

REVIEW

Arbuscular mycorrhizal fungi and plant resilience in the face of climate change: ecological and physiological mechanisms and sustainable applications

Esther Rodrigues Alves dos Reis^{1*} 

¹Undergraduate student in Biological Sciences (B.Sc.), University Estácio de Sá, Belo Horizonte, Brazil.

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*Corresponding Author:

Esther Rodrigues Alves dos Reis, University Estácio de Sá, Belo Horizonte, Brazil. Email: estherreis2012@gmail.com

Abstract: Climate change has intensified environmental stresses such as drought, salinity, nutrient limitations, and extreme temperatures, threatening plant productivity and ecosystem stability worldwide. This systematic review aimed to synthesize current scientific evidence regarding the role of arbuscular mycorrhizal fungi (AMF) in enhancing plant resilience to climate change-related stresses. A systematic literature review was conducted following PRISMA guidelines, including studies published between 2001 and 2026, retrieved from major scientific databases. A total of 43 eligible studies were analyzed. The results demonstrated that AMF significantly improve plant tolerance to drought, salinity, and multiple simultaneous stressors through enhanced water and nutrient acquisition, increased photosynthetic efficiency, activation of antioxidant defense systems, osmotic adjustment, hormonal regulation, and modulation of stress-responsive genes. In addition, AMF contribute to soil aggregation, nutrient cycling, carbon sequestration, and ecosystem stability, supporting sustainable agricultural practices and ecological restoration initiatives. The findings highlight that AMF-mediated resilience results from integrated physiological, biochemical, molecular, and ecological mechanisms operating across multiple biological scales. Therefore, arbuscular mycorrhizal fungi represent a promising biological resource for climate adaptation, sustainable land management, and the development of more resilient agricultural and natural ecosystems.

Keywords: Abiotic stress; Climate adaptation; Mycorrhizal symbiosis; Soil sustainability; Ecosystem resilience; Plant–fungus interactions.

1. Introduction

Climate change represents one of the greatest environmental challenges of the 21st century, profoundly affecting the structure and functioning of natural and agricultural ecosystems. The rise in global average temperature, the increased frequency of extreme weather events, changes in precipitation patterns, and the intensification of environmental degradation processes have increased plants' exposure to multiple stress factors, including drought, salinity, nutrient deficiency, and heatwaves (Bennett; Classen, 2020; Duarte; Maherali, 2022). These factors compromise essential physiological processes, such as photosynthesis, nutrient uptake, growth, and reproduction, resulting in productivity losses and

reduced ecosystem resilience to environmental disturbances.

In this context, arbuscular mycorrhizal fungi (AMF), belonging to the phylum Glomeromycota, stand out as fundamental components of terrestrial ecosystems due to their symbiotic association with approximately 80% of known plant species. This mutualistic interaction is characterized by the exchange of resources between the organisms involved, in which plants provide carbon compounds to the fungi, while the fungi enhance the plants' capacity to absorb water and mineral nutrients, especially phosphorus, nitrogen, and micronutrients (Smith; Smith, 2011; Chen et al., 2018). In addition to their role in plant nutrition, mycorrhizal fungi influence ecological processes

related to soil stability, nutrient cycling, primary productivity, and the maintenance of biodiversity (Berruti et al., 2016; Kumar et al., 2025).

In recent decades, scientific evidence has shown that the benefits provided by mycorrhizal fungi extend beyond nutrient uptake. Several studies indicate that these associations play a crucial role in plant tolerance to different types of abiotic stress, promoting physiological, biochemical, and molecular changes capable of increasing plant survival under adverse environmental conditions (Begum et al., 2019; Jajoo & Mathur, 2021; Wahab et al., 2023). Among the mechanisms described, the following stand out: improved water relations, increased water use efficiency, hormonal regulation, activation of antioxidant systems, cellular osmotic adjustment, and modulation of gene expression associated with the stress response (Auge, 2001; Cheng et al., 2021; Wang et al., 2024).

Drought is considered one of the most severe environmental factors affecting crop production and the maintenance of terrestrial ecosystems. Experimental studies and meta-analyses demonstrate that plants associated with FMA exhibit greater root development, higher photosynthetic capacity, better nutrient uptake, and greater physiological efficiency under water-deficient conditions compared to non-mycorrhizal plants (Chandrasekaran, 2022a, 2022b; Das; Sarkar, 2024; Tang et al., 2022). Furthermore, fungi can induce the biosynthesis of growth-regulating compounds and signaling molecules related to stress adaptation, strengthening plants' ability to respond to prolonged drought conditions (Ruiz-Lozano et al., 2016; Wang et al., 2023).

Another growing challenge associated with climate change is the expansion of areas affected by soil salinization, a phenomenon exacerbated by water scarcity, inadequate irrigation, and rising sea levels in coastal regions. In these environments, FMAs contribute to maintaining cellular ionic balance, reducing the toxic effects of excess sodium, and preserving the integrity of cell membranes, thereby promoting plant growth even under high salt concentrations (Evelin et al., 2019; Dastogeer et al., 2020; Boorboori; Lackóová, 2025). Recent evidence also indicates that these fungi can simultaneously mitigate different stress factors, enhancing plant tolerance to complex environmental scenarios that combine drought, heat, and salinity (Duc et al., 2018; Formenti et al., 2026; Etesami, 2026).

In addition to their direct benefits to plant

physiology, AMF play an important role in the sustainability of agroecosystems and in mitigating the impacts of climate change. The presence of these fungi is associated with increased soil carbon storage, improved physical structure of soil aggregates, reduced dependence on chemical fertilizers, and enhanced soil health, factors considered essential for more resilient and sustainable production systems (Conti et al., 2025; Shukla et al., 2025). Thus, AMF have been recognized as important allies for climate adaptation strategies and for the development of environmentally sustainable agricultural practices (Nadeem et al., 2014; Nie et al., 2024).

Despite the growing number of publications on the subject, the available literature is widely scattered across studies focused on specific stresses, isolated physiological mechanisms, or applications targeted at particular production systems. Previous reviews have separately addressed aspects related to drought, salinity, plant nutrition, or biochemical responses induced by FMA (Latef et al., 2016; Lenoir et al., 2016; Jajoo; Mathur, 2021; Nie et al., 2024). However, there are still few comprehensive syntheses that integrate the ecological, physiological, and functional mechanisms underpinning plant resilience in the face of the multiple stresses associated with global climate change.

Given this context, the present systematic review sought to answer the following research question: How do arbuscular mycorrhizal fungi contribute to plant resilience in the face of climate change, and what ecological, physiological, and functional mechanisms underpin this response? Unlike previous reviews focused on specific stress factors, this study adopts an integrative approach to gather and analyze evidence related to the main adaptation mechanisms promoted by AMF, while simultaneously discussing their implications for ecosystem conservation, sustainable agriculture, and strategies for addressing climate change. Thus, the objective of this review was to critically synthesize the available scientific knowledge on the role of arbuscular mycorrhizal fungi in promoting plant resilience in the face of contemporary environmental challenges.

