Second Edition

CLIMATE CHANGE AND AGRICULTURAL ECOSYSTEMS

CURRENT CHALLENGES AND ADAPTATION

Edited by
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Joginder Singh, and Gustavo Santoyo

ELSEVIER

Climate Change and Agricultural Ecosystems

19

Sustainable agricultural practices using beneficial fungi under changing climate scenarios

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Chapter Outline

19.1 Introduction

The connection of agriculture, climate change, and sustainability has emerged as a critical focal point in global discourse, as humanity confronts the challenges of ensuring food security under the growing threats of environmental degradation and

Climate Change and Agricultural Ecosystems. DOI: https://doi.org/10.1016/B978-0-443-26520-4.00028-7

climate change (Ortiz et al., 2021). As a result, conventional farming methods are being reconsidered and updated to become more resilient and sustainable (Okoronkwo et al., 2024). Over the past few decades, increased research funding has led to innovations that have improved crop adaptation to deteriorating soil health and climate stresses. The use of soil microbes is one of them. In addition to influencing the interaction between soil microorganisms and their function in generating biofertilizers and biopesticides, they are utilized as microbial inoculants and consortia to alleviate the effects of climate change on crop yields (Inbaraj, 2021; Kavadia et al., 2020).

The obvious effects of climate change manifest numerous impacts such as altered precipitation patterns, rising temperatures, increased frequency of extreme weather events, and shifts in pest and disease dynamics (Guo et al., 2021). These aggravate soil erosion, environmental degradation, and the loss of biodiversity in addition to endangering agricultural productivity (Eekhout & de Vente, 2022; Habibullah et al., 2022). Therefore, in order to reduce the risks associated with climate change and to advance ecological resilience and sustainability, creative and adaptable agricultural practices should be continuously revised. Therefore, innovating means of harnessing the potential of beneficial microbes in the environment presents a promising prospect for sustainable agricultural practices and food security despite the challenges posed by climate change (Singh et al., 2023). Fig. 19.1 explains some impacts of beneficial fungi in sustainable agricultural practices.

Beneficial fungi, including a diverse array of symbiotic and endophytic species, offer a natural, compelling solution in this context. Fungi form intricate relationships with plants, aiding nutrient uptake, disease suppression, and stress tolerance. Also, they contribute to soil health, carbon sequestration, and ecosystem stability, offering multifaceted potential that can be exploited for sustainable agriculture (Alori et al., 2017; Eze et al., 2024). In light of the current climate change era, this study examines the diverse functions of beneficial fungi in sustainable agricultural practices. It is talked about how crucial it is to modify cropping techniques in response to climate change challenges.

19.2 Impacts of climate change on sustainable agricultural systems

Changing climate conditions can substantially affect agricultural productivity and food security (Yadav et al., 2018). Variations in temperature, humidity, and precipitation can cause growing seasons to be disrupted, crop yields to be decreased, soil microbial activities that promote plant growth to be increased, and the prevalence of pests and diseases to rise. Fisheries, aquaculture, and livestock production are all impacted by climate change, which may cause problems with the availability of food (Cheng et al., 2022). This might have unintended detrimental effects on people's health by leading to starvation, infections from contaminated water, illnesses brought on by the heat, and various degrees of mental health issues (Myers & Bernstein, 2011). Rocha et al. (2022) noted that the population of humans is most susceptible to the effects of climate change. This is due to the fact that the effects of climate change, such as heat waves, extreme weather, and altered disease patterns, can weaken immunity in people, raising

