil degradation associated with overgrazing, which is a major driver of rangeland deterioration and soil carbon loss. Furthermore, enhanced root biomass, greater soil aggregation, and increased soil organic matter promoted by AMF are expected to contribute to long-term soil carbon sequestration and ecosystem resilience, supporting nature-based climate change mitigation strategies in drylands (Conant & Paustian, 2002; Anon., 2010; Henry *et al*., 2024).

**Practical applications:** The application of native AMF *Panicum turgidum* systems should be aligned with regional land management and restoration frameworks to maximize their ecological and socioeconomic benefits. Their integration into restoration programs can support the objectives of the United Nations Convention to Combat Desertification and its Land Degradation Neutrality initiative by enhancing vegetation establishment, improving soil stability, restoring degraded rangelands, and increasing ecosystem resilience to drought. Incorporating AMF-inoculated *P. turgidum* into sustainable grazing management, native revegetation, and ecosystem restoration programs could contribute to long-term land productivity, biodiversity conservation, and soil carbon storage while supporting climate adaptation and sustainable land management in arid regions. These approaches are also consistent with international recommendations promoting nature-based solutions and integrated dryland restoration to achieve sustainable development and climate resilience.

**Molecular characterization of desert AMF communities:** Future studies should characterize native AMF communities associated with *Panicum turgidum* using culture-independent molecular tools. Root and rhizosphere soil samples should be analyzed through high-throughput amplicon sequencing targeting AMF-specific regions of the rRNA operon, particularly SSU, ITS, or LSU markers, to identify dominant and rare AMF taxa. Because primer choice strongly influences AMF diversity estimates, validated AMF-specific primer sets should be selected before sequencing (Kohout *et al*., 2014; Van Geel *et al*., 2014). Recent studies show that metabarcoding and high-throughput sequencing are effective for profiling AMF communities in roots and soils across arid and desert ecosystems (Luo *et al*., 2020; Chávez-González *et al*., 2024). Combining morphological spore identification with SSU–ITS–LSU sequencing would provide more reliable taxonomic resolution of desert AMF associated with *P. turgidum* (Gagou *et al*., 2025). Sequence data should further be compared with curated AMF databases such as Global AMFungi to monitor shifts in AMF diversity under drought, salinity, grazing, and climate-change gradients (Větrovský *et al*., 2023).

**Future methodologies for long-term monitoring:** Long-term monitoring of AMF *Panicum turgidum* interactions under climate change scenarios should combine field-based ecological surveys, controlled drought experiments, and molecular approaches. Permanent monitoring plots should be established across rainfall, salinity, soil-type, and grazing gradients to assess seasonal changes in *P. turgidum* growth, survival, biomass, root traits, and AMF colonization. Root staining and microscopy can be used to quantify arbuscules, vesicles, and hyphal colonization, while soil spore counts and glomalin-related soil protein measurements can indicate AMF abundance and soil aggregation potential. High-throughput sequencing of AMF marker regions, such as SSU rRNA or ITS, should be applied to track shifts in native AMF community composition over time. These data should be integrated with soil moisture, temperature, electrical conductivity, nutrient status, remote-sensing vegetation indices, and climate projections to model the resilience of AMF *P. turgidum* symbiosis under future drought and warming scenarios.

## Conclusion

Arid and semi-arid ecosystems are increasingly threatened by prolonged drought, salinity, land degradation, and climate change, necessitating sustainable biological approaches for ecosystem restoration and vegetation resilience. *Panicum turgidum* Forssk. is an ecologically important perennial desert grass that demonstrates remarkable adaptation to harsh environmental conditions through specialized morphological, physiological, and biochemical mechanisms. Its extensive root system, C4 photosynthetic pathway, osmotic adjustment capacity, and association with beneficial soil microorganisms contribute substantially to survival under water-deficient conditions. Among the most significant biological interactions enhancing drought tolerance in *Panicum turgidum* is its symbiotic relationship with arbuscular mycorrhizal fungi (AMF). AM fungi improve plant water uptake, nutrient acquisition, root system development, water use efficiency, and photosynthetic performance under drought stress. Furthermore, AMF enhance antioxidant defense systems, regulate phytohormonal signaling, stimulate osmoprotectant accumulation, and contribute to expression of stress-responsive genes that collectively improve plant adaptation to arid environments. The extensive fungal hyphal networks also improve soil aggregation, rhizosphere stability, nutrient cycling, and water retention, thereby contributing to desert ecosystem stability and reduction of desertification processes. Studies conducted in desert ecosystems of Saudi Arabia, Kuwait, and neighboring arid regions indicate strong compatibility between *Panicum turgidum* and native AM fungal communities, with high levels of root colonization reported under natural environmental conditions. These interactions highlight the ecological significance of AMF-mediated symbiosis in sustaining vegetation productivity and resilience in dryland ecosystems. Despite substantial advances in understanding AMF-mediated drought tolerance, important gaps remain concerning long-term field evaluations, molecular mechanisms of AM symbiosis, and impacts of climate change on fungal diversity and colonization dynamics. Future research integrating ecological, physiological, molecular, and microbiological approaches will be essential for developing effective AMF-based restoration and sustainable land management strategies. Overall, the utilization of native arbuscular mycorrhizal fungi in association with *Panicum turgidum* represents a promising, environmentally sustainable approach for improving drought resistance, restoring degraded rangelands, combating desertification, and enhancing ecosystem resilience in arid and semi-arid regions.

## Future Recommendations

1. Long-term field studies should be conducted in natural desert ecosystems to evaluate seasonal dynamics, persistence, and ecological stability of AMF–*Panicum turgidum* associations under varying environmental conditions.
2. Advanced molecular and genomic investigations are needed to identify drought-responsive genes, transcription factors, aquaporins, and phytohormonal signaling pathways involved in AMF-mediated drought tolerance.
3. Comprehensive molecular characterization of native AM fungal diversity in Saudi Arabian and Gulf desert ecosystems should be prioritized to identify climate-resilient fungal strains suitable for restoration programs.
4. Future studies should evaluate the impacts of climate change variables, including elevated temperature, prolonged drought, and salinity stress, on AM fungal colonization efficiency and ecosystem functioning.
5. Research should focus on development of AMF-based biofertilizers and inoculation technologies suitable for large-scale rangeland restoration and sustainable desert agriculture.
6. Integrated studies involving soil microbiomes, rhizosphere interactions, and ecosystem-level responses are necessary to better understand the ecological role of AM fungi in desert ecosystem resilience.
7. Sustainable land management programs should incorporate native perennial grasses such as *Panicum turgidum* together with indigenous AM fungi to improve vegetation establishment, reduce soil erosion, and combat desertification in degraded drylands.
8. Interdisciplinary collaboration among ecologists, microbiologists, plant physiologists, and environmental scientists is recommended to develop holistic strategies for restoration and conservation of arid ecosystems.

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