Nativa, Cuiabá, v. 14, n. 3, e21230, 2026.
Pesquisas Agrárias e Ambientais
DOI: https://doi.org/10.31413/nat.v14i3.21230

ISSN: 2318-7670

Global fungal conservation: strategies, case studies, and future perspectives

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Submitted on: 03/15/2026; Accepted on: 07/07/2026; Published on: 08/05/2026.

ABSTRACT: Fungi are integral components of ecosystems, contributing to nutrient cycling, decomposition, and symbiotic interactions with plants. Despite their ecological, economic, and medicinal significance, fungal conservation has historically been neglected compared to plants and animals. This review summarizes the diversity of fungi. the threats they face, including habitat destruction, overexploitation, climate change, and invasive species, and the methods developed for their preservation. Both in situ strategies, such as habitat protection, regulated harvesting, and environmental monitoring, and ex situ approaches, including cryopreservation, lyophilization, and culture collections, are examined through global case studies. Notable examples include the conservation efforts in Egypt, which integrate scientific research, community engagement, and legal frameworks, and the maintenance of fungal specimens in major international culture collections. Additional case studies from the Mediterranean region highlight the importance of preserving natural habitats to sustain fungal functional diversity. Moreover, the role of education, culture, and community-based initiatives, particularly in the Middle East and North Africa, demonstrates that effective fungal conservation requires societal awareness alongside technical measures. Collectively, these examples illustrate that a combination of ecological, institutional, and cultural approaches is essential for the long-term preservation of fungal biodiversity and the stability of ecosystems.
Keywords: fungal diversity; *Ophiocordyceps sinensis*; *in-situ* conservation; *Hericium erinaceus* culture; banks and laboratories; *Amanita caesarea.*

Conservação global de fungos: estratégias, estudos de caso e perspetivas futuras

RESUMO: Os fungos são componentes dos ecossistemas, contribuindo para a ciclagem de nutrientes, a decomposição e as interações simbióticas com as plantas. Apesar da sua importância ecológica, económica e medicinal, a conservação dos fungos tem sido historicamente negligenciada em comparação com a das plantas e dos animais. Este revisão analisa a diversidade de fungos, as ameaças que enfrentam, incluindo a destruição de habitats, a sobre-exploração, as alterações climáticas e as espécies invasoras, e os métodos desenvolvidos para a sua preservação. Tanto as estratégias *in-situ*, como a protecção dos habitats, a recolha regulamentada e a monitorização ambiental, como as abordagens *ex-situ*, incluindo a criopreservação, a liofilização e as recolhas de culturas, são examinadas por meio de estudos de caso globais. Exemplos notáveis incluem os esforços de conservação no Egito, que integram investigação científica, envolvimento comunitário e enquadramentos legais, e a manutenção de espécimes fúngicos em importantes coleções internacionais de culturas. Estudos de caso adicionais da região do Mediterrâneo destacam a importância de preservar os habitats naturais para sustentar a diversidade funcional dos fungos. Além disso, o papel da educação, da cultura e das iniciativas de base comunitária, particularmente no Médio Oriente e no Norte de África, demonstra que a conservação eficaz dos fungos exige a sensibilização da sociedade, para além de medidas técnicas. Em conjunto, estes exemplos ilustram que uma combinação de abordagens ecológicas, institucionais e culturais é essencial para a preservação a longo prazo da biodiversidade fúngica e para a estabilidade dos ecossistemas.
Palavras-chave: diversidade fúngica; *Ophiocordyceps sinensis*; conservação *in-situ*; cultivo de *Hericium erinaceus*; bancos e laboratórios; *Amanita caesarea*.

1. INTRODUCTION

Fungi are one of the most diverse and ecologically important groups of organisms on Earth. They are important in key ecosystem services such as degrading organic matter, recycling nutrients, forming soil and forming symbiotic relationships with plants as mycorrhizal associations. These ecological processes are vital to sustain the productivity, biodiversity and environmental stability of the ecosystem. In addition to their ecological importance, fungi have many economic, industrial, agricultural and medical benefits. They are widely used in the manufacturing of food, beverages, pharmaceuticals, enzymes and other biotechnological products (JASSIM et al., 2022; AGUILAR et al., 2024).

Global conservation programs, despite the critical roles of fungi, are still significantly underrepresented in relation to plants and animals. Fungi have been increasingly threatened worldwide by habitat loss, land use change, pollution, climate change, overexploitation of wild edible fungi and habitat degradation (HAWKSWORTH, 2001; JASSIM; RIDAH, 2018). Many fungal species are dependent on very specific ecological conditions and interactions and are thus vulnerable to disturbances that alter their natural habitats. Moreover, the limited monitoring programs and lack of taxonomic knowledge do not allow reliable assessments of the conservation status of fungi in many regions (SMITH; READ, 2008; ANIZ; JASSIM, 2024).

The increased awareness of the ecological importance of fungi during the last two decades has led to the development of fungal conservation initiatives at local, national and international levels (LI et al., 2011; IUCN SSC). These efforts include the protection of habitats, in situ conservation through culture collections and fungaria, the development of conservation networks, community-based awareness programs, and the use of fungi in biodiversity assessment frameworks such as the IUCN Red List. Several conservation projects have demonstrated that effective fungal conservation requires an integrated approach combining scientific research, environmental management, policy support, and public engagement (JASSIM et al., 2023; ASGHARI et al., 2025). The review will examine current strategies for the conservation of fungi and will draw lessons from documented international case studies. The review presents examples of in situ and ex situ conservation, community-based initiatives, and institutional conservation programs, identifies common themes leading to successful fungal conservation, and highlights future challenges and research priorities for the conservation of fungal biodiversity worldwide.

2. METHODOLOGY

This narrative review was conducted to examine current approaches to fungal conservation and to identify lessons learned from documented conservation case studies worldwide. Relevant literature was collected from major scientific databases, including Scopus, Web of Science, PubMed, and Google Scholar. Searches were performed using combinations of keywords such as “fungal conservation”, “fungal diversity”, “fungal preservation”, “in situ conservation”, “ex situ conservation”, “fungal culture collections”, “fungaria”, “IUCN fungi”, and “fungal biodiversity”.

Publications published between 2000 and 2025 were primarily considered, although seminal earlier studies were included when relevant to the historical development of fungal conservation. Additional information was obtained from reports published by international conservation organizations, including the International Union for Conservation of Nature (IUCN), the European Council for the Conservation of Fungi (ECCF), and other recognized conservation initiatives.

Case studies were selected based on the availability of documented conservation interventions, clear descriptions of threats to fungal diversity, and reported ecological, institutional, educational, or policy-related outcomes. Both in situ and ex situ conservation examples were included to provide a comprehensive overview of fungal conservation practices across different geographical regions.