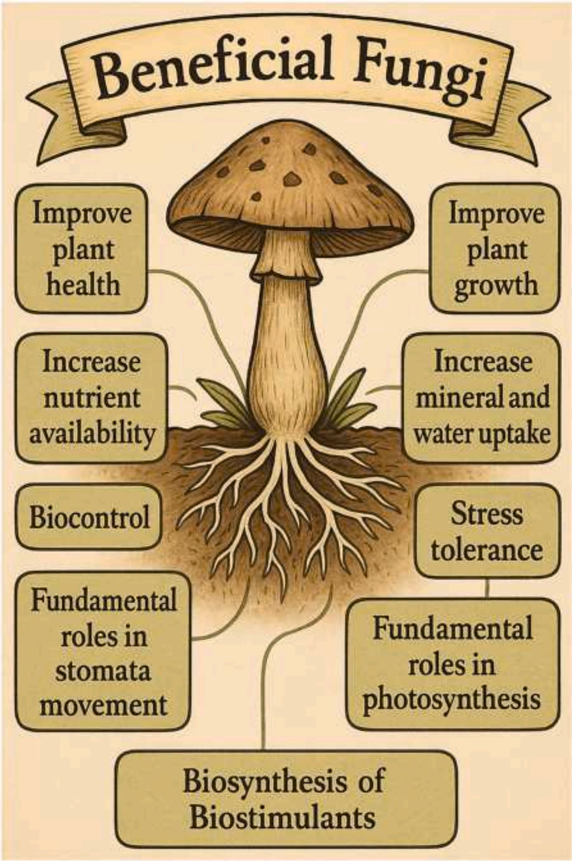

Figure 19.1 Impacts of beneficial fungi in sustainable agricultural practices.

their risk of developing respiratory issues, heat-related illnesses, vector-borne infections, waterborne infections, and other infections (Ebi et al., 2021). Susceptible populations, including the elderly, children, and marginalized communities, are particularly at higher risk of being affected by climate change-related stresses, leading to loss of livelihood, chronic exposure to pollutants and extreme weather patterns, epidemiological illnesses, and adaptive challenges to the changing socioeconomic landscape (Rocklöv & Dubrow, 2020).

Crop productivity is negatively impacted by climate change in a number of ways, including decreased soil fertility and crop yield, limited soil water availability, increased soil erosion, and increased pest spread (Tajudeen et al., 2022). According to Grigorieva et al. (2023), the negative impacts of climate change are expressed in terms of reduced crop yields and crop area.

Also, the impacts of climate change can have significant economic consequences (Kalkuhl & Wenz, 2020). Circular economic growth can be significantly slowed down by a number of factors, including damage to infrastructure, higher healthcare costs, disruptions to agriculture and food production, and the loss of coastal features and tourism revenue. These consequences may exacerbate already-existing disparities by causing social and economic inequality. The adverse effects of climate change encompass financial setbacks, escalated expenses for labor, and equipment (Grigorieva et al., 2023).

Dangerous climatic events such as flooding, extreme heat, and drought have led to soil degradation, which results in low crop yields (Agbola & Fayiga, 2016). Climate change negatively impacts crop productivity by decreasing soil fertility, and increasing soil erosion (Tajudeen et al., 2022). Due to changes in the ideal temperature ranges, climate change has also jeopardized the survival and integrity of many species, hastening the loss of biodiversity by gradually altering the ecosystem structures.

19.3 Importance of adapting cropping practices to climate change challenges

Adaptation refers to actions designed to increase the ability of individuals and communities to decrease harms from climate change that will occur in numerous parts of human life (Orlove, 2022). Hence, adapting cropping practices means activities aimed at increasing the cropping practice's ability to lessen the harms from climate change. Adaptation of cropping practices to climate change includes changes in a cropping practice in response to variations in climate situations (Akinnagbe & Anugwa, 2015). Cropping practices can adapt in response to a series of events, such as temperature and precipitation levels, that cause droughts (in terms of intensity and/or frequency), which have an impact on crop yield (Smit et al., 2000). Crop varieties and management, innovative breeding techniques and changes in land use, water and soil management, agronomic practices, farmer training, and knowledge transfer are some of the crop practices that could be adjusted to the challenges posed by climate change (Grigorieva et al., 2023).