2. Material and Methods

2.1 Study Design

This study consists of a systematic literature review conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021). The review

aimed to systematically identify, evaluate, and synthesize the available scientific evidence regarding the contribution of arbuscular mycorrhizal fungi (AMF) to plant resilience under climate change, with particular emphasis on the physiological, biochemical, ecological, and agronomic mechanisms involved in plant adaptation to abiotic stresses.

2.2 Search Strategy and Study Selection

The bibliographic search was conducted in early April 2026, with the final search completed on April 30, 2026, using five major scientific databases: Web of Science, Scopus, PubMed, ScienceDirect, and Google Scholar. These databases were selected due to their broad coverage in the areas of ecology, microbiology, plant physiology, environmental sciences, and agriculture.

Searches were performed using combinations of controlled keywords and Boolean operators, including terms such as “arbuscular mycorrhizal fungi”, “climate change”, “plant resilience”, “abiotic stress”, “drought tolerance”, “salinity stress”, “sustainable agriculture”, and “mycorrhizal symbiosis”. The complete search strings used for each database are provided in Supplementary Table S1, allowing full reproducibility of the search strategy.

All retrieved records were exported and compiled into a single database for screening. Duplicate records were identified and removed before the selection process. Subsequently, titles and abstracts were screened by the author according to predefined eligibility criteria. Studies considered potentially relevant were subjected to full-text assessment to determine their suitability for inclusion in the qualitative synthesis.

Eligible studies were published between 2001 and 2026 and investigated the role of arbuscular mycorrhizal fungi in mitigating climate change-related abiotic stresses, including drought, salinity, extreme temperatures, nutrient limitation, and combinations of multiple environmental stresses. Experimental studies, review articles, systematic reviews, and meta-analyses reporting physiological, biochemical, ecological, or agronomic aspects of AMF-mediated plant resilience were included.

Studies were excluded if they (i) did not directly address arbuscular mycorrhizal fungi; (ii) focused exclusively on taxonomy or molecular characterization without ecological or physiological relevance; (iii) consisted of conference abstracts, technical notes, or documents without full-text availability; or (iv)

represented duplicate publications retrieved from multiple databases.

The complete list of studies included in this review, together with their main characteristics, is presented in Supplementary Table S2.

2.3 Data Extraction and Analysis

From the selected studies, we extracted information regarding the year of publication, study type, organisms evaluated, environmental conditions investigated, physiological and ecological mechanisms described, as well as the main effects attributed to mycorrhizal symbiosis. The evidence obtained was organized and interpreted through qualitative synthesis, allowing the identification of recurring patterns regarding the role of arbuscular mycorrhizal fungi in improving nutrient uptake, water regulation, antioxidant activity, maintenance of photosynthesis, hormonal modulation, and increased plant tolerance in the face of different environmental stress scenarios related to climate change.

2.4 Study selection process

The study selection process followed the PRISMA guidelines (Page et al., 2021) and was conducted in four stages: identification, screening, eligibility, and inclusion.

In the identification stage, 312 records were retrieved from the consulted databases. After verifying and removing 68 duplicate records, 244 studies remained for analysis. In the screening stage, the titles and abstracts of the remaining 244 records were evaluated for relevance to the research topic. In this phase, 172 studies were excluded for not directly addressing arbuscular mycorrhizal fungi, mechanisms of tolerance to environmental stresses, or relationships with climate change.

Subsequently, 72 articles were considered potentially eligible and subjected to full-text review. During the full-text evaluation, 29 studies were excluded for failing to meet the established inclusion criteria, primarily because they had a focus distinct from the review's objectives, insufficient information on AMF mechanisms of action, or a lack of direct relationship with environmental stresses associated with climate change.

At the end of the process, 43 studies met all eligibility criteria and were included in the qualitative synthesis of this review. In addition to these studies, the publication by Page et al. (2021), used exclusively as a methodological

reference for applying the PRISMA protocol, was added to the reference list, bringing the total number of bibliographic references in the manuscript to 44.

The study selection process is presented in Figure 1.

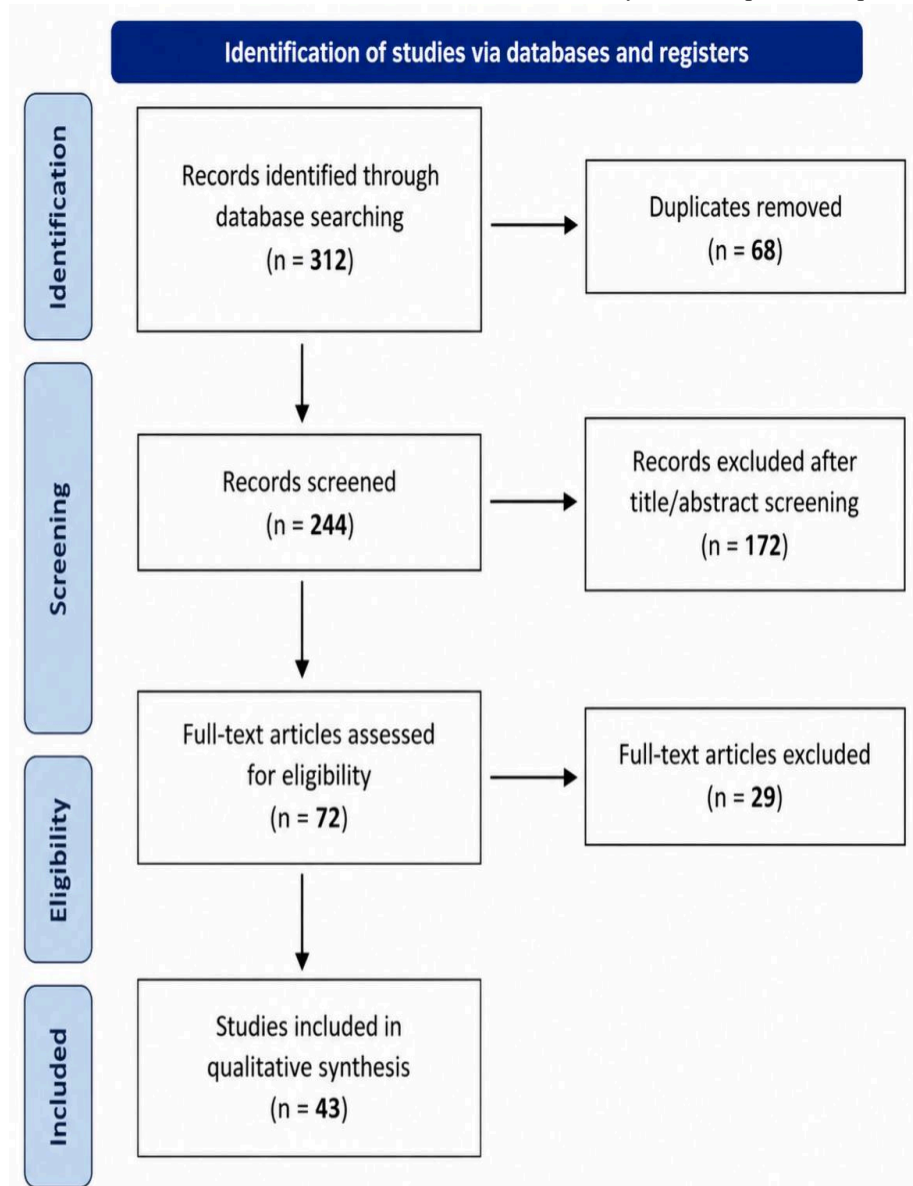


Figure 1. PRISMA flow diagram illustrating the literature search, screening, eligibility assessment, and study selection process adopted in this systematic review. Source: Adapted from Page et al. (2021).

