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Review Article

Revolutionizing food security: The transformative role of fungi in the 21st century

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Abstract
With increasing global population density and climate change, the sustainability of food production poses new challenges. These are factors such as food inflation, climate change, natural disasters, and diseases affecting crops among others. Consequently, fungi have evolved as a pillar of ecological agriculture in the twenty-first century. Some of the diverse applications of fungi include biological control, synthesis of antifungal compounds, symbiotic relationship with plants, and enhancement of soil structure. They also function as decomposers in ensuring nutrient availability in the soil, and as biostimulants to enhance plants' growth, plant disease management and enhanced resistance to abiotic stressors such as water scarcity, and salinity and mitigate the impact of climate change. Furthermore, fungi play other important roles in food security, such as in the processing of various foods including cheese, bread, fermented products and other sources of protein, vitamins, and dietary fiber, while foods of fungi origin prevent lifestyle diseases. New approaches in fungal biotechnology present the hope of eliminating hunger and malnutrition through food production, preservation, and packaging among others. Although, challenges persist in the management of pathogenic fungi in agriculture, however, it is important to leverage the beneficial role of fungi and encourage further exploration of its transformative potential towards a secured global food security.

Keywords: *Biofortification, biotechnology, global food security, fungi-based products, symbiotic relationships, soil fertility, mycorrhizae.*

Introduction

Fungi are a diverse group of organisms that contribute significantly to the promotion of food security. They are eukaryotic organisms with a distinct nucleus and other membrane-bound organelles within their cells (Roberson, 2020). Several biological activities that take place in the biosphere depend on the interaction of fungi with their environment (Abdel-Aziz et al., 2018; Gupta et al., 2017). Fungi could be found in almost every environment; hence its hosts and habitats are highly varied (Hurdeal et al., 2021). Also, the fungi kingdom is diversified into seven distinct recognized phyla consisting of *Ascomycota*, *Basidiomycota*, *Chrytridiomycota*, *Zygomycota*, *Glomeromycota*, *Blastocladiomycota* and *Neocallimastigomycota* (Egbuta et al., 2016). However, only a few species have been extensively studied (Holiachuk and Kosylovych, 2021), and the phylum *Ascomycota* represents 75% of all the identified fungi (Egbuta et al., 2016). Fungi are heterotrophic in nature, they obtain their nutrients by absorbing organic matter from their

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environment (Zhao et al., 2022). The prominent ecological roles of fungi in the environments include parasites, recyclers, symbionts, and decomposers (Sudharsan et al., 2023), and they frequently establish mutualist interactions with surrounding organisms to provide minerals, water, and carbon dioxide. As saprophytes, fungi derive energy from organic matter, breaking down and thriving on dead material. Thereby indicating their relevance in ecology and agricultural sustainability (Snow, 2020).

The importance of fungi in the 21st century is numerous due to their ability to produce various bioactive compounds ranging from antibiotics to anticancer, and immunosuppressants (Fadiji and Babalola, 2020; Manganyi and Ateba, 2020). These compounds are used in drug development to treat various human diseases. Fungi are also used to produce enzymes to diagnose conditions such as fungal infections (Devi et al., 2020). Fungal application has also been utilized in biotechnology, such as producing biofuels, food additives, and enzymes for industrial processes and using biodegradable plastics and other sustainable materials (Singh and Thakur, 2023). Furthermore, the relevance of fungi in environmental sustainability has equally been explored based on their contribution to the ecosystem maintenance through the degradation of organic matter, such as fallen leaves and dead animals, into nutrients that other organisms can reuse. Some species of fungi which includes *Aspergillus niger* (Chau et al., 2023), *Pleurotus osreatus* (Ramamurthy et al., 2024), Mycorrhizal fungi such as *Glomus* species (Herath et al., 2021; Solís-Ramos et al., 2021) have been reported for their bioremediation of the environmental pollutants, which have the potentials of entering the food chain. These fungal properties have also led to their essential role in sustainable agriculture, where they have been harnessed for their roles in improving soil fertility and structure, control of plant diseases, and improved plants' performance and productivity (Gunyar and Uztan, 2021; Ojuederie and Babalola, 2017). Fungi also form symbiotic relationships with plants, as in the case of mycorrhizae association (Khaliq et al., 2022), which results in more efficient nutrient uptake and better plant health (Igiehon and Babalola, 2017). Furthermore, fungi-based products and biotechnologies have been shown to increase crop yields (Meyer et al., 2020), reduce food waste (Sabater et al., 2020), and address malnutrition (Bankefa et al., 2021). As the global population increases, the biotechnological application of fungi offers promising solutions to the food security challenges in the 21st century (Srivastava et al., 2019).