According to Akinnagbe and Anugwa (2015), Farmers frequently use the following adaptation strategies for their crops: using drought-tolerant crop varieties; crop diversification; altering cropping patterns and planting dates; conserving soil moisture through appropriate tillage techniques; increasing irrigation efficiency; and afforestation and agroforestry. The United Nations Sustainable Development Goals, which sought to safeguard the environment and guarantee that everyone lives in peace and prosperity, will be achieved through cropping practices that are adjusted to the challenges posed by climate change. sustainable cultivation of food (Çakmakçı et al., 2023). A key factor in reducing the adverse effects of climate change will be cropping practices adaptation, which may involve changes to field-scale management techniques (Lehmann et al., 2013).

Additionally, some of the effects of climate change are occurring more quickly than previously thought, and cropping practices will need to adapt to these trends if they are to continue (Rahmstorf et al., 2007). Differences in annual rainfall, average temperature, heat waves, alterations in weeds, pests or microbes, universal alteration of atmospheric CO_2 or ozone level, and instabilities in sea level, all due to climate change, impede total crop production and compromise food security worldwide (Raza et al., 2019). By using specially designed fertilization regimes in single-crop cultivation systems, cropping practices can be adjusted to the challenges posed by climate change. This reduces the need for inputs, water waste, fossil fuels, and unharvested products, all of which lower emissions and boost net productivity (Turner-Skoff & Cavender, 2019). Additionally, by lowering the amount of methane released during animal production, choosing plant-based protein sources (like pulse crops) rather than animal-based proteins lowers agricultural greenhouse gas emissions (Volk et al., 2023). Cropping practices that are adjusted to the challenges posed by climate change will: lower exposure to damage risk; increase resilience to inevitable damage; and enable the cropping system to seize new opportunities (Akinnagbe & Anugwa, 2015).

19.4 Activities of beneficial fungi that enhance crop and cropping system efficiency in the climate change era

Beneficial fungi adopt strategies, either direct or indirect, to help crops and cropping systems in the face of climate change. Production of phytohormones, nitrogen fixation, phosphate solubilization, siderophore formation, and antimicrobial metabolites are all part of the direct beneficial mechanism (El Enshasy et al., 2020).

Endophytic fungal annexation encourages physical changes and alters gene expression in the plants, thus elevating plant productivity through higher photosynthesis rate, encouraging the growth of the shoots and roots, improving uptake and nutrient use efficiency, and providing resistance to biotic (pathogens and pests) and abiotic stress (drought, salinity, high temperature, high CO_2, and metal toxicity) (Grabka et al., 2022). Beneficial fungi act as biostimulants to yield certain bioactive compounds, phytohormones, phosphate solubilization factors, etc., to improve root growth, seed germination, and plant growth promotion (Rustamova et al., 2022). Many fungi, such as *Penicillium, Aspergillus, Curvularia, Trichoderma, Mesorhizobium, Aspergillus fumigatus, Aspergillus niger, Alternaria thlaspis, Metapochonia rubescens*, have been identified and reported to have ability to solubilize and mobilize phosphorus, potassium, and zinc salts thereby boosting plant metabolic activity, plant growth resulting in high crop production (Haro & Benito, 2019; Mehta et al., 2019; Yung et al., 2021). They execute phyto stimulation via lowering plant hormone ethylene levels by 1-aminocyclopropane-1-carboxylate deaminase (ACC), escalating plant growth (Singh et al., 2015). Additionally, they break down biomass and reuse it into the environment, which increases the host's availability of nitrogen and increases its uptake of zinc and phosphorus, leading to phyto immobilization (Yung et al., 2021).

Through the immobilization of osmolytes and the stabilization of membrane ion conductivity under stress conditions brought on by climate change, phyto immobilization ultimately increases plants' ability to withstand abiotic stresses (Verma et al., 2022). Beneficial fungi disrupt pathogens’ quorum sensing (QS) by inhibiting the production of signal molecules that initiate infections. Take, for instance, the production of QS inhibitors that can break down QS signal molecules, such as chitinases, pectinases, and lactonases. These inhibitors prevent pathogen invasion and lead to reduced plant disease symptoms (Saeki et al., 2020). *Curvularia geniculata* mediates plant growth through phosphate solubilization and phytohormone production (Priyadharsini & Muthukumar, 2017).