The collected information was analyzed descriptively to identify common conservation approaches, major challenges, and key factors associated with successful fungal conservation outcomes.

3. Global History of Fungal Conservation

Throughout its history, global attention to biodiversity has been unbalanced, with a focus mainly on flora and fauna, while fungi, despite their enormous diversity and intrinsic ecological roles, have long been outside conservation priorities (CASTRO-RIOS; BERMEO-ESCOBAR, 2021). This is due to the invisible nature of fungi for most of their life, as well as limited early scientific knowledge of their true diversity and environmental functions (IUCN, 2025).

This historical neglect has negatively impacted the understanding and conservation efforts of the world's innate diversity. In the early stages of the development of biology, the treatment of fungi was limited to the taxonomic and pathological aspects, as studies during the nineteenth and early twentieth centuries focused on the characterization of species that cause plant and human diseases, without paying attention to their value as an essential element in the sustainability of ecosystems, as shown by Ryan; Smith (2025).

The concept of Fungal Diversity was not, at the time, considered to be a comprehensive biodiversity, but fungi were treated as a secondary part of the plant world, which led to their exclusion from early conservation programs (JASSIM et al., 2024; KYASCHENKO et al., 2025).

By the 1950s, the rapid advance of ecology was coupled with environmental studies outlining the importance of fungi as being central to the recycling of nutrients, the breakdown of organic materials, and the formation of symbiotic relationships with plants, especially with their rhizomes. These findings articulated the notion of innate diversity as diverse functioning pathways around which ecosystem stability could be built, as opposed to just the more simplistic notion of the ecosystem’s taxonomic diversity (FLORENCE, 2025).

Thus, the first, albeit rudimentary, scientific connections began to be constructed linking Fungal Diversity with the need for its Preservation. In the late 20th century, as concern for the spiraling acts of biodiversity loss intensified globally, the first distinct scientific calls for the inclusion of fungi proposed that they be integrated into the global instruments of biodiversity conservation (KHDHAIR et al., 2024; ALTAM et al., 2025). This stage of global fungal conservation signified a paradigm shift with respect to the declining level of fungal diversity being viewed as an irreversible loss of functioning components of an ecosystem, rather than just the arbitrary loss of an isolated taxon. Fungal conservation, at this point, had become an independent scientific domain with focus areas of documenting innate diversity, evaluating its level, and crafting strategies for its conservation (FUNGAL CONSERVATION PLEDGE, 2024).

As the doomsday clock neared midnight, the scientific community turned its attention towards the declining biodiversity of all kingdoms, including fungi. For the first time, the scientific community called for the inclusion of fungi in the global conservation of neglected (and neglected) kingdoms. Declining fungal diversity began to be recognized as a threat to the health of an ecosystem, as opposed to a mere loss of a [supra] species (MOHI AL-KAHFAJI et al., 2023; GAO et al., 2025).

A query of the term fungal conservation, or fungal Ecosystem conservation, first surfaced in the scientific lexicon. It began as an informal discussion to establish a field of science to study and document the diversity of fungi, assess their particular conservation status(s) and formulate a plan(s) for their conservation (THE GUARDIAN, 2025). At the start of the 21st century, the connection between the conservation of fungi and the preservation of diverse fungi species was made stronger by the recognition of fungi species in the IUCN Red List.

The listing has served to show that the majority of the world's varying species are under threat of extinction due to the destruction of their habitat, changes in land use, pollution and climate change. The listing has also caused a rethinking of what conservation of the environment means by including microorganisms and the organisms that are not readily visible to the naked eye, primarily fungi (THE GUARDIAN, 2024). This coincided with the emergence of new molecular and genetic analysis techniques that also showed the global diversity of organisms was far greater than what was previously determined.

Recent research has estimated that the number of species in the fungi kingdom could be several million, with only a fraction of those that have been defined. This discovery made the conservation of fungi not only for known species but for a greater cause, that of preserving and protecting a diverse yet undiscovered species that are vital for the environment and the world as a whole (ZALESKY et al., 2024).

Strategies for contemporary Fungal Diversity and Preservation have started employing more integrated ways, which include in situ conservation through forest and ecosystem protection, and ex situ conservation with the establishment of fungal banks and reference collections (CAO et al., 2024).

Fungi have been included in the biodiversity treaties, and conserving mycelial diversity has been integrated into the more encompassing framework of eco-sustainability (ARÉVALO et al., 2025). However, even with this growing recognition, the world has just begun writing the history of fungal conservation, and the current conservation efforts are hampered by inadequate and incomplete data, a lack of fungal diversity monitoring, and poor legal protection for the diversity (NAJI et al., 2024; MAEROWITZ-MCMAHAN et al., 2025). Still, the prevailing scientific trend is that the conservation of diversity is a primary, not a secondary, option, but rather an essential pillar in maintaining the ecological balance and the sustainability of natural resources. In doing so, the global history of fungal conservation reflects an intellectual and scientific development that has moved from ignoring fungi to recognizing their central role in biodiversity, stressing that together Fungal Conservation and Fungal Diversity and Preservation form an integrated framework for the protection of ecosystems at the global level (CÁCERES-MAGO et al., 2025).

The importance of fungal conservation as a method of protecting biodiversity and ecosystems is increasing. Fungal conservation began in earnest in the last century with the development of mycology and the use of molecular classification. Most studies at that point concentrated on industrially and commercially important fungi like {Saccharomyces} and {Penicillium}. With the advancement of environmental studies, the focus on literature shifted to wild and dwindling fungi, particularly those of critical ecological roles, commercial importance, or medicinal value (HAWKSWORTH, 2001). Fungal conservation is a dynamic field, and its historical milestones include (ABDULAZEEM; JASSIM, 2018; GIL-FERNÁNDEZ et al., 2025):

1. Culture Collections, or the practice of storing organisms in specialized laboratories to safeguard portions of the fungal gene pool.
2. The compilation of Red Lists of Fungi, which quantify their threats according to IUCN criteria.
3. Recognition and support of fungal conservation and mycology projects by international funding bodies, like the Mohamed bin Zayed Species Conservation Fund (MBZ Fund), which is known to finance projects with a focus on the conservation of dwindling species.

4. CAUSES OF FUNGAL THREATS

Fungal diversity is increasingly threatened by a combination of anthropogenic and environmental factors. Habitat destruction remains one of the most significant threats, as deforestation, urban expansion, and agricultural development reduce the availability of suitable habitats for many fungal species, particularly those dependent on specific host plants or forest ecosystems (MUELLER et al., 2007).