Fungi in sustainable agriculture

Some of the factors that hinder the realization of sustainable food production include increasing population density globally, climate change, food inflation, natural disasters, and diseases affecting agriculture (Wahbeh et al., 2022). Whereas, fungal applications have immensely contributed to the promotion of sustainable agriculture practices in the 21st century. Fungi have been harnessed for biological control, production of antifungal compounds, formation of symbiotic relationships with plants, improvement of soil health, and helping plants resist abiotic stress (Elnahal et al., 2022). In addition, fungi have been deployed to manage crops diseases and pests, such as the fungus *Trichoderma* which can colonize the roots of plants and provide protection against soil-borne pathogens. It has well been investigated for the biocontrol of a variety of plant diseases, including Fusarium wilt, root rot, and damping-off (El-Sharkawy et al., 2021; Guzmán-Guzmán et al., 2023). These sustainable crop protection strategies reduce the need for chemical pesticides and improve crop productivity.

One of the most significant contributions of fungi to food security is their roles as decomposers, through which they maintain healthy soils and release of nutrients required for plants' growth

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(Table 1). Healthy soil harboring a diverse range of beneficial fungi can lead to more productive crops and better food security (Ulian et al., 2020). Fungi offer some essential ecological services, including nutrient cycling in the soils and releasing of essential nutrients such as phosphorus, potassium, and nitrogen required for plant growth. Fungi, such as Mycorrhizal, form symbiotic relationships with plant roots, aiding nutrient absorption from the soil and improving plant growth and productivity (Wahab et al., 2023). More so, some fungi produce compounds that have antimicrobial or antifungal properties, making them effective at controlling plant pathogens. An instance is the fungus *Penicillium* which produces the antibiotic penicillin that is now used in the treatment of bacterial infections in humans and animals (Emmanuel and Igoche, 2022). Also, the fungus *Beauveria bassiana* produces a compound that can control pests like the diamondback moth and the Asian citrus psyllid (Qin et al., 2021) (Table 1).

Fungi's role as biostimulants has equally been reported, as fungi produce compounds that stimulate plant growth and improve plant health. An example is the fungus *Trichoderma* which is capable of producing enzymes that break down plant cell walls and make nutrients available for plants' use. This aids in improving plant growth and resistance to pests and diseases (Guzmán-Guzmán et al., 2023; Olowe et al., 2020). Furthermore, fungi demonstrate resistance to abiotic stress factors like drought and salinity. Some fungi produce compounds that protect plants from oxidative stress and help them survive adverse conditions (Branco et al., 2022). They also contribute to the storage of carbon in soils, and this enables to reduce of the amount of carbon in the atmosphere, while contributing to efforts to mitigate climate change (He et al., 2020). Fungi thereby maintain the soil structure, which is achieved by producing a network of thread-like structures called hyphae. These structures create channels in the soil and improve the soil's ability to hold water and air, and in turn, help to promote healthy root growth and plant development.

Fungal-based foods and nutritional security

Fungi play an important role in ensuring food security, which makes them an essential component of sustainable agricultural practices. Fungi are used in the production of many types of food, including bread, beer, cheese, and fermented products like soy sauce and miso (Chen et al., 2022). Moreover, the addition of fungi to food production increases the variety of food available to people, and this directly promotes food security. Such is the case of mushroom cultivation, which has gained increasing prominence in the food industry as an alternative source of protein, vitamins, minerals, and dietary fiber for human consumption (Raman et al., 2021). At the same time, some types of fungi are developed as meat substitutes, with low calories and fat, thereby making them ideal for promoting health and preventing chronic diseases (Bankefa et al., 2021; Neuenschwander et al., 2023). As a result, various lifestyle diseases have been addressed through balanced diets consisting of functional foods and nutraceuticals of these fungal origins (Bell et al., 2022). The various aspects of food components including the quality nutritional value, antimicrobial properties, peptide synthesis, biofunctionality and reduction in antinutritive components have been improved through microbial synthesis. It is on this basis that alternative food resources have received key consensus due for the health benefits and nutritional value it possess (Mariutti et al., 2021).