The incidental beneficial mechanism includes resistance to abiotic and biotic stressors (modifying the metabolism process), biocontrol, etc. (Singh et al., 2021). Beneficial fungi defend plants indirectly by triggering a defense response or promoting plant growth (Zubair et al., 2021). As a result, the host undergoes a wide range of biochemical and molecular defensive processes that serve as a defense mechanism against numerous pathogens (Ayaz et al., 2023). Endophytic fungi potentially execute munificent global roles in the host plant via phytostimulation, phytoimmobilization, phytostabilization, phytotransformation, phytoremediation, and biocontrol (Adeleke et al., 2022b). They are reported to produce secondary metabolites, which include bioactive antimicrobial siderophores, which may execute defense against various pathogens (Srinivas et al., 2020). They inhibit the pathogens' pathogenicity over different materials such as lipopeptides, biosurfactants, bacteriocins, volatiles, and enzymes that have antimicrobial properties by reducing the development or metabolic activity of pathogens (Babalola, 2010).

Under chilling stress, *Funneliformis mosseae* inoculation significantly improved the content of related secondary metabolites, including phenols, flavonoids, lignin, DPPH activity, and phenolic compounds (Chen et al., 2013). *Glomus mosseae* under low temperature stress increased leaf activities of superoxide dismutase, ascorbate peroxidase, guaiacol peroxidase, ascorbate, and glutathione, but decreased leaf concentrations of malondialdehyde, and hydrogen peroxide in crops (Liu et al., 2017).

19.5 Benefits and efficacy of sustainable agricultural practices using beneficial fungi

Rhizosphere soil fungi, such as *Trichoderma* spp., *Gliocladium virens*, *Penicillium digitatum, Aspergillus flavus, Actinomucor elegans, Podospora bulbillosa*, and arbuscular mycorrhizal fungi, can improve the growth of the shoots and roots of crop plants, the germination of seeds, the production of chlorophyll for photosynthesis, and the copious production of crops (Adedayo & Babalola, 2023a). Applications of beneficial fungi overwhelm the usage of agrochemicals and likewise prevent plants from biotic and abiotic stresses (Malgioglio et al., 2022). The beneficial fungi improve plant root extension, encourage plant growth development (seed germination and seedling strength and photosynthetic efficiency), protection from various kinds of phyto-pathogens, and also support soil improvements (Kumari et al., 2021). Plant growth-promoting fungi could suppress plant diseases by producing inhibitory chemicals and inducing immune responses in plants against phytopathogens, and have therefore proven to be effective biofertilizers and biopesticides, and are considered a feasible, attractive economic approach for sustainable agriculture

(El-Saadony et al., 2022). As stated by Muthuraman and Murugaragavan (2020), beneficial fungi conjointly play a basic role in different physiological processes as well as mineral and water uptake, chemical change, stomata movement, and biosynthesis of compounds termed biostimulants, auxins, lignan, and ethylene to enhance the flexibility of plants to ascertain and cope environmental stresses like drought, salinity, heat, cold, and significant metals. Beneficial fungi produce large quantities of bioactive compounds that can be used as agrochemicals for crop protection (Ayaz et al., 2023). Table 19.1 reported some of the benefits of using beneficial fungi for sustainable agricultural practices in a changing climatic scenario