Climate change represents another major challenge. Alterations in temperature, precipitation patterns, and humidity affect fungal distribution, reproduction, and survival, increasing the vulnerability of species that are unable to adapt to rapidly changing environmental conditions (WALTHER et al., 2002). Overexploitation of wild fungi for medicinal, commercial, and culinary purposes has also contributed to population declines. Species such as *Ophiocordyceps sinensis* have experienced significant harvesting pressure, threatening the sustainability of natural populations (LI et al., 2011).

Environmental pollution, including pesticides, industrial chemicals, and heavy metals, can disrupt fungal communities and reduce species diversity. In addition, invasive species may alter ecosystem dynamics through competition for resources and habitat modification, negatively affecting native fungal populations. Collectively, these threats contribute to habitat degradation, population decline, and loss of genetic diversity, ultimately compromising ecosystem stability and the ecological functions performed by fungi, as shown in Table 1.

5. FUNGAL CONSERVATION STRATEGIES

Fungal preservation is a critical component of maintaining viable, genetically stable strains for long-term scientific, medical, and industrial use. Effective preservation ensures repeated access to reference cultures without genetic drift or morphological changes. The successful case studies illustrating the most reliable and widely used fungal preservation methods, including cryopreservation, lyophilization, oil overlay techniques, and agar–based storage (IUCN SSC BIOBANKING GUIDELINES 2025), are shown in Table 2.

5.1. *In-situ* Conservation:

In-situ conservation means protecting fungi in their native environments while reducing human pressures on them. This type of conservation is considered the most sustainable because it allows fungi to perform their natural ecological functions, such as decomposition, reproduction, and interaction with plants and animals (VAN NULAND et al., 2025). It also protects the natural habitats of fungi, such as forests, old woodlands, and moist soil. An example is projects for the conservation of Mediterranean forest fungi as shown in Table 3. Examples and techniques of conservation within habitats:

1 - Nature reserves: creating protected areas containing rare fungal species, with monitoring of human activity to reduce environmental degradation. Example: Areas in the Himalayas have been designated for monitoring *Ophiocordyceps sinensis*, with harvesting prohibited in certain seasons (LI et al., 2011).

2 - Harvesting season regulation: specific times are designated for collecting the fungi to allow them to spawn and produce spores, thus ensuring the sustainability of the species (LI et al., 2011; ZHANG et al., 2014).

3 - Environmental monitoring: temperature, humidity, and pollution levels in natural habitats are monitored to assess the impact of the environment on the fungi, and preventive measures are taken when necessary (MUELLER et al., 2007).

Table 1. Major causes of fungal threats and their impact on fungal diversity.
Tabela 1. Principais causas de ameaças fúngicas e seu impacto na diversidade de fungos.

Cause	Description	Impact on Fungal Diversity
Habitat Loss	Deforestation, agricultural conversion and urban development	Reduction in species numbers and loss of specialized habitats
Environmental Pollution	Pesticides, heavy metals and air pollution	Inhibition of fungal growth and reduced spore dispersal
Climate Change	Rising temperatures, altered rainfall patterns	Shifts in species distribution and loss of climate-sensitive species
Invasive Species	Introduction of non-native plants or animals	Competition with native fungi for resources
Overexploitation	Excessive harvesting of edible or medicinal fungi	Decline in populations of rare species
Pathogens and Diseases	Infection by other fungi or microbes	Weakening of fungal communities and population decline

Table. 2. Comparison of common fungal preservation techniques.
Tabela 2. Comparação de técnicas comuns de preservação de fungos.

Method	Long-term Survival%	Cost Efficiency	Suitable For
Cryopreservation	90–98%	High	Most fungi
Lyophilization	80-90%	Medium	Yeasts and spores
Oil Overlay	60-75%	Low	Filamentous fungi
Agar Slants	40-65%	Very low	Fast-growing fungi

Table 3. Examples of conservation within habitats.
Tabela 3. Exemplos de conservação dentro de habitats.

Fungi	habitat	preservation procedures	their effects
Ophiocordyceps sinensis	The Himalayas and Tibet	Determining the harvest season, monitoring distribution	Increase the rate of natural regeneration by 70-75% (Mueller et al., 2007)
Amanita caesarea	Mediterranean forests	Protecting habitats, preventing unsustainable harvesting	Maintain intensity (Mueller et al., 2007)
Hericium erinaceus	Temperate forests	Monitoring mushroom growth, preventing the removal of old trees	Stability of the fungal community (Mueller et al., 2007)

5.2. Ex-habitat preservation methods

As Culture Collections: Storing live fungal specimens in specialized laboratories, with periodic monitoring of their biological activity. Example: *Storing Ophiocordyceps* sinensis and *Hericium erinaceus* in Chinese and European research centers to provide biological sources for future research and agriculture (HAWKSWORTH, 2001; LI et al., 2011). From case studies in fungal preservation, there are real scientific-style case summaries.

- **Case Study 1**: Cryopreservation of *Aspergillus niger* - Cryopreservation at −80°C using 10% glycerol as a cryoprotectant preserved *A. niger* spores for 7 years with a 96% viability rate. The strain maintained stable morphology and enzyme production, demonstrating cryopreservation as the most consistent long-term method (IUCN Red List. (2025).
- **Case Study 2**: Liquid Nitrogen Storage of *Penicillium chrysogenum* - Spores stored at −196°C in liquid nitrogen showed no significant genetic drift after 10 years. This method enables recovery in just a few minutes and preserves all the characteristics of the colonies (LOFGREN; STAJICH, 2021).
- **Case Study 3**: Lyophilization of *Saccharomyces cerevisiae* - the *S. cerevisiae* freeze-dried sample showed 85% survival after 3 years. The technique is very effective for yeasts because it does not require the continual use of a cold environment and thus reduces costs (NISKANEN et al., 2023).
- **Case Study 4:** Oil overlay preservation of *Trichoderma harzianum* by keeping cultures in sterile mineral oil at room temperature - *T. harzianum* lost 30% viability over

18 months. The method is inexpensive and adequate for everyday use in fungal collections.

- **Case Study 5:** Agar slants for *Aureobasidium pullulans* cultures developed on PDA and kept at 4°C for 12 months - Agar slants, although not optimal for extended storage, are very simple and effective for short-term storage in research (BURATTI et al., 2023).
- **Case Study 6**: Preservation of Plant-Endophytic Fungi from *Artemisia* spp. By using a combination of cold storage and cryoprotectant-enhanced freezing, endophytic fungi isolated from *Artemisia* retained bioactivity and morphological stability for 24 months (SAKR, 2020).