2.5 Methodological Limitations

Although this review followed a systematic and transparent methodology based on PRISMA recommendations, some limitations should be acknowledged. The included studies exhibited substantial heterogeneity regarding plant species, AMF taxa, soil characteristics, experimental designs, environmental

conditions, and measured response variables, limiting direct comparisons among studies and precluding a formal quantitative meta-analysis.

Furthermore, a considerable proportion of the available evidence originated from greenhouse or laboratory experiments, which may not fully represent the complexity of field conditions and long-term ecosystem processes. Differences in experimental

duration, inoculation methods, and environmental stress intensity also contributed to variability among reported outcomes.

Another limitation is the predominance of studies involving crops, whereas relatively few investigations have focused on native plant species, natural ecosystems, or long-term field experiments. These knowledge gaps highlight the need for future research integrating long-term ecological studies, field-based experiments, multi-stress scenarios, and advanced molecular approaches to better understand the ecological functions and practical applications of AMF under future climate change scenarios.

3. Results

3.1. Characterization of the included studies

After applying the eligibility criteria, 43 studies were included in the systematic review. The publications spanned the period from 2001 to 2026, reflecting a significant increase in scientific interest in arbuscular mycorrhizal fungi (AMF) in recent decades. Although classic studies established the ecological foundations of

mycorrhizal symbiosis, most of the publications were recorded after 2018, a period marked by growing concern about the impacts of climate change on natural and agricultural ecosystems.

The selected studies included narrative reviews, systematic reviews, meta-analyses, and experimental research conducted under field, greenhouse, and laboratory conditions. The investigations covered different plant species, including crops, forest species, medicinal plants, and species native to arid and semi-arid environments.

The thematic analysis of the selected studies demonstrated a clear predominance of research focused on drought tolerance mediated by arbuscular mycorrhizal fungi (AMF), followed by investigations addressing salinity stress, physiological and biochemical adaptation mechanisms, and sustainable agricultural applications. Additional themes included ecological aspects of AMF-plant interactions, nutrient acquisition, carbon sequestration, fungal responses to climate change, and the mitigation of multiple simultaneous environmental stresses. The distribution of the main thematic categories identified among the included studies is presented in Figure 2.

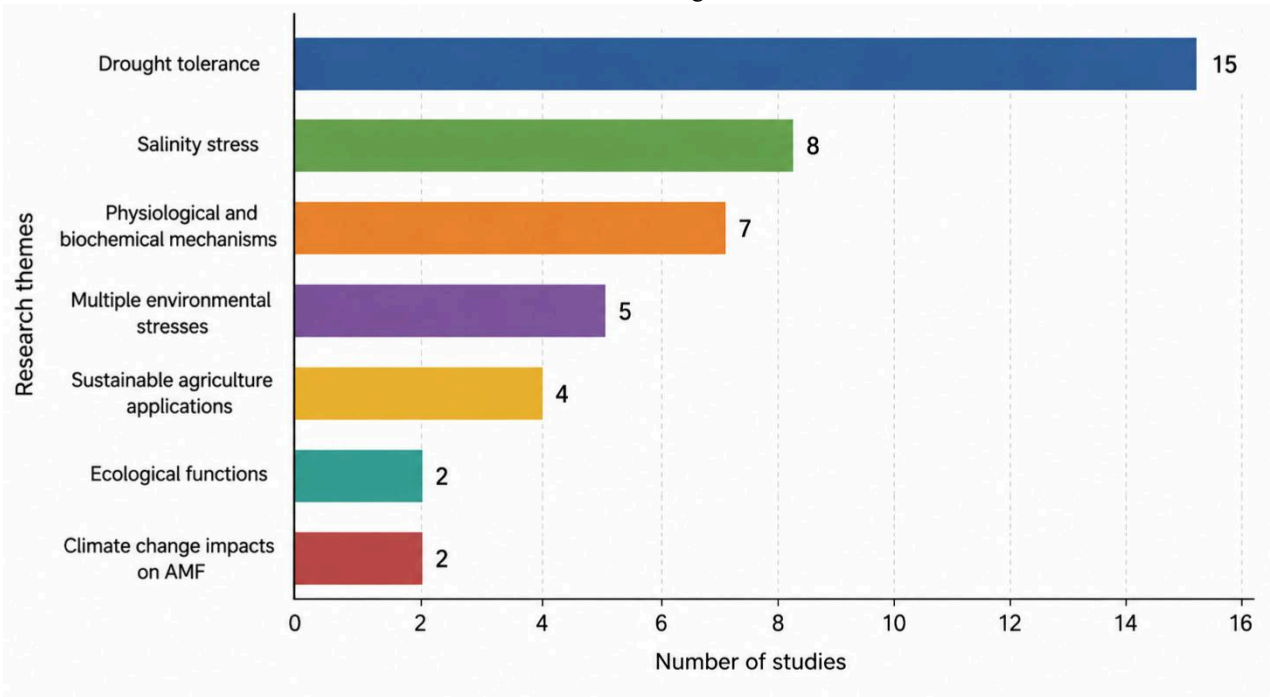


Figure 2. Distribution of the main research themes identified among the studies included in the systematic review, highlighting the relative frequency of investigations addressing different climate change-related abiotic stresses and AMF-mediated responses. Source: Author (2026).

3.2. Contributions of arbuscular mycorrhizal fungi to drought tolerance

Drought was the most frequently investigated stress factor among the studies analyzed. The results showed a consensus regarding the positive effect of AMF in mitigating the impacts of water deficit on plant growth

and physiological performance.

The studies reported a significant increase in above-ground and root biomass in mycorrhizal plants subjected to water stress. In different plant species, the mycorrhizal association promoted greater root system development, expanding the capacity to exploit the soil and favoring water uptake from deeper layers. This effect was observed both in individual experiments and in meta-analyses that synthesized results from different regions and cropping systems.

In addition to the effects on growth, several studies reported improvements in photosynthetic efficiency and in the maintenance of leaf water potential. Plants associated with AMF exhibited higher photosynthetic rates, greater stomatal conductance, and better water status compared to non-mycorrhizal plants. These benefits were often accompanied by increased water-use efficiency, a characteristic particularly relevant in scenarios of water scarcity intensified by climate change.

Another common finding was a reduction in damage caused by oxidative stress. Studies have shown increased activity of antioxidant enzymes and increased production of protective compounds capable of minimizing the effects of reactive oxygen species generated during periods of drought. As a result, there was less cellular degradation and better maintenance of essential metabolic functions.