Biopreservation also involves the application of microorganisms to extend the shelf life of food products through the antimicrobial compounds they produce. Such antimicrobial compounds include organic acids, enzymes, and secondary metabolites, which have been shown to effectively preserve the quality and safety of food products, reduce food waste, and increase food security

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(Garcha and Natt, 2012) (Table 1). Biopreservation using fungi-based products has potential applications in various food industries, including dairy, meat, vegetables, and fruits, as well as in food packaging and storage (Ajith and Sunita, 2017). Similarly, fungi are essential in producing biofortified foods, such as foods that have been intentionally bred or selected to contain higher levels of essential nutrients, including vitamins and minerals (Sands et al., 2009). Fungi can be used to enrich food with nutrients through their ability to synthesize and accumulate vitamins and minerals. Some fungal species also produce high levels of vitamin D when exposed to UV light (Jiang et al., 2020). Additionally, fungi are used to make food supplements, such as yeast-based supplements, that can address malnutrition among poor resource populations with restricted access to nutrient-rich foods (Dobrzyńska et al., 2023). Fungi-based biotechnologies have the potential to increase the availability and accessibility of biofortified foods, thereby improving the health and well-being of populations globally (Table 1).

Innovations in fungal biotechnology

The use of fungal biotechnologies towards the production of bio-based products indicates the opportunity of eradicating hunger and malnutrition and sustaining global food security (Demirel et al., 2024). Many species or strains of filamentous fungi have been of benefit and have been used in the global manufacturing and agriculture industries. They serve as a source of raw materials for food, pharmaceutical, cosmetic, and chemical industries (Kalra et al., 2020). *Aspergillus* is rapidly becoming popular for its application as a model organism for genome manipulation majorly due to the development of whole-genome sequencing (Seekles et al., 2022).

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Table 1: Relevance of fungi to food security in the 21st century