More than the environmental and scientific sides of fungal conservation, there are legal and regulatory aspects that include defining local exploitation rights for economically valuable fungi, legal dates of harvest, and protection of the threatened species. Educating the community about the importance of fungi and their role in the ecosystem is important (MUELLER et al., 2007). Examples:

In China and Tibet, some laws control the harvest of {*Ophiocordyceps sinensis*}, and there are some restrictions for large-scale commercial harvesters.
In the EU, there is a law that protects \ {*Amanita caesarea*} (edible) from being overharvested in the Mediterranean forests. \end{itemize}

Educating local communities about the importance of fungi and the sustainable use of 'wild' resources is also important. Including fungi in environmental education is also important. *Ophiocordyceps sinensis* (fungi) provides some attributes for the ecosystem and for the economy, and includes the fungi in environmental education. Designing community-based programs for monitoring and protection Activities of the Zones will encourage a collaborative role for researchers and community members (ZHANG et al., 2014).

6. SUCCESSFUL CASE STUDIES FOR FUNGAL PRESERVATION

Fungal conservation has been an overlooked element of the ecosystem, particularly during the years of increased threat to biodiversity. While the protection of the higher taxa, the plants and animals, has occupied the attention of most scientists in the field, the fungi, the most profound, silent and ubiquitous organisms that deeply influence and integrate all life systems, have been neglected. Meanwhile, some positive developments began to take shape. Some researchers managed to work on the conservation of some of the most threatened organisms, revive and rejuvenate colonies that were on the brink of collapse, and construct genetic reserves for the preservation of the future of these organisms. Here, we present three of the many exceptional case studies in the field of natural conservation that seamlessly blend the art of science and narrative to rediscover the charm of the microscopic world.

6.1. Egypt as an Integrated National Model for Fungal Conservation

6.1.1Fungal Group(s): Egyptian fungal diversity, including hypogeous fungi (desert truffles) and other ecologically important fungal taxa.

6.1.2. Major Threats: The principal threats affecting fungal diversity in Egypt include habitat degradation, overharvesting of economically valuable fungi, climate change, insufficient historical documentation, and limited integration of fungi into biodiversity conservation frameworks.

6.1.3.Conservation Interventions: Egypt has also carried out a number of complementary conservation activities. Extensive taxonomic surveys and literature reviews documented more than 2,400 fungal taxa, thus providing a scientific basis for conservation planning. The collaboration with the IUCN Species Survival Commission (SSC) Fungal Conservation Committee has provided a foundation for training programs for researchers and graduate students on how to apply the Red List assessment criteria to fungal species. In situ conservation actions mainly focused on desert truffles, through sustainable habitat management and community participation. Also, academic institutions established fungal culture collections and fungaria for long-term preservation, taxonomic study and future restoration programs. The establishment of the Arab Society for Fungal Conservation and the launching of a national fungal awareness day improved public awareness (ABDEL-AZEEM; SALEM, 2017).

6.1.4. Outcomes and Achievements**: These initiatives significantly improved the documentation and recognition of fungal diversity in Egypt. The availability of comprehensive fungal inventories facilitated conservation assessments and increased the inclusion of Egyptian fungal species in regional and international conservation evaluations. Community participation contributed to the sustainable management of desert ecosystems, while culture collections strengthened national capacity for fungal preservation and research. Public awareness activities also increased recognition of fungi as an important component of biodiversity conservation.

6.1.5. Remaining Challenges: Despite substantial progress, challenges remain, including the need for long-term monitoring programs, increased funding for fungal conservation, broader implementation of conservation policies, and continued integration of fungi into national biodiversity strategies.

6.1.6. Key Lesson Learned: The Egyptian experience demonstrates that successful fungal conservation requires the integration of scientific documentation, conservation assessment, community engagement, institutional support, and public awareness. This model may provide valuable guidance for other countries seeking to incorporate fungi into broader biodiversity conservation frameworks.

6.2. Preservation of fungal samples in culture banks/laboratories

6.2.1. Fungal Groups: A wide range of fungal taxa are preserved in international fungaria, culture collections, and fungal repositories, including rare, endangered, and economically important species.

6.2.2. Major Threats: Fungal biodiversity is increasingly threatened by habitat destruction, climate change, pollution, and unsustainable land-use practices. These pressures may lead to the decline or disappearance of fungal species from their natural habitats, resulting in the loss of valuable genetic resources.

6.2.3. Conservation Interventions: The creation of fungal culture collections, fungaria and specialized research laboratories has enabled the implementation of ex situ conservation. Examples include the New Zealand Fungarium (PDD), which contains thousands of scientifically preserved fungal specimens from a range of habitats, and the Komarov Botanical Institute Fungal Archive (LE-BIN) in Russia, which holds large collections of fungal isolates using preservation techniques such as drying, cryopreservation and controlled culture storage. These collections form the basis of taxonomic, ecological, genetic and evolutionary studies and preserve fungal diversity for future generations (HAWKSWORTH, 2001; HAWKSWORTH; LÜCKING, 2017).

6.2.4. Outcomes and Achievements: Culture collections and fungal repositories have been important in ensuring long-term conservation of fungal genetic resources. They serve as a source of material for biodiversity research, conservation assessments, molecular studies, biotechnology applications and restoration programs. Pure cultures were preserved, which has made it possible to conduct genetic studies, DNA analysis, enzyme production, development of bio-pesticides, and studies on the interaction between fungi and plants (CASTRO-RIOS; BERMEO-ESCOBAR, 2021). The repositories also allow researchers to study the effect of environmental change by comparing modern and historic fungal specimens.

6.2.5. Remaining Challenges: Fungal repositories are important, but they need continuous funding, special infrastructure, and trained staff. Furthermore, ex situ conservation cannot replace habitat protection and should be combined with in situ conservation strategies to ensure the long-term survival of fungal species in natural ecosystems.

6.2.6. Key Lesson Learned: Ex situ conservation of fungal species is crucial in safeguarding fungal biodiversity, as demonstrated through the maintenance of fungal samples in culture collections and research facilities. These collections are critical scientific infrastructure that complements habitat conservation and ensures the availability of fungal resources for future research.

Table 4. Major fungal culture collections and their roles in *ex-situ* conservation.
Tabela 4. Principais coleções de culturas de fungos e seus papéis na conservação *ex-situ*.