3.3. Mitigation of the Effects of Salinity

Salinity was the second most frequently identified theme among the included studies. The results showed that AM fungi contribute significantly to plant performance in environments with high salt concentrations.

Most studies reported increased uptake of essential nutrients and reduced excessive sodium accumulation in plant tissues. This mechanism helped maintain cellular ionic balance and reduced the toxic effects associated with soil salinization.

Significant improvements in the growth of plants exposed to salt stress were also observed. Several studies reported increases in biomass, leaf area, root length, and agricultural productivity in mycorrhizal individuals. In addition, greater stability of cell membranes and a lower

incidence of oxidative damage were observed, indicating additional physiological protection provided by the symbiotic association.

Meta-analyses included in this review reinforced these results by demonstrating consistent positive effects of AMF on physiological and biochemical parameters related to salt tolerance in different plant species.

3.4. Responses to multiple stresses associated with climate change

A trend observed in recent studies has been the investigation of scenarios involving multiple stress factors. Among the most common combinations were drought and high temperatures, drought and salinity, as well as the interaction between nutritional limitations and adverse climatic conditions.

The results indicated that the benefits of mycorrhizal symbiosis persist even when plants are simultaneously subjected to different environmental stressors. In several cases, the positive effects were more pronounced than those observed under isolated stresses.

The studies demonstrated increased physiological stability of plants, maintenance of photosynthetic activity, and improved metabolic performance under conditions of multiple environmental stresses. Studies conducted on agricultural species demonstrated that inoculated plants exhibited higher survival and productivity when simultaneously exposed to drought and heat.

Adaptive responses were also identified, involving anatomical modifications, changes in root growth patterns, and greater efficiency in the use of available soil resources.

3.5. Key physiological and biochemical mechanisms associated with plant resilience

The analysis of the selected studies revealed a broad set of physiological, biochemical, molecular, and ecological mechanisms associated with the positive effects of arbuscular mycorrhizal fungi (AMF) on plant resilience under environmental stress conditions. Figure 3 summarizes the main mechanisms identified in the literature and their respective contributions to stress tolerance.

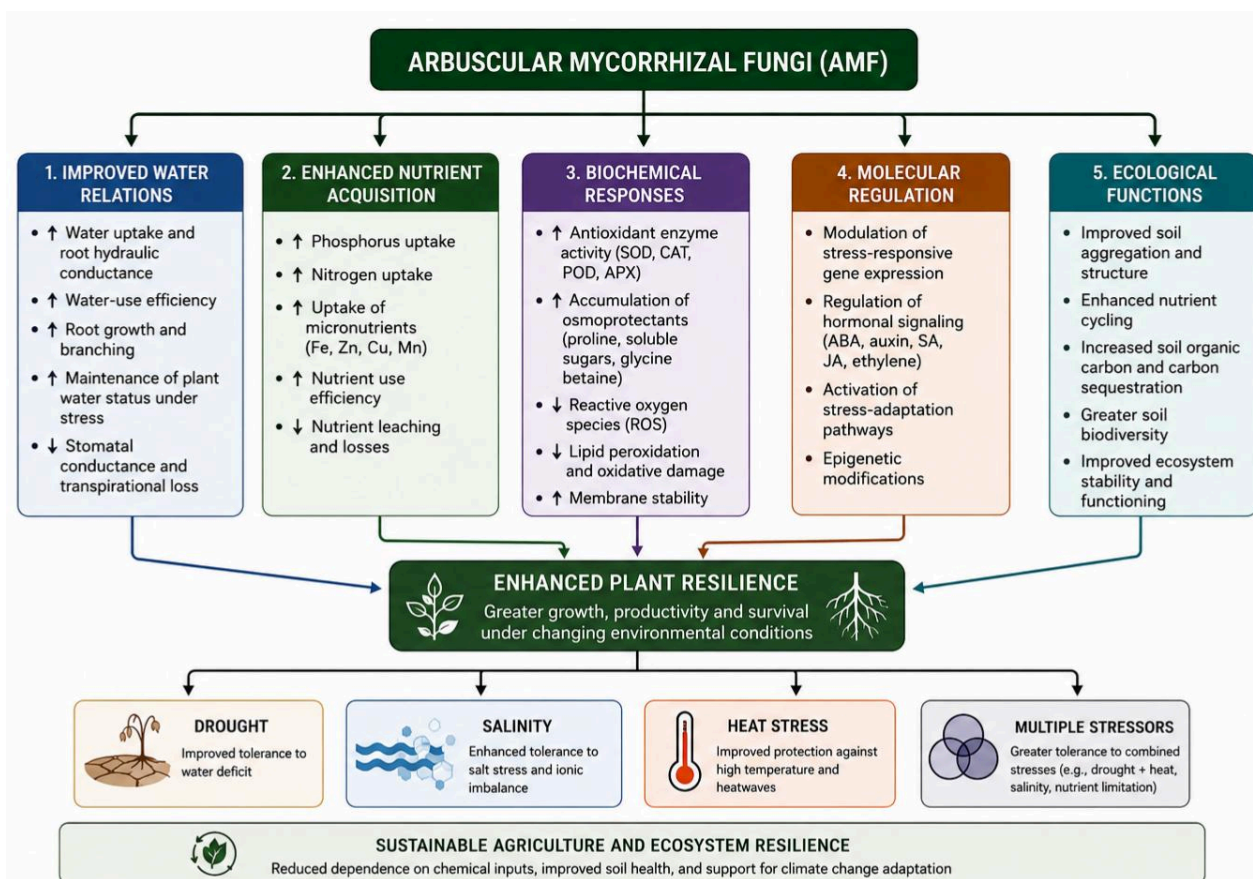


Figure 3. Schematic overview of the principal physiological, biochemical, and ecological mechanisms through which arbuscular mycorrhizal fungi (AMF) enhance plant resilience to climate change-related abiotic stresses, including improvements in water relations, nutrient acquisition, antioxidant defense, osmotic adjustment, and soil–plant interactions. Source: Author (2026).

Among the physiological responses most frequently reported were increased water uptake, improved acquisition of mineral nutrients, and enhanced photosynthetic performance. These benefits are largely attributed to the extensive extraradical hyphal network formed by AMF, which expands the volume of soil explored and increases plant access to water and nutrients beyond the rhizosphere depletion zone.

At the biochemical level, numerous studies documented higher activities of antioxidant enzymes, including superoxide dismutase, catalase, and peroxidases, as well as increased accumulation of osmoprotective compounds. These responses contribute to reducing oxidative damage, preserving membrane integrity, and maintaining cellular metabolism under adverse environmental conditions.

The reviewed literature also highlighted the importance of hormonal regulation in AMF-mediated stress tolerance. Symbiotic associations were frequently

associated with alterations in the production and signaling of phytohormones involved in root architecture, plant growth, stomatal regulation, and stress responses. Furthermore, molecular investigations revealed changes in the expression of genes related to water transport, nutrient uptake, antioxidant defense systems, and stress-responsive signaling pathways.