19.6 Economic and environmental feasibility of adopting fungi in sustainable agriculture

In the majority of cases, climate-smart systems that incorporated beneficial fungi outperformed the conventional control, with some even achieving a yield gain of over 60% (Thierfelder & Mutenje, 2018). Due to their biomass, hyphal network, and longer life cycle, fungi are more advantageous over bacteria for bioremediation of polluted agricultural soil (Kour et al., 2024). Utilizing arbuscular mycorrhizal fungi as a biofertilizer increases nutrient uptake, stimulates plant growth hormones, and expedites the decomposition of organic wastes, all of which can increase crop yield (Osemwegie et al., 2021). In nature, fungi are commonplace, and their various strains give their species greater specificity against pests and illnesses. They are self-sustaining because the infection spreads by means of spores, which are generated in vast quantities and persist so long as the right conditions for growth are present. As a result, application costs are also decreased (Singh et al., 2018). A deeper understanding of the physiological responses of these microbes to stress can help develop a more robust and resilient agroecosystem, even though research supports the use of mycorrhizae and fungal endophytes as an environmentally friendly alternative to combat drought stress (Raghuwanshi, 2018). With their varied functional diversity and dispersal mechanisms, fungi constitute a significant and diverse component of the majority of ecosystems on Earth. The expanding body of knowledge regarding microbial biogeography is demonstrating how different fungal assembly patterns and processes are from bacterial ones. Their ability to successfully adapt and impact the environment is rooted in their multifaceted capacity to interact tempo-spatially with an increasingly diverse array of physical, chemical, and biological ecosystem components (Bahram & Netherway, 2022). Furthermore, their ubiquitous distribution, diverse ecological roles, remarkable biological diversity, and high sensitivity have favored them as one of the most important groups of environmental bio-indicators (Warnasuriya et al., 2023). Suffice it to say that their existence, quantity, and nature can be used to make inferences about the quality of the environment or detect environmental contaminants by less rigorous laboratory analyses or in situ visual inspections. As a result, they aid in soil fertility by breaking down plant and animal waste through enzymatic processes. Many also interact with soil fauna and saprophytic bacteria to maximize access to nutrients from rocks and organic remains,

Table 19.1 Benefits of using beneficial fungi for sustainable agricultural practices.

Beneficial fungi	Climatic factor/ stress condition	Crop	Effects	References
Ascomycetes	Semiarid	Maize	Improves physiological attributes of maize	Akinola et al. (2023)
Trichoderma species	Management of root rot diseases	Tomato	Improved crop health and productivity	Olowe, Nicola, Asemoloye, Akanmu, Babalola (2022)
Trichoderma species	Pathogenic *Fusarium* species	Maize, banana, and cassava	Inhibit the growth of *Fusarium* pathogens in vitro.	Olowe, Nicola, Asemoloye, Akanmu, Sobowale et al. (2022)
Trichoderma koningii, Purpureocillium lilacinum, Mortierella alpina	Biotic stress: Powdery mildew disease caused by *Oidium neolycopersicum*	*Solanum lycopersicum*	The fungi isolate promotes the production of tomatoes from Healthy rhizosphere soil and reduces the phytopathogen activities	Adedayo et al. (2023a)
Trichoderma spp., *Gliocladium virens*, *Penicillium digitatum*, *Aspergillus flavus*, *Actinomucor elegans*, *Podospora bulbillosa*, Arbuscular mycorrhizal fungi	Abiotic and biotic conditions	*Solanum lycopersicum, Cucumis sativus, Zea mays, Oryza sativa, Triticum aestivum, Zea mays*, etc.	Plant growth-promoting fungi promote abundant production of various crops	Adedayo and Babalola (2023a)
Ascomycota and *Basidiomycota*	Plant diseases; *Oidium neolycopersicum*	*Solanum lycopersicum*	Fungi produce plant-growth-promoting genes that contribute to the abundant production of tomatoes and inhibit or eradicate disease invasion	Adedayo et al. (2023b)