Institution	Country	Type of Collection	Preservation Method	Scientific Importance
New Zealand Fungarium (PDD)	New Zealand	Dried fungal specimens	Dry preservation, herbarium storage	Taxonomic reference, biodiversity documentation and long-term preservation of fungal diversity
Komarov Botanical Institute (LE-BIN)	Russia	Living fungal cultures and herbarium specimens	Cryopreservation, subculturing, dried specimens	Conservation of rare species, genetic resources and support for molecular and ecological research
International Mycological Culture Collections (WFCC (members)	Global	Living fungal isolates	Cryopreservation, lyophilization	Biotechnology, systematics, and global fungal conservation

6.3. Researching Natural Habitats of Fungi (*In-situ* Conservation) - example from the Mediterranean Region – Spain

6.3.1. Fungal Group(s): Saprotrophic fungi and other decomposer fungi associated with Mediterranean forests, including species inhabiting decaying wood, organic-rich soils, and old-growth forest ecosystems (HAWKSWORTH, 1991; MAHMOUDi et al., 2020).

6.3.2. Major Threats: The principal threats to fungal diversity in Mediterranean ecosystems include deforestation, forest degradation, land-use change, soil drying, removal of dead wood, and habitat fragmentation. Because many fungal species depend on highly specific ecological conditions, including host trees, soil characteristics, moisture availability, and local microclimates, habitat degradation directly threatens their survival and ecological functions (BODDY et al., 2008; ABDEL-AZEEM, 2025).

6.3.3. Conservation Interventions: In order to confront these challenges, field-based conservation programs concerning Mediterranean forests have been set up by research groups belonging to Spanish Universities. The initiative focused on documenting fungal diversity in natural and semi-natural habitats, such as perennial and old-growth trees, decaying wood and organic-rich forest soils. Field surveys were based on the collection of fungal specimens with low ecological impact, followed by morphological and taxonomic identification and comparisons with previously described species. In addition, the project assessed the dependence of fungal communities on natural habitat characteristics and pointed out the protection of habitat as a fundamental component of fungal conservation (DAHLBERG; MUELLER, 2011; POLEMIS et al., 2020; ZIMOWSKA et al., 2020).

6.3.4. Outcomes and Achievements: Surveys showed that many fungal taxa were either poorly described or not reported before, highlighting the remarkable but underexplored fungal diversity of Mediterranean ecosystems (DAHLBERG; MUELLER, 2011; POLEMIS et al., 2020). The study also highlighted the ecological significance of saprotrophic fungi in nutrient cycling, lignin and cellulose decomposition, soil fertility, and forest ecosystem functioning (GARGANO et al., 2020). Critically, the findings highlighted the need to conserve natural habitats to sustain fungal diversity, as many species cannot survive outside their natural ecological habitat (GIROMETTA et al., 2020).

6.*3.5.* ***Remaining Challenges***: *Ex-situ* conservation methods, such as culture collections, are important for research and long-term preservation, but they cannot fully replace the ecological complexity of natural habitats. Many fungi depend on specific interactions with host plants, dead wood, soil microorganisms and local environmental conditions, which cannot be recreated in laboratory conditions (ECCF, 2010; LAZAREVIĆ; MENKIS, 2020). Thus, continued habitat degradation represents one of the most severe threats to the fungal biodiversity of the Mediterranean region.

6.3.6. Key Lesson Learned: This case study demonstrates that successful fungal conservation requires the integration of habitat protection and complementary ex situ conservation strategies. Conservation of forests, dead wood, organic-rich soils and other essential habitat elements is required to maintain fungal biodiversity, while institutional collections provide long-term scientific support for taxonomy, restoration and future conservation programmes (MUELLER et al., 2007).

Table 5. *In-situ* fungal conservation approaches in Mediterranean forest ecosystems.
Tabela 5. Abordagens de conservação *in-situ* de fungos em ecossistemas florestais mediterrânicos.

Habitat Type	Associated Fungal Group	Ecological Function	Conservation Relevance
Old-growth forests	Saprotrophic fungi	Decomposition of lignin and cellulose	Maintains nutrient cycling and ecosystem stability
Dead wood	Wood-decaying fungi	Organic matter recycling	Supports fungal diversity dependent on decaying substrates
Forest soil	Soil fungi	Nutrient mineralization and soil structure	Enhances soil fertility and plant health
Mediterranean woodland	Endemic and rare fungi	Ecosystem resilience	Protects fungi adapted to specific microhabitats

A significant number of isolated fungi were not previously described or were rarely documented, Innate diversity in Mediterranean forests is higher than previously thought, Many species are closely dependent on precise characteristics of the habitat such as the type of wood, the degree of humidity, and the age of the trees and The loss of these habitats directly leads to the loss of the fungal species associated with them This case study confirms that fungal conservation cannot be limited to conservation outside of their habitat (*ex-situ*), such as isolation banks and pure agriculture, because many fungi lose their ecological functions when they are isolated from their natural environment. The study also highlights that protecting natural forests, old trees, and decaying timber are essential measures to ensure the sustainability of innate diversity, particularly in sensitive ecosystems such as the Mediterranean Sea (NAKASONE et al., 2004).

6.4. Case Study: Increasing Community Knowledge and the Importance of Culture in the Preservation of Fungi - Example of the Middle East and North Africa (MENA) Region

6.4.1.Fungal Group: Native fungal diversity of the Middle East and North Africa (MENA) region, including ecologically important fungi associated with desert, steppe, mountain, and coastal ecosystems (ABDEL-AZEEM; SALEM, 2013).

6.4.2. Major Threats: One of the biggest challenges for fungal conservation in the MENA region is the lack of awareness amongst the public about the ecological and economic importance of fungi. Fungi are usually thought of either as dangerous organisms or as resources of limited value, while their basic ecological functions are largely ignored. Furthermore, fungal conservation does not receive much attention in environmental policies and educational programmes. Other important limitations are limited field surveys, insufficient funding for research, and the lack of institutions specialized in mycology (PEREIRA, 2025; ABDEL-AZEEM; SALEM, 2013).

6.*4.3.* ***Conservation Interventions***: To overcome these challenges, a number of community-based initiatives have been established, most notably the Arab Society for the Conservation of Fungi, an NGO dedicated to the promotion of fungal conservation in the MENA region. The Society aims at cataloguing the regional fungal diversity, promoting scientific research, supporting young mycologists, and enhancing cooperation between researchers and local communities (HAWKSWORTH, 1991; MOHAMED et al., 2021).

Among its conservation activities are the organization of educational workshops and public lectures in accessible scientific language, correction of common misconceptions regarding beneficial and poisonous fungi, promotion of citizen participation in fungal documentation through photography and field surveys and promotion of citizen-science initiatives that actively involve students, amateur naturalists and local communities in biodiversity monitoring (Tsing, 2015; ECCF, 2010).