In addition to these physiological and molecular responses, several studies emphasized the ecological functions of AMF, including improvements in soil aggregation, nutrient cycling, carbon storage, and plant–soil interactions. Together, these mechanisms demonstrate that AMF contribute to plant adaptation through an integrated network of responses operating across multiple biological scales, from cellular regulation to ecosystem functioning.

3.6. Ecological Importance and Sustainable Applications

The results demonstrated that the benefits of AMF are not limited to the individual plant level but extend to

ecological processes and ecosystem functioning.

Several studies have highlighted the contribution of AMF to improving soil physical structure through aggregate formation and stabilization, thereby increasing water retention and reducing erosion processes. Positive effects on nutrient cycling and carbon storage in soils were also identified.

In the agricultural context, the analyzed studies pointed to significant potential for reducing dependence on chemical fertilizers and increasing the efficiency of production systems. The use of mycorrhizal inoculants was frequently described as a promising strategy for strengthening crop resilience in the face of challenges posed by climate change.

Furthermore, the studies indicated relevant applications in ecological restoration programs, the recovery of degraded areas, and the conservation of plant biodiversity, especially in environments subject to drought, soil degradation, and climate extremes.

3.7. *Emerging Trends in the Literature*

Recent studies have highlighted a growing interest in topics related to climate adaptation, regenerative agriculture, carbon sequestration, and sustainable soil management. There has also been an expansion in research aimed at understanding the molecular mechanisms involved in plant-fungus interactions.

Another identified trend was the increase in the number of systematic reviews and meta-analyses, reflecting the consolidation of knowledge regarding the benefits of AMF in different environmental contexts. These advances indicate that arbuscular mycorrhizal fungi are increasingly recognized as strategic components for building agricultural systems and ecosystems that are more resilient to global climate change.

4. Discussion

4.1 *Arbuscular mycorrhizal fungi as key components of plant resilience under climate change*

The findings of this systematic review demonstrate that arbuscular mycorrhizal fungi (AMF) play a central role in enhancing plant resilience under climate change-related environmental stresses. The predominance of studies addressing drought, salinity, and multiple stress interactions reflects growing scientific concern regarding the increasing vulnerability of both agricultural and natural ecosystems to global climatic changes (Bennett & Classen, 2020; Duarte; Maherali, 2022).

The benefits provided by AMF extend beyond improved nutrient acquisition and encompass

physiological, biochemical, molecular, and ecological processes that collectively increase plant fitness under adverse conditions. These observations reinforce the concept that mycorrhizal symbiosis represents one of the most important biological strategies for plant adaptation to environmental disturbances (Smith & Smith, 2011; Chen et al., 2018; Kumar et al., 2025). Nevertheless, AMF-mediated responses should not be considered universally consistent, as the magnitude of plant benefits depends on multiple interacting factors, including fungal identity, host plant genotype, soil characteristics, nutrient availability, and the intensity and duration of environmental stress.

Furthermore, climate change affects not only plants but also fungal communities themselves. Chanda et al. (2020) emphasized that alterations in temperature, precipitation patterns, and soil conditions can modify fungal diversity and ecosystem functioning, highlighting the importance of understanding how AMF communities respond to future environmental scenarios. Similarly, Bennett and Classen (2020) pointed out that current knowledge remains geographically biased, with most available studies originating from a limited number of climatic regions and agricultural systems. This imbalance restricts the extrapolation of current findings to ecosystems with contrasting environmental conditions.

Although the overall evidence supports a positive role of AMF in mitigating climate-related abiotic stresses, the reported benefits vary substantially among studies. Greenhouse experiments frequently demonstrate stronger improvements in plant growth and stress tolerance than field trials, where heterogeneous soil conditions, native microbial communities, and fluctuating environmental variables may reduce inoculation efficiency and alter symbiotic performance. Moreover, many studies focus on short-term physiological responses, whereas the persistence of AMF-mediated benefits under long-term climate change scenarios remains insufficiently understood. These considerations highlight the importance of interpreting current evidence within its experimental context and reinforce the need for long-term, field-based investigations across diverse ecosystems.

4.2 *AMF-mediated drought tolerance*

Drought was the most extensively studied stress factor among the selected publications, reflecting its status as one of the most severe consequences of climate change for terrestrial ecosystems. The consistent positive effects of AMF on plant growth, biomass accumulation, and physiological performance observed across the reviewed studies corroborate previous syntheses and meta-analyses (Auge, 2001; Chandrasekaran, 2022a, 2022b; Das;

Sarkar, 2024). Nevertheless, although the overall trend is positive, the magnitude of AMF-mediated drought tolerance varies considerably among studies, indicating that symbiotic effectiveness is strongly influenced by biological and environmental context.

The increased root development and expansion of the soil exploration zone through fungal hyphae constitute fundamental mechanisms underlying drought tolerance. According to Smith & Smith (2011), AMF significantly enhance access to water and nutrients beyond the root depletion zone, improving plant resource acquisition under limiting conditions. Similar conclusions were reported by Tang et al. (2022), who demonstrated that mycorrhizal associations simultaneously improve drought tolerance and nitrogen-use efficiency. However, the efficiency of these mechanisms depends on factors such as soil texture, phosphorus availability, root system architecture, and the compatibility between host plants and specific AMF taxa.

Recent meta-analyses further confirmed that AMF substantially increase biomass production, root growth, and nutrient uptake under water-deficit conditions (Chandrasekaran, 2022b). Additionally, improvements in photosynthetic activity and water-use efficiency reported by Shang et al. (2026) indicate that AMF help maintain carbon assimilation processes even during prolonged drought events. Despite these encouraging findings, substantial heterogeneity among experimental designs—including drought intensity, experimental duration, and inoculation procedures—limits direct comparisons among studies and may contribute to the variability observed in reported effect sizes.

The reduction of oxidative stress represents another important adaptive mechanism. Begum et al. (2019), Cheng et al. (2021), and Wang et al. (2024) demonstrated that AMF stimulate antioxidant defense systems, resulting in lower accumulation of reactive oxygen species and reduced cellular damage. These findings are consistent with those reported by Jajoo and Mathur (2021), who described AMF as “underground saviors” capable of protecting plants through integrated physiological and biochemical responses. Hormonal regulation also appears to play a critical role in drought adaptation. Ruiz-Lozano et al. (2016) demonstrated that mycorrhizal symbiosis stimulates strigolactone biosynthesis under water-deficit conditions, whereas Wang et al. (2023) identified molecular pathways associated with enhanced drought tolerance mediated by AMF. Together, these mechanisms explain the superior performance frequently observed in mycorrhizal plants under water scarcity.

Despite the robust body of evidence supporting AMF-mediated drought tolerance, important knowledge gaps remain. Most studies have been conducted under

controlled greenhouse conditions using single fungal isolates and relatively short experimental periods. In contrast, field conditions involve fluctuating climatic variables, heterogeneous soils, and competition with native microbial communities, all of which may influence AMF establishment and functional performance. Consequently, caution is warranted when extrapolating greenhouse results to agricultural systems. Future research should increasingly emphasize long-term, field-based experiments and comparative evaluations of different AMF species and inoculation strategies to identify the conditions under which drought mitigation is most effective.