Mechanism	Activities	Associated Fungi	References
Biocontrol	Biopesticides	*Beauveria bassiana, Metarhizium anisopliae, Trichoderma harzianum, Paecilomyces lilacinus, Paecilomyces fumitories, Cordyceps sinensis*	Mascarin and Jaronski (2016), Sharma et al. (2013); Song et al. (2019); Tozlu et al. (2018); Woolley (2018); (Woolley et al., 2020);
	Bioherbicides	*Colletotrichum truncatum, Fusarium* spp, *Myrothecium verrucaria, Phoma* spp., *Alternaria* spp.	Berestetskiy et al. (2018); Boyette et al. (2014); Morin et al. (2000); Rai et al. (2021); Weaver et al. (2021)
	Induced systemic resistance	*Trichoderma harzianum, Piriformospora indica, Mycorrhizal fungi, Cladosporium cladosporioides, Aspergillus terreus*	Attia et al. (2022); Chaibub et al. (2020); El-Sayed et al. (2022); Li et al. (2022); Yadav et al. (2021)
Food productions	Biofertilizer	Arbuscular mycorrhizal fungi (AMF), *Trichoderma* spp., *Beauveria bassiana, Phanerochaete chrysosporium*	Dini and Ulfah (2021); Kumar and Dubey (2020); Sasongko et al. (2019)
	Plant growth promotion	*Trichoderma* spp., *Glomus* spp., *Gigospora* spp., *Piriformospora indica, Serendipita indica*	Dewir et al. (2023); Dias et al. (2020); Kundu et al. (2022)
Decomposers	Biodegradation	White-rot fungi, *Aspergillus niger, Pleurotus spp., Myrothecium* spp., *Phanerochaete chrysosporium*	Dhir (2022); Kathiravan and Gnanadoss (2021)
	Nutrient cycling	Mycorrhizal fungi, Lichens, Saprotrophic fungi *(Aspergillus, Trichoderma, Penicillium, Rhizophus, Mucor,* Endophytic fungi	Devi et al. (2020); Rana et al. (2019)
	Agroecological management (Composting, Biochar amendments etc)	Mycorrhizal fungi, *Trichoderma, Beauveria bassiana, Metarhizium anisopliae, Laccaria bicolor*	Akanmu et al. (2021); Akanmu et al. (2020); Gupta et al. (2022); Khan (2021)
Biodiversity maintenance	Bioremediation	AMF, White-rot fungi, *Fusarium oxysporum, Pleurotus* spp.,	Chaudhary et al. (2023); Zhuo and Fan (2021)
	Mycoremediation	*Pleurotus ostreatus, Stropha ria rugoso-annulata, Agaricus bisporus, Trametes versicolor, Phanerochaete chrysosporium*	Sekan et al. (2019); Uddin et al. (2020)
	Bioabsorption	*Trichoderma harzianum, Aspergillus niger, Pleurotus ostreatus, Cunninghamella elegans, Rhizopus arrhizus, Penicillium* sp..	Bibbins-Martínez et al. (2023); Mohapatra et al. (2022)
Food processing and preservation	Fermentation	*Trichoderma harzianum, Pleurotus ostreatus, Cunninghamella elegans, Rhizopus arrhizus, Penicillium* sp	Solomon et al. (2019)
	Biofortification	AMF, *Trichoderma* spp., *Aspergillus oryzae, Mycofertilizers,* Endophytic fungi	Dhiman et al. (2022); Ku et al. (2019)
	Biopreservation	*Penicillium chrysogenum, Rhizopus oligosporus, Debaryomyces hansenii, Aspergillus niger*	Hernández et al. (2022)
	Biodetoxification	*Trametes versicolor, Phanerochaete chrysosporium, Pleurotus* spp., *Aspergillus niger, Mycoremediation Consortium*	Chugh et al. (2022)
Medicinal role	Development of drugs and therapies	*Penicillium* spp., *Taxomyces andreanae, Cordyceps sinensis, Penicillium griseofulvum, Aspergillus terreus, Tolypocladium inflatum*	Bhattarai et al. (2021); Díaz-Godínez (2015)

Engineering efforts began as early as the 1950s and include practically every aspect of fungal biotechnology, such as controlling morphological forms and mutagenesis and attaining very high yields of the desired product (Madzak, 2021).

In addition, fungi have exhibited bioremediation characteristics by breaking down pollutants which could be heavy metals or organic contaminants in the soil. This process has significantly reduced the impact of pollution on soil health and promoted the remediation of contaminated sites

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(Adamatzky et al., 2021). *Paecilomyces farinosus* and *A. flavus* were reported for the degrading harmful chemical contents, and reduction of soil toxicity caused by Benzo [a] pyrene (Morelli et al., 2012). Moreso, some members have been investigated for the removal of mercury in soils, while the roles of others in biofuel production, medical, and pharmaceutical have similarly been reported (Egbuta et al., 2016).

Challenges and opportunities in fungal applications
Due to their pervasive existence, fungi are widely distributed across various environments. Furthermore, the wide range of substrates that filamentous fungi grow on also facilitated their widespread dispersal in the environment around the globe (Bahram and Netherway, 2022). However, some species of filamentous fungi, including *Aspergillus, Fusarium, Alternaria,* and *Penicillium* have been reported for causing plant diseases and food spoilage. Many also produce toxins and induce cytotoxicity in human and animal cells, causing immunosuppression and DNA damage (Egbuta et al., 2017; Olowe et al., 2022b). *Fusarium verticillioides* is another filamentous fungus known for its pathogenic and mycotoxigenic contaminations of grains, thereby causing a reduction in yield quantity and quality commonly in crops of agricultural importance, especially in maize (Akanmu et al., 2020). The adverse impact of this pathogen has been felt through the health impairment and losses recorded in both households and nations' economies (Omotayo and Babalola, 2023). However, the problem of food contamination coupled with the adverse climatic condition, favored by the ongoing climate change thereby creates sources of threat to food security and safety. Hence, the challenge currently facing the agricultural sector is how to satisfy the food demand of the increasing population by ensuring higher agricultural yield and food protection without endangering the environment or compromising the health of people and animals during crop production.