6.4.4. Outcomes and Achievements: These initiatives have contributed to increasing public awareness of fungal biodiversity and its ecological significance while strengthening communication between scientists and society. Community participation has improved the documentation of local fungal diversity and encouraged greater public engagement in conservation activities. Furthermore, these programs have highlighted the importance of integrating education, culture, and citizen science into fungal conservation strategies throughout the MENA region (MOHAMED et al., 2021).

6.*4.5.* ***Remaining Challenges***: Despite these positive developments, fungal conservation in the MENA region continues to face important challenges, including inadequate institutional support, limited financial resources, insufficient mycological expertise, and the need for stronger integration of fungi into national biodiversity conservation policies and educational curricula (ABDEL-AZEEM; SALEM, 2013).

***6.4.6. Key Lesson Learned*:** This case study shows that the success of fungal conservation relies not only on scientific research but also on community engagement, environmental education and cultural awareness. Fostering the collaboration of researchers, educators, policy makers and local communities is an effective framework for promoting long-term fungal conservation throughout the MENA region (HAWKSWORTH, 1991; ECCF, 2010).

An innovative aspect of this study is the use of art, painting, and photography as a means of raising awareness, an approach with historical and cultural roots. Anthropological studies indicate that some ancient peoples used images of fungi in petroglyphs, manuscripts and ritual symbols. This reflects an early realization of its environmental or symbolic importance. In the modern context, use: scientific illustration, fungi photography and environmentally themed art exhibitions.

As a means of arousing the interest of the younger generations in the world of fungi, and linking science with visual culture, educational studies have shown that images and artistic representations increase learnability and promote emotional attachment to living organisms, including fungi.

These efforts have resulted in: Increasing public interest in mycology, documenting previously unregistered native fungal species, enhancing the participation of students and young researchers in mycology studies and creating a gradual awareness of the importance of protecting the natural habitats of fungi. This confirms that the conservation of fungi does not only depend on scientific and technical tools, but also requires a cultural and cognitive shift in society's view of fungi. The model of the Arab Society for the Conservation of Fungi shows that community engagement and the use of culture and art can be effective and complementary tools to traditional scientific conservation.

Table 6. Community and culture-based approaches to fungal conservation in the Middle East and North Africa (HAWKSWORTH, 1991).
Tabela 6. Abordagens baseadas na comunidade e na cultura para a conservação de fungos no Oriente Médio e no Norte da África (HAWKSWORTH, 1991).

Approach	Target Audience	Tool Used	Expected Outcome
Public awareness campaigns	General public	Workshops, lectures	Increased understanding of fungal ecological roles
Citizen science initiatives	Students and volunteers	Field surveys, fungal photography	Documentation of local fungal diversity
Artistic representation of fungi	Youth and artists	Youth and artists	Enhanced cultural interest and emotional connection to fungi
Academic–community collaboration	Researchers and NGOs	Joint projects and training	Strengthened regional fungal research capacity

6.5. Species-Specific case studies in fungal conservation

Preservation of Polypore Fungi is not merely the protection of individual species; it also subsumes the conservation of unique and diminutive elements of the overall biodiversity. Morels and wood-decaying fungi are nutritionally and/or medicinally beneficial (PHILLIPS; ROGER 2010). However, thousands of unexplored and undocumented species remain. In addition to general challenges affecting conservation, such as habitat loss, deforestation and soil pollution, fungal habitats are threatened. Furthermore, there is a lack of scientific documentation: many species are undiscovered or have not yet been studied.

Monitoring is difficult: some fungi appear only seasonally or in remote and hard-to-reach places. Lack of resources and policies: fungal protection is often neglected compared to animals and plants. However, there are successful examples of fungal preservation (FRANCIS-BAKER; TIFFANY, 2021).

6.5.1. Chanterelle fungi (*Cantharellus cibarius*, Arnolds, 1991): are an ectomycorrhizal fungus that is directly dependent on the health of forest systems, as it is symbiotically associated with the roots of temperate forest trees such as beech (Fagus) and pine (Pinus). The importance of this fungus lies in its active role in improving the absorption of mineral elements, especially phosphorus and nitrogen, which has a positive impact on forest stability and soil health (Golden chanterelle (GIROLLE, 2020)). Over the last few decades, the populations of Chanterelles have faced a drastic decline due to numerous factors throughout Europe (BOA, 2004). These factors include the destruction of forests, the compaction of soils due to foot traffic, and overharvesting. This can severely impact the fungal mycelium, leading to a reduced ability of the fungus to fruit. This can lead to negative impacts on the sustainability of the populations (KUO; MICHAEL, 2018).

The conservation strategies devised have focused on the protection of the habitat and not on direct interventions with the individual fungi. This is due to the fact that the trees in the forests where these fungi live need to be protected (DAHLBERG, 2002). The forests of Europe have been established as nature reserves to protect the trees, along with monitoring of the logging activities (BUYCK et al., 2016). This allows for the logging to be balanced with the ecology of the fungi. Morel and Chanterelles have been observed in a remote nature reserve over several years. The research team placed awareness signs, created pathways for the visitors to follow, and prohibited logging. These actions resulted in a successful outcome (THORN et al., 2017). The fungi continued to grow over multiple seasons, and the balance of the ecosystem was restored. The most important lesson from this was that with the protection of an ecosystem's habitat, the entire ecosystem will be preserved (CHANG; MILES, 2004). The monitoring program of chanterelles involves tracking other types of fungi in some Scandinavian countries. The International Union for Conservation of Nature (IUCN) does not indicate that chanterelles are listed as vulnerable.

Their own documentation, however, suggests that a nearing assessment of this species falls within the definition of Near Threatened (NT) for range (geographic) shrinking and associated habitat loss (ROYSE, 2014). Examples like these illustrate that some fungal species need such areas of habitat-level protection along with sustainable management and not mere individual protection.

6.5.2. The shiitake (*Lentinula edodes*): The shiitake mushroom (Lentinula edodes) serves as a case study in mushroom conservation, having gone from collection as a wild edible fungal fruit body in the forest to being mass-produced along with a multitude of other edible fungi that are now also commercially cultivated. It is a saprotrophic fungus, meaning that it decomposes on dead (decaying) wood, and it plays an important role in the carbon cycle by decomposing lignin and cellulose as a constituent of the wood. Historically, there was a time when the wild edible fungi (mushrooms) were harvested commercially, and this resulted in the depletion of the associated (host) forests and, in turn, created a mushroom void (the absence of fungal fruit bodies) in the forests of East Asia. This threat was negated by an unorthodox method of conservation (something that was, in the past, considered more of a depletion than of conservation): the implementation of sustainable systems for the cultivation of the vegetative mycelial state and fruiting bodies of the desired species.