4.3 Salinity stress mitigation

Salinity represents another major challenge expected to intensify under future climate scenarios. The reviewed studies consistently demonstrated that AMF improve plant performance under saline conditions by promoting nutrient acquisition, reducing sodium toxicity, and maintaining cellular homeostasis. Nevertheless, the effectiveness of AMF under saline environments is not uniform, varying according to salinity intensity, soil characteristics, plant species, and the identity of the fungal symbiont.

The results are consistent with previous reviews conducted by Evelin et al. (2019), Latef et al. (2016), and Dastogeer et al. (2020), all of which highlighted the importance of mycorrhizal associations in alleviating ionic and osmotic stress. AMF contribute to maintaining favorable K^+/Na^+ ratios, preserving membrane integrity, and reducing oxidative damage, thereby increasing plant survival and productivity in salt-affected soils. In addition, improved nutrient uptake and enhanced water relations contribute to maintaining metabolic activity under osmotic stress, reinforcing the multifunctional role of AMF in salinity tolerance.

More recently, Boorboori & Lackóová (2025) reinforced these conclusions by demonstrating that AMF-mediated salinity tolerance is supported by multiple physiological pathways, including ion regulation, antioxidant activity, and osmotic adjustment. These integrated responses explain the consistent increases in biomass, root development, and photosynthetic performance reported in the literature. However, considerable methodological heterogeneity among studies—including differences in salt concentration, exposure duration, inoculation protocols, and AMF species—makes direct comparisons difficult and may explain the variability observed in plant responses.

Moreover, most available evidence has been generated under controlled greenhouse conditions, where salinity is applied uniformly, and environmental variables are

tightly regulated. Under field conditions, salinity often interacts with other stressors, such as drought, nutrient limitations, and temperature fluctuations, creating more complex scenarios that may alter the effectiveness of mycorrhizal symbiosis. Future research should therefore prioritize long-term field experiments and comparative evaluations of different AMF taxa to identify fungal species and inoculation strategies that provide stable benefits under naturally saline environments.

4.4 Responses to multiple environmental stresses

One of the most important trends identified in recent research is the growing recognition that plants are frequently exposed to multiple simultaneous stressors rather than isolated environmental constraints. Climate change often combines drought, salinity, heat stress, and nutrient limitations, generating highly complex environmental conditions (Duarte; Maherali, 2022).

The studies analyzed indicate that AMF maintain their beneficial effects even under these combined stress scenarios. Experimental evidence presented by Duc et al. (2018) demonstrated improved performance of tomato plants subjected simultaneously to drought and heat

stress. Similar results were reported by Hussain et al. (2026), who observed enhanced growth and physiological stability in mycorrhizal lilies exposed to combined drought and high temperatures.

Recent reviews by Formenti et al. (2026), Etesami (2026), Choudhary et al. (2026), and Samanta et al. (2025) suggest that the multifunctional nature of AMF is fundamental for coping with complex environmental disturbances. Rather than acting through a single mechanism, these fungi simultaneously regulate water relations, nutrient uptake, antioxidant defenses, hormonal signaling, and metabolic stability, generating a synergistic response that enhances plant resilience.

These findings reinforce the potential of AMF as an important component of climate-smart agriculture. Since future environmental conditions are expected to expose crops to multiple concurrent stresses rather than isolated factors, the multifunctional mechanisms provided by AMF may offer more stable and sustainable improvements in crop resilience than strategies targeting a single stress factor.

A summary of the main abiotic stresses, AMF-mediated responses, and reported plant benefits is presented in Table 1.

Table 1. Summary of the main abiotic stresses associated with climate change, arbuscular mycorrhizal fungi (AMF)-mediated responses, and reported benefits for plant performance.

Abiotic stress	Main AMF-mediated responses	Reported plant benefits
Drought	Enhanced water uptake, improved root hydraulic conductivity, increased nutrient acquisition, and activation of antioxidant defenses	Increased biomass, improved photosynthetic performance, enhanced water-use efficiency, and greater drought tolerance
Salinity	Maintenance of Na^+/K^+ homeostasis, osmotic adjustment, enhanced nutrient uptake, and activation of antioxidant defenses	Reduced ionic toxicity, improved growth, higher biomass, and increased survival under saline conditions
Heat stress	Enhanced antioxidant activity, maintenance of photosynthetic processes, and improved water relations	Improved physiological stability, enhanced photosynthetic efficiency, and increased heat tolerance
Combined stresses	Simultaneous regulation of water relations, nutrient uptake, antioxidant defenses, and metabolic homeostasis	Increased resilience, improved growth, and greater tolerance to multiple concurrent environmental stresses

Source: Author (2026).

4.5 Physiological, biochemical, and molecular mechanisms

The evidence compiled in this review demonstrates that the benefits provided by AMF emerge from a highly integrated network of physiological, biochemical, and molecular processes. Enhanced water uptake, maintenance of plant water status, improved nutrient acquisition, and increased photosynthetic efficiency constitute the primary physiological mechanisms

supporting plant adaptation under stress conditions (Chen et al., 2018; Chen et al., 2021).

At the biochemical level, increased antioxidant enzyme activity and accumulation of osmoprotective compounds are among the most frequently reported responses (Begum et al., 2019; Chandrasekaran, 2022a). These adaptations reduce oxidative damage and preserve cellular functions during periods of environmental stress.

Recent molecular studies have considerably expanded our understanding of the regulatory mechanisms involved

in AMF-mediated resilience. Feng et al. (2020) highlighted the importance of lipid-mediated signaling pathways in stress responses, while Wang et al. (2023) and Wang et al. (2024) identified modifications in the expression of genes related to water transport, nutrient metabolism, and antioxidant defenses.

Reviews conducted by Lenoiret al. (2016), Latef et al. (2016), Wahab et al. (2023), and Nie et al. (2024) further reinforce the idea that AMF-mediated resilience results from coordinated responses operating across multiple

biological scales, from gene expression to whole-ecosystem functioning.

Collectively, the available evidence indicates that AMF-mediated resilience results from the interaction of physiological, biochemical, molecular, and ecological processes acting across multiple levels of biological organization. The main mechanisms identified in the reviewed literature and their contributions to plant stress tolerance are summarized in Table 2.

Table 2. Main mechanisms by which arbuscular mycorrhizal fungi enhance plant resilience under climate change-related abiotic stresses.