Arbuscular mycorrhiza fungi, *Trichoderma harzianum, Purpureocillium lilacinum, Metarhizium anisopliae, Penicillium spp., Aspergillus sp., Coprinellus radians, Neurospora spp., Paecilomyces spp. Epichloë typhina and Curvularia protuberata*	Abiotic and biotic stress	*Solanum lycopersicum, Zea mays, Arabidopsis thaliana*	Promote the production of the crop and prevent biotic including plant diseases, and abiotic stress including heavy metal toxicity, drought, salinity, extreme temperature	Babalola et al. (2022)
Rhizobium spp., Arbuscular mycorrhizal (AM) fungi, *Metarhizium brunneum*, *Sargassum vulgare*, *Acanthophora spicifera*, *Ascophyllum nodosum*, *Trichoderma* spp., *T. viride*, *P. chrysogenum*, *Cladosporium cladosporioides*, *Aspergillus fumigatus*	Abiotic stress	Crop plants	Fungi implement Biostimulant activities in various crop plants	Adedayo and Babalola (2023b)
Bradyrhizobium spp., *Filobasidiella, Ustilago, Tilletia, Metarhizium, Sordaria, Coprinopsis, Sclerotinia, Gibberella, Phaeosphaeria, Podospora, Ajellomyces, Aspergillus, Aspergillus fumigatus, Saccharomonospora sp.*,	Biotic and abiotic stress	*Vigna unguiculata, Helianthus annuus, Zea mays, Oryzae sativa*	Endophytic fungi improve the growth as well as abundant production of crops	Babalola and Adedayo (2023)
Ascomycota, Basidiomycota, and Blastocladiomycota	Biotic stress (plant diseases); *Oidium neolycopersicum*	*Solanum lycopersicum*	They contribute to plant growth promotion by improving the health status of the crop plant	Adedayo et al. (2022)

(*Continued*)

Table 19.1 (Continued)

Beneficial fungi	Climatic factor/ stress condition	Crop	Effects	References
Arbuscular mycorrhizal fungi	Abiotic stress	*Triticum spp., Populus spp., Zea mays, Pisum sativum*	The fungi promote plant growth and development by tolerating the various abiotic stress	Koza et al. (2022)
Trichoderma asperellum, Glomus tortuosum, Glomus ethunicatum	Abiotic stress	*Solanum lycopersicum, Zea mays, Vigna radiate, Trifolium repens, Latuca sativa, Thymus vulgaris*	Plant growth-promoting fungi relief crops from abiotic stresses	Adeleke et al. (2022a)
Trichoderma viride and *Penicillium chrysogenum*	Soft root disease; *Fusarium oxysporum, Aspergillus wenti, Penicillium digitatum*	*Citrus sinensis*	The fungi provide biological control activities against the phytopathogens causing soft rot diseases in sweet oranges	Omomowo et al. (2020)

even though they perform biodegradation functions. For instance, one of nature's forces behind sustainable agriculture is the symbiotic relationship between plants and fungi. Through their interactions with bacteria and other living things, including animals, fungi are able to complete their life cycle in varying degrees of symbiosis. A symbiotic relationship between some bacteria and fungi can help transform atmospheric nitrogen into forms that are useful to biological systems (Rashid et al., 2016). While bacteria are the main nitrogen-fixing organisms, some fungi can play a supportive role in Nitrogen fixation. Mycorrhizal fungi form mutualistic associations with plant roots, enhancing nutrient uptake (Khaliq et al., 2022). In some cases, these mycorrhizal associations can also facilitate the colonization of nitrogen-fixing bacteria. The fungus offers a favorable environment for the bacteria, such as protection from harsh conditions and a carbon source. In return, the bacteria provide the plant with fixed nitrogen in the form of ammonia or other nitrogen compounds.

Fungal hyphae grow beyond the root nutrient depletion zone and are much finer than plant roots. They can access soil pores containing plant essential nutrients that are hitherto inaccessible to their host (Begum et al., 2019; Watts et al., 2023). It is equally logical to hypothesize that the penetrating hyphae, while extending beyond the rhizospheric zone, interact with numerous niches of microorganisms and hyphae from other rhizosphere zones to sustain soil ecological functions, structure, ecophysiology, metabolic dynamism, and soil health. Therefore, harnessing soil fungi's potential to drive soil ecosystem activities is promising for sustainable climate-smart agriculture, reducing reliance on synthetic fertilizers (Clocchiatti et al., 2021).

19.7 Using beneficial fungi to enhance plant growth and resistance to pests and diseases

Beneficial fungi positively impact sustainable agriculture under different climate scenarios as discussed in Table 19.2.