Conservation efforts have focused on reducing pressure on wild populations by promoting commercial farming, along with preserving wild strains in genetic banks. Restrictions have also been imposed on the harvesting of wild shiitake in some areas, with local communities receiving economic support to transition to farming instead of harvesting (HYDE et al., 2019). Preserved in culture banks (Ex situ) in Japan and the United States to safeguard agricultural and pharmaceutical research. In a modern laboratory, researchers collected samples of this rare fungus and cultured them in Petri dishes with controlled environments to ensure their growth and stability. Cryopreservation and low-temperature preservation techniques were used, with every detail of the sample being recorded: its source, date of collection, and growth characteristics, as in Figure 1.

Figure 1. Shelves containing preserved fungal samples, illustrating the cryopreservation process: sample preparation with cryoprotectant, transfer to liquid nitrogen, and long-term storage to maintain genetic and physiological properties.
Figura 1. Prateleiras contendo amostras preservadas de fungos, ilustrando o processo de criopreservação: preparação da amostra com crioprotetor, transferência para nitrogênio líquido e armazenamento a longo prazo para manter as propriedades genéticas e fisiológicas.

6.5.3. Morel **(*Morchella* spp.):** Morel fungi are among the most complex fungi in terms of their life cycle, exhibiting seasonal and irregular fruiting, and are often associated with environments affected by fires or environmental disturbances. This complexity makes their conservation a scientific and management challenge. High commercial demand for morel has led to intensive harvesting, particularly after forest fires, where short fruiting periods are exploited without regard for natural regeneration. Climate change has also disrupted fruiting timing, making monitoring more difficult (PILZ et al., 2007). Conservation strategies have relied on regulating collections after fires, imposing temporary bans in the years immediately following environmental disturbances, and establishing long-term monitoring programs to study population dynamics. Molecular research has also been conducted to understand the genetic structure of different species within this genus (BUSCOT, 1994).

A conservation study in its natural habitat (In situ) in North America, with recording of its seasonal growth data, has helped sustain its commercial collection. According to the IUCN framework, some morel species can be classified as Vulnerable (VU) according to criterion (A) relating to declining numbers of individuals, but the great variation between species has led to the absence of a unified global classification (KUO et al., 2012).

Morchella spp. (Morel fungi): Found in temperate forests and sometimes in areas affected by wildfires. A globally sought-after culinary mushroom, it commands high prices.

Preservation: Regulating the harvesting season. Supporting projects related to large-scale industrial agriculture. Monitoring mushroom distribution to ensure that it does not occur.

6.5.4. *Hericium erinaceus* (Lion's fungi): Grows in temperate forests of East Asia and Europe, and is considered a rare mushroom in some areas due to the removal of old-growth trees. A highly nutritious mushroom, it contains antioxidant compounds and is used to treat nervous system disorders and improve memory (BERTZ et al., 2013).

Conservation Strategies: Growing mushrooms on dedicated farms to reduce pressure on natural forests. Establishing gene banks to store samples and encouraging local communities to preserve old-growth trees that support fungi growth.

6.5.5. *Amanita caesarea* (Emperor fungi): Found in the Mediterranean forests of Europe, it is characterized by its bright orange color and large cap. It is edible and in demand in local markets, making it vulnerable to overexploitation. Caesar's fungi are a root fungus of high historical and cultural value, having been associated with ancient Roman cuisine (LUPALA et al, 2025). However, this mushroom is highly sensitive to environmental conditions and depends on relatively stable forests. This fungus has experienced a decline in some of its areas of distribution due to the loss of broadleaf forests, in addition to public safety problems due to confusion with poisonous Amanita species, which has led to restrictions on its collection in some countries. Efforts have been made to increase public awareness of the biological accidents and the pressure on the populations of the reserves of the natural habitats. According to the IUCN (C), the candidate classification of Caesar's mushroom is Endangered to Near Threatened (NT) and Vulnerable (VU) populations (LUPALA et al, 2025).

- Problems with preservation: Over-collecting Endangers natural populations. Dense forests and natural reserves maintain their density. Restricting the collection of wild mushrooms can help educate local communities on the density of non-selective mushroom harvesting.

- Agricultural Nitrogen Fungus: A beneficial fungus for sustainable agriculture because of its positive effect on soil health and control of plant pathogens (HARMAN, 2006).

- Preservation Methods: Creating preserved strains in laboratories for research and/or agricultural use. Investigating the natural distribution of the fungus for its sustainable utilization (BOA; PEREZ-MORENO, 2005).

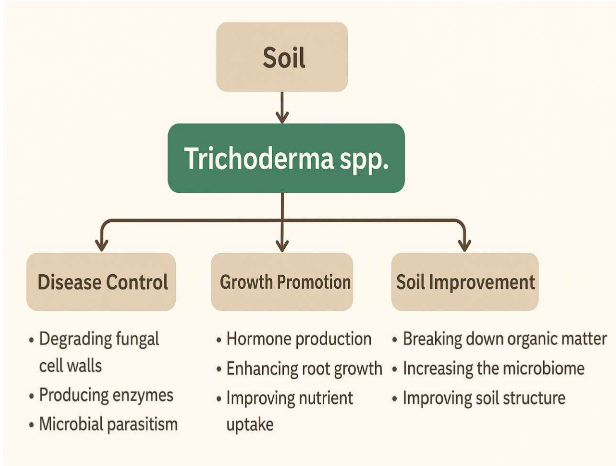

Figure 2. How *Trichoderma* spp. works in sustainable agriculture.
Figura 2. Como *Trichoderma* spp. atua na agricultura sustentável.

Table 7. Applications of *Trichoderma* spp. in Sustainable Agriculture.
Tabela 7. Aplicações de *Trichoderma* spp. na agricultura sustentável.

Field	Role of *Trichoderma* spp.	Agricultural Benefit	Examples of Application
Disease Control	Producing cell-wall-degrading enzymes (chitinase, glucanase) and parasitizing pathogenic fungi	Reducing root diseases and wilt infections	Control of *Fusarium, Rhizoctonia*, Pythium
Growth Promotion	Producing plant hormones such as IAA and GA	Increasing biomass, root length, and plant vigor	Seed coating or soil inoculation before planting
Nutrient Uptake	Enhancement: Solubilizing phosphorus and increasing the availability of Fe and nitrates	Reducing the need for chemical fertilizers	Application with organic fertilizers or compost
Induced Systemic Resistance (ISR)	Stimulating plant immune responses	Improving plant tolerance to biotic and abiotic stresses	Treating seedlings before transplantation
Soil Improvement	Decomposing organic matter and enriching the soil microbiome	Enhancing soil structure and organic content	Mixing with compost or farmyard manure
Bioremediation	Degrading pesticide residues and soil contaminants	Reducing soil toxicity and improving fertility	Application in polluted or degraded soils

6.5.6. *Ganoderma lucidum* (medicinal fungi): Grows on deciduous trees in East Asia and is known as Reishi. It is used in Chinese medicine to treat inflammation, cancer, and heart disease (PATERSON, 2006).