Mechanism Category	Main Effects of AMF	Contribution to Stress Tolerance
Water Relations	Increased water uptake, root hydraulic conductivity, root growth, and water-use efficiency	Improves plant performance under drought and water deficit conditions
Nutrient Acquisition	Enhanced uptake of phosphorus, nitrogen, and micronutrients; improved nutrient-use efficiency	Maintains plant nutrition under adverse environmental conditions
Biochemical Responses	Activation of antioxidant enzymes (SOD, CAT, POD, APX); accumulation of osmoprotectants; reduction of oxidative damage	Protects cellular structures against stress-induced reactive oxygen species
Molecular Regulation	Modulation of stress-responsive genes; hormonal signaling (ABA, auxins, jasmonic acid, salicylic acid); activation of adaptation pathways	Enhances physiological adjustment and long-term stress adaptation
Soil Structure and Aggregation	Production of glomalin and stabilization of soil aggregates	Improves soil water retention and resistance to degradation
Nutrient Cycling	Increased microbial activity and nutrient turnover	Supports soil fertility and ecosystem functioning
Carbon Sequestration	Greater carbon storage in soil organic matter and fungal biomass	Contributes to climate change mitigation and ecosystem sustainability
Ecosystem Resilience	Maintenance of biodiversity, ecosystem stability, and plant community recovery	Enhances ecosystem resistance and recovery following disturbances

Source: Author (2026).

4.6 Ecological importance and sustainable applications

Beyond their direct effects on plants, AMF play fundamental roles in ecosystem functioning and in the long-term sustainability of agricultural and natural ecosystems. The formation and stabilization of soil aggregates, improvement of nutrient cycling, and enhancement of soil carbon storage are among the most important ecological services provided by these fungi (Berruti et al., 2016; Conti et al., 2025; Shukla et al., 2025).

Cardoso Filho et al. (2017) highlighted the importance of mycorrhizal symbiosis for plant nutrition and sustainable agricultural systems, emphasizing the potential of AMF to reduce dependence on synthetic

fertilizers while maintaining or improving crop productivity. This perspective is supported by Nadeem et al. (2014), who demonstrated that mycorrhizae and other beneficial microorganisms can significantly improve crop performance under stressful environmental conditions.

Recent evidence indicates that AMF are increasingly recognized as essential components of climate-smart agriculture and regenerative farming systems (Kumar et al., 2025; Nie et al., 2024). However, the effectiveness of commercial inoculants may vary depending on AMF species, soil conditions, and crop management, highlighting the importance of site-specific evaluations before large-scale application.

The ecological significance of AMF also extends to ecosystem restoration and biodiversity conservation. Diagne et al. (2020), Usman et al. (2021), and Madouh &

Quoreshi (2023) emphasized the importance of mycorrhizal associations in facilitating plant establishment, promoting vegetation recovery, and increasing ecosystem resistance to environmental disturbances. These functions are particularly relevant in degraded landscapes and regions highly vulnerable to climate change.

These ecological functions highlight the contribution of AMF not only to ecosystem restoration but also to the long-term resilience of natural and agricultural ecosystems under climate change.

4.7 Species-specific responses of arbuscular mycorrhizal fungi

Although arbuscular mycorrhizal fungi (AMF) are often treated as a single functional group, a growing body of evidence shows that different taxa exhibit distinct ecological strategies and vary substantially in their capacity to enhance plant tolerance to abiotic stresses. These differences are linked to fungal life-history traits, hyphal architecture, nutrient acquisition efficiency, colonization dynamics, and interactions with both host plants and soil environments.

Among the most widely studied taxa, species of the genus *Rhizophagus*, particularly *Rhizophagus irregularis*, consistently show high effectiveness in improving drought tolerance. These fungi enhance root colonization, promote water uptake through extensive extraradical hyphal networks, increase phosphorus acquisition, and stimulate antioxidant enzyme activity. Together, these effects contribute to improved photosynthetic performance and greater biomass accumulation under water-deficit conditions (Cheng et al., 2021; Wang et al., 2023; Tanget al., 2022).

Species of *Funneliformis*, especially *Funneliformis mosseae*, have been extensively reported to mitigate both drought and salinity stress. Their beneficial effects include improved ionic homeostasis via better Na^+/K^+ regulation, enhanced osmotic adjustment, increased nutrient uptake, and activation of antioxidant defense systems, which collectively reduce oxidative damage under stressful conditions (Evelin et al., 2019; Dastogeer et al., 2020; Boorboori; Lackóová, 2025).

Other genera, such as *Claroideoglossum*, show promising performance under nutrient-limited soils and combined stress conditions, although the available evidence remains more limited. Studies suggest that these fungi may possess efficient nutrient foraging strategies and maintain functional symbiosis even under adverse environments, indicating potential value for sustainable agricultural systems.

Members of *Diversispora* have gained attention due to

their ecological plasticity and role in maintaining AMF community diversity. Rather than consistently producing the strongest individual plant growth responses, they may contribute to ecosystem stability by complementing the functional roles of other AMF taxa within diverse microbial assemblages.

Species of *Gigaspora* are characterized by extensive extraradical mycelial development, which enhances soil exploration and nutrient acquisition. However, their relatively slow colonization rates may reduce their effectiveness during early plant establishment compared with rapidly colonizing taxa such as *Rhizophagus*. As a result, their performance is strongly influenced by host species, soil characteristics, and environmental conditions.

Overall, current evidence demonstrates that AMF-mediated stress tolerance cannot be generalized across taxa. There is considerable functional variation among species, and inoculation outcomes depend on multiple interacting factors, including fungal identity, host genotype, soil properties, native microbial communities, and the type and intensity of environmental stress. Therefore, the careful selection of AMF species or consortia should be considered essential for optimizing plant resilience under climate change scenarios.

In summary, the benefits conferred by AMF are highly species-dependent. For example, *Rhizophagus irregularis* is frequently associated with improved phosphorus uptake, water-use efficiency, and drought tolerance, whereas *F. mosseae* is strongly linked to enhanced antioxidant activity and osmotic regulation under salinity and drought stress. *Claroideoglossum etunicatum* has also shown positive effects on nutrient acquisition and stress mitigation in several crops, while *Diversispora* spp. exhibit variable performance depending on soil conditions and host identity. These species-specific responses reinforce that AMF effectiveness depends not only on fungal identity but also on environmental context and plant genotype, underscoring the importance of targeted AMF selection for sustainable agricultural applications.

4.8 Limitations and challenges for agricultural application

Despite the considerable potential of arbuscular mycorrhizal fungi (AMF) to enhance plant tolerance to climate-related stresses, several challenges still limit their consistent application under field conditions. One of the main constraints is the high variability in AMF performance across different environments. Results obtained under controlled greenhouse conditions often differ substantially from those observed in agricultural fields, where multiple biotic and abiotic factors interact

simultaneously.

The effectiveness of AMF inoculation is strongly influenced by soil characteristics, including texture, pH, nutrient availability, moisture, and organic matter content. In particular, high phosphorus availability frequently suppresses mycorrhizal colonization and reduces the benefits provided by AMF. Moreover, introduced inoculants must compete with indigenous AMF communities that are already adapted to local environmental conditions, which can reduce inoculation success and persistence.

Another important limitation concerns the variability among commercial inoculants. Differences in propagule viability, fungal species composition, inoculum quality, storage conditions, and production methods often result in inconsistent performance. The absence of standardized protocols for inoculum production and quality control further complicates comparisons among studies and limits large-scale agricultural adoption.