Certain fungi infiltrate the tissues of plants, creating a home for bacteria that fix nitrogen from the atmosphere and convert it into nitrate that is used by plants to grow (Burragoni & Jeon, 2021). Furthermore, Fungi facilitate the uptake of nutrients by plants, improving their capacity to absorb nitrogen, phosphorus, and other micronutrients. In order to enhance plant growth and development, fungal hyphae pierce the soil to obtain nutrients that are not accessible to the plant's root system. Plants are also able to withstand a variety of environmental stresses thanks to this symbiotic relationship. It epigenetically promotes the production of bioactive substances that have anti-biotic and antibiotic qualities against pathogens, saline, drought, and high temperatures (Zhang et al., 2023). The plant hosts' defense systems are strengthened by the metabolites, which also make them more resilient to harsh environmental conditions and adaptation. Thus, it is impossible to undervalue the role that fungi play in host plants' ability to withstand disease. Certain endophytic fungi give plants the ability to resist various diseases by producing bioactive compounds with antifungal or antibacterial qualities that inhibit the growth of pathogens (Zeilinger, 2023). Endophytic fungi, for instance, can act as a first line of defense against

Table 19.2 Roles of beneficial fungi under changing climate scenarios.

S/N	Fungi	Impact	Role of the beneficial fungi	References
1	Mycorrhiza sp., *Trichoderma* sp., *Chaetomium* sp., and *Gliocladium* sp	They enhance plant growth, suppress abiotic stress conditions, and influence a number of biochemical developments and functions	Biofertilizer, Biocontrol agents	Odoh et al. (2020)
2	*Glomus fasciculatum, Glomus mosseae)*	Augmented the concentration of total phenolic compounds, flavonoids, and phenolic acid contents.	Tool for improving health-promoting compounds in vegetable	Khalid et al. (2017)
3	*Glomus* spp	Improve plant growth	Biofertilizer	Arya et al. (2018)
4	*Aspergillus awamori, Penicillium citrinum*	Stimulatory effect on chickpea plant growth.	Biofertilizer	Mittal et al. (2008)
5	*Trichoderma asperellum*	Increased chickpea (*Cicer arietinum*) growth parameters in the presence of plant pathogen *Fusarium equiseti* in chickpea	Biofertilizer, Biocontrol	Adnani et al. (2024)
6	*Trichoderma harzianum*	Increased plant height, stem circumference, leaf number, total phosphorus in the rubber tree leaves, shoot fresh weight, root fresh weight, shoot dry weight, and root dry weight	Biofertizer	Promwee et al. (2014)
7	*Curvularia geniculate*	Superior growth	Biofertilizer	Priyadharsini and Muthukumar (2017)
8	*Penicillium sp*	Plant growth promotion	Drought-adaptive bioinoculants	Kour et al. (2020)
9	*Funneliformis mosseae*	Higher fresh weight and dry weight of the crop	Alleviation of chilling stress	Chen et al. (2013)
10	*Glomus mosseae*	Higher concentrations of soluble sugar, proline, P, and K	Resistance of plants against low-temperature stress	Liu et al. (2017)
11	*Gigaspora rosea, Glomus clarum, G. rosea + G. clarum*	Higher dry matter and superoxide dismutase and peroxidase enzyme activities	Biofertilizer	Sapelli et al. (2024)

pathogens by colonizing plant tissues and providing a barrier against invasion (Baron & Rigobelo, 2022). Additionally, by boosting the immune response, they can strengthen the plant's resistance to disease. Additionally, they generate compounds that promote plant growth, such as gibberellins, cytokinins, and auxins, which can boost nutrient uptake, encourage root and shoot growth, and increase overall plant vigor. Endophytic fungi have the potential to enhance crop yields, increase biomass, and grow larger root systems (Tripathi et al., 2022).

19.8 Conclusion

In climate change scenarios, beneficial fungi are important for sustainable agriculture in a variety of ways. Their benefits to disease prevention, soil health, sequestration of carbon, and overall ecosystem resilience make them invaluable allies in combating climate change-related agricultural challenges. Agricultural systems that are resilient and sustainable must be developed by putting in place measures that support and maximize the potential of these fungi. Under scenarios of a changing climate, beneficial fungi can play a variety of roles in sustainable agricultural practices, including biofertilizer, biocontrol agents, and abiotic stress bioremediators.

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