The beneficial microbes have been applied as biocontrol consortia to manage plant diseases; such entails the Plant Growth Promoting Rhizobacteria (PGPR) investigated against *Botrytis cinera* which is the grey mold fungus. They were as well found effective against the fungi; *Nigrospora sphaerica, Alternaria alternata,* and *Fusarium equiseti* (Akanmu and Babalola, 2024). Furthermore, the rhizosphere-associated microbes *Bacillus*, *Pseudomonas*, *Enterobacter*, and *Microbacterium oleivorans* have demonstrated biological control activities against *Fusarium verticillioides* which is a major patho-toxigenic fungus ravaging maize cultivation (Omotayo and Babalola, 2023). Also, PGPR proved to be an adequate substitute for botrycides, a chemical-based treatment for managing the disease. According to Orozco-Mosqueda et al. (2023), PGPR is considered a great alternative to chemical use in preventing grey mold disease in various crops (Akanmu and Babalola, 2024).

Similarly, the plant-growth-promoting fungi (PGPF) which includes *Trichoderma* species, Arbuscular mycorrhizal fungi, *Penicillium digitatum, Gliocladium virens, Aspergillus flavus, Podospora bulbillosa, Actinomucor elegans,* among others have demonstrated ability to improve agricultural output and ensure they are environmentally safe. The PGPF are fungal species that inhabit the rhizosphere of agricultural plants and exhibit functions that maintains the plants' sustainability. They are biotic inducers that contribute to the sustainability of agriculture and serve essential purposes which entails seed germinations, development of shoot and root systems, chlorophyll production, and improved crop yield. These are achieved through the mineralization of important minor and major elements essential for the sustenance of plant growth and production (Adedayo and Babalola, 2023). This claim was further validated in another investigation where

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we recorded that AMF inoculation significantly increased maize development, colonization of root and the spore count of AMF in comparison to the control (Fasusi et al., 2021). *Trichoderma* spp., equally a candidate of PGPF, has been described as the best fungal ally in the biological control management of plant diseases (Guzmán-Guzmán et al., 2023). *Trichoderma* is among the most researched and employed microorganisms. As a result of a range of biocontrol mechanisms of *Trichoderma*, including antibiosis, parasitism, induction of plant defense systems, and synthesis of secondary metabolites, *Trichoderma* species are highly effective biocontrol agents and have demonstrated the ability to antagonize other plant pathogens and pests (Olowe et al., 2022a). More so, various *Trichoderma* species, combined with other plant-beneficial microorganisms that promote plant development, have been utilized in agriculture as part of creative bioformulations (Guzmán-Guzmán et al., 2023). In addition, *Alternaria cassiae* has demonstrated biological control properties in managing coffee senna (*Cassia occidentalis*) and sickle pod (*Cassia obtusifolia*) (Hoagland and Boyette, 2021). Furthermore, the inherent advantage of beneficial microbes in the rhizosphere has also been explored by applying biochar and compost as soil amendments. The sustained effects of compost and biochar incorporation to AMF communities demonstrated the importance and efficacy of this agroecological management in future agricultural practices (Akanmu et al., 2020; Xin et al., 2022).

Conclusion

Fungi gain increasing relevance as their beneficial roles and applications towards attaining sustainable agriculture and food security in the 21st century are unveiled. These include its applications in improving soil health improvement, promotion of plant growth and yield, and evolving innovations in fungal biotechnology, food production, and preservation. Fungi have been found effective in mitigating the climate change effects, drought, soil salinity, and other abiotic influences, while they also act as biostimulants in plant disease management, bioremediation of polluted soils and maintenance of ecological biodiversity. In addition, fungi play an important role in nutritional security as many fungi-derived foods and nutraceuticals offer a good source of dietary fiber, vitamins and high-quality proteins are used to manage or treat related lifestyle diseases. Furthermore, the largely but yet to be fully explored biotechnological advances in the field of fungi can provide bio-based solutions to eradicate hunger and malnutrition across the world. Meanwhile, some fungal species remain pathogens of some important agricultural crops, causing menace to plant development and yield. Hence, to attain optimum benefits from fungi, it is essential to balance their positive contributions with effective management strategies that mitigate the risks associated with pathogenic species. This balanced approach will therefore make fungi a transformative agent for shaping sustainable food systems in the future globally.

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