Plant genotype also plays a decisive role in determining the success of AMF symbiosis. Host species—and even cultivars within the same species—may differ considerably in their compatibility with specific AMF taxa, leading to substantial variation in growth promotion and stress tolerance. This host specificity highlights the need for selecting compatible plant–fungus combinations rather than assuming universal effectiveness.

Economic factors should also be considered when evaluating the feasibility of AMF-based technologies.

Although inoculation can reduce fertilizer requirements and improve crop resilience, production costs, application logistics, storage, and uncertain field performance may limit adoption by farmers, particularly in large-scale agricultural systems. Comprehensive cost–benefit analyses under diverse production scenarios are therefore needed.

Addressing these limitations will require standardized inoculant production, better characterization of native AMF communities, optimization of host–fungus matching, and validation through long-term, multi-location field trials. Overcoming these challenges is essential for translating the well-documented benefits of AMF into reliable and economically viable agricultural practices under climate change.

4.9 Knowledge gaps and future perspectives

Although significant progress has been made in understanding the role of arbuscular mycorrhizal fungi in plant adaptation to environmental stress, important knowledge gaps persist. A considerable proportion of the available evidence derives from greenhouse-based experiments, which often fail to capture the complexity of ecological interactions occurring under natural conditions (Millar; Bennett, 2016). This limitation highlights the need for long-term field studies capable of assessing AMF-mediated resilience under realistic climate change scenarios. The major research gaps and future priorities identified in this review are summarized in (Table 3).

Table 3. Major knowledge gaps and future research priorities regarding AMF-mediated plant resilience under climate change.

Knowledge gap	Research priority	Future research needs
Limited long-term field studies	High	Conduct multi-year field experiments under realistic climate change scenarios
Insufficient understanding of AMF species-specific performance	High	Compare the functional traits and effectiveness of different AMF taxa across crop species and environmental conditions
Limited research on multiple simultaneous abiotic stresses	High	Investigate AMF responses under combined drought, salinity, heat, and nutrient limitations
Limited integration of molecular, physiological, and ecological approaches	Medium–High	Integrate multi-level analyses linking gene expression, physiological responses, and ecosystem functioning
Limited evaluation of native AMF communities	High	Assess the effectiveness of indigenous AMF

Variability in the effectiveness of commercial inoculants	High	communities for sustainable agricultural systems Develop site-specific inoculation strategies and evaluate interactions with native soil microbiomes
Limited understanding of climate change impacts on AMF communities	Medium–High	Examine how future climatic scenarios influence AMF diversity, community composition, and ecosystem functioning
Limited evidence supporting large-scale agricultural implementation	High	Evaluate the economic feasibility, scalability, and long-term sustainability of AMF-based technologies under field conditions

Source: Author (2026).

Another important limitation concerns the predominance of agricultural species in current research. Native vegetation communities, particularly those occurring in biodiversity hotspots and climate-vulnerable ecosystems, remain underrepresented in the literature. Long-term field studies are therefore necessary to better understand the ecological dynamics of AMF under realistic climate change scenarios.

Future research should increasingly adopt integrative and interdisciplinary approaches to improve understanding of AMF-mediated plant resilience under climate change. One of the main priorities is the establishment of long-term field experiments capable of capturing seasonal variability, soil heterogeneity, and the cumulative effects of multiple environmental stressors. Such studies are essential because the majority of current evidence still originates from short-term greenhouse experiments, which may overestimate the effectiveness of AMF under controlled conditions.

Advances in multi-omics technologies also represent a promising research frontier. The integration of metagenomics, metatranscriptomics, metabolomics, and proteomics can provide a comprehensive understanding of the molecular and functional mechanisms governing plant–AMF interactions. These approaches may identify key genes, signaling pathways, and metabolic networks involved in stress tolerance while revealing how fungal communities respond to changing environmental conditions.

Another important direction involves investigating AMF within the broader context of the plant microbiome. Rather than functioning in isolation, AMF interact continuously with bacteria, other fungi, and soil microorganisms that collectively influence nutrient

cycling, plant health, and ecosystem functioning. Understanding these complex microbial networks may facilitate the development of microbial consortia with greater stability and effectiveness than single-species inoculants.

Future studies should also evaluate AMF performance under realistic climate change scenarios using Free-Air CO₂ Enrichment (FACE) experiments and other field-based climate manipulation platforms. These experimental systems allow simultaneous assessment of elevated atmospheric CO₂, warming, altered precipitation regimes, and other environmental drivers, providing more reliable predictions of AMF-mediated resilience under future climatic conditions.

At larger spatial scales, ecological network analyses and ecosystem-level modeling should be incorporated to better understand how AMF contribute to biodiversity maintenance, soil ecosystem services, and vegetation stability. Coupling ecological data with climate modeling may improve predictions of fungal distribution, host–symbiont dynamics, and ecosystem resilience under different climate change scenarios, thereby supporting the design of more effective strategies for sustainable agriculture, ecological restoration, and climate adaptation.

5. Conclusion

This systematic review demonstrated that arbuscular mycorrhizal fungi (AMF) play a fundamental role in enhancing plant resilience to climate change-related environmental stresses. The evidence synthesized from the selected studies showed that AMF improve plant tolerance to drought, salinity, nutrient limitations, and multiple simultaneous stressors through a combination of physiological, biochemical, molecular, and ecological

mechanisms.

Among the main benefits identified were increased water and nutrient acquisition, enhanced photosynthetic performance, activation of antioxidant defense systems, hormonal regulation, osmotic adjustment, and modulation of stress-responsive genes. These mechanisms contribute to maintaining plant growth, productivity, and survival under adverse environmental conditions. Furthermore, the reviewed literature highlighted the importance of AMF in improving soil structure, promoting nutrient cycling, increasing carbon sequestration, and supporting ecosystem stability.

Beyond their ecological relevance, AMF represent a promising biological resource for sustainable agriculture and climate adaptation strategies. Their capacity to reduce dependence on chemical fertilizers, improve resource-use efficiency, and enhance crop performance under environmental stress makes them valuable tools for developing more resilient and environmentally sustainable production systems. In addition, their potential applications in ecological restoration and biodiversity conservation reinforce their strategic importance in addressing current and future environmental challenges.

Despite the substantial progress achieved in recent years, important knowledge gaps remain, particularly regarding the long-term responses of AMF communities to climate change and their performance under complex field conditions. Future research should prioritize long-term experiments, ecosystem-scale investigations, and integrative approaches combining ecological, physiological, and molecular perspectives to improve understanding of plant–fungus interactions in changing environments.

Overall, the findings of this review highlight arbuscular mycorrhizal fungi as key components of plant adaptation and ecosystem resilience under global climate change, emphasizing their potential contribution to sustainable land management, food security, and environmental conservation.

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Author's Contributions

The author conceived and designed the study, collected and analyzed the data, interpreted the results, drafted the manuscript, and approved the final version for publication.

Ethics

The author declares that this manuscript complies with current ethical standards. The study did not involve experimentation on humans or animals. All data used were obtained and utilized in accordance with applicable standards and guidelines. The author assumes responsibility for clarifying and resolving any ethical issues that may arise following publication.