Conservation Strategies: Sustainable cultivation to reduce pressure on natural trees. Use of ex situ techniques such as culture collections and cryopreservation. Monitoring natural habitats to ensure the self-renewal of fungi.

6.5.7. *Wood-decaying fungi*: This functional group comprises quite a number of species responsible for the breakdown of dead wood, a process that is critical for the sustainability of forests (NORDÉN et al., 2025). Due to the ecological importance of these fungi, however, they have been neglected for a long time owing to the forest management policy of dead wood removal. Such an approach resulted in the loss of the microhabitats that these fungi need, which in turn resulted in a drop in their diversity (STOKLAND et al., 2012).
Contemporary conservation efforts have responded to this by gaining policies that advocate for the retention of deadwood in forests and a reconsideration of old practices of intensive clearing. Most of these species have been assessed and by IUCN are classified as Vulnerable (VU) and Endangered (EN), especially by criteria (A) and (B); thus, they are sensitive indicators of ecosystem health (HOTTOLA et al., 2009).

6.5.8. Saving the coral reef fungus (*Clavaria fragilis*) from extinction in Europe: *Clavaria fragilis* was not well-known to the general public; it is neither a large nor a common species, nor is it considered an economically important fungus (HOLMSKJOLD, 1790). But scientists know very well that it is an indicator of the health of European grassy meadows, and that a decline in its numbers is an early indicator of the deterioration of traditional ecosystems (ROODY, 2003). The story began in the spring of 2005 in one of Sweden's grassy reserves, when a team of mycologists noticed that the fungus had almost completely disappeared (DAVIS et al., 2012). These reserves were traditionally managed through animal grazing. Still, the cessation of grazing for years led to the accumulation of thick layers of grass, causing a change in soil moisture and surface illumination, factors that this delicate type of fungus cannot tolerate (ARORA; DAVID, 1986).

The researchers decided to implement an environmental restoration project based on "reactivating the traditional system." Low-intensity grazing was reintroduced, and the affected areas were manually cut to remove the accumulated vegetation. It took scientists months to monitor changes in the soil, and it took only a year before the first mycelium threads began to reappear at the edges of low-lying areas (CORNER, 1950). In 2008, the first cluster of white, coral-like fruiting bodies appeared, standing upright above the grass surface. This was the first living evidence that the ecosystem was recovering and that natural rebalancing was still effective even after years of degradation. This experiment later became a model to be emulated in the rest of Europe (MCHUGH et al., 2001). It proved that fungi do not need complex interventions as much as they need an understanding of their environmental behavior and a restoration of the conditions that constitute part of their natural existence (RODE LIJST, 2008). The story of *Clavaria fragilis* is an example of the success that is achieved when a person works with nature and not against it.

6.5.9. Laboratory preservation of black truffle fungus (*Tuber melanosporum*) – Gene Bank Construction (Hall et al., 2007; Zambonelli et al., 2017): While coral reef fungi have ecological value, black truffles possess a dual value: both ecological and economic. They are among the most expensive edible fungi in the world, and their declining production in Europe over the past decades has created an agricultural and economic crisis, prompting researchers to consider new conservation techniques (STACKEBRANDT; SMITH, 2015). This success story began in a microbiology laboratory in France in 2012, when a research group noticed that truffles were declining not only due to climate change, but also due to a loss of genetic diversity (CROUS et al., 2016).

As monocultures became more commonplace, their diversity, which provided resilience in terms of infectious diseases, climate change, and other environmental factors, began to disappear. Hundreds of samples were taken and tested from different areas, including the Pyrenees, the Tuscan woods, and the Balkan valleys. Researchers began their analyses and gene banking of Myriostoma and other truffle species. They applied PCR and DNA replication, and then sent the samples to be cryogenically preserved, keeping the mycelium for decades at -80°C. They developed refined mycorrhizal seedling systems, which made the artificial cultivation of truffles possible (HALLENBERG et al., 2014). By 2018, more than 700 strains, many previously unrecorded, had been added to the preserved gene bank. This restoration of genetic diversity to the commercial farms has improved the mushrooms' resistance to heat and drought. This has, in turn, salvaged truffle production in the Mediterranean region's commercial farms (STROBEL, 2003).

6.5.10. Analytical Case Study: *Ophiocordyceps unilateralis* – A biological enigma and a scientific preserve. A dangerous parasite that became a worldwide model for conserving nature:

Brazilian researchers documented phenomena in the rainforest involving Wood Ants. Wood Ants would inexplicably leave the safety of their colonies, climb plants, penetrate leaves, and die. Later, long, sword-like fungal structures would protrude from their heads (HALLENBERG et al., 2014). Although this organism is termed the "Ant fungus", it is more commonly referred to by scientists as Ophiocordyceps, which describes the genus of parasitic fungi that defies description because of the fear and intrigue it instills. Ophiocordyceps parasitically infects a variety of insects, including but not limited to ants, butterflies, and caterpillars (ZIMMER; CARL, 2019).

Ophiocordyceps unilateralis has been termed the "Zombie ant fungus" because of its parasitic behavior, which leads to the infection and death of a host ant. The death of the host ant, which has been "Zombified," is actually beneficial to the parasitism and the dissemination of spores, as it causes the ant to die at the top of a plant. *Ophiocordyceps sinensis* is known as "caterpillar fungus" because it lives on the larval stage infection of certain insects (RYAN et al., 2000). *Ophiocordyceps sinensis* is popular in the traditional medicines of Tibet, India, and China, and it is one of the most sought-after fungi in the Tibetan region, which is at an elevation of 3000-5000 meters, in the high Himalayas (MONGKOLSAMRIT et al., 2012).

Ophiocordyceps sinensis has proven to be a valuable fungus to the local economy as it is sold for thousands of dollars per kilogram in both local and international markets (EVANS et al., 2011). Nonetheless, the fungal species has suffered from over collection, and along with climate change, which alters the distribution of the fungus and the life cycle of the insects the fungus relies on, and the loss of the fungus's natural habitats due to human encroachment and overgrazing (Sung et al., 2007), has further contributed to the decline approximately 140 species of the genus \ {Ophiocordyceps} are known, with the most famous being \9t{*Ophiocordyceps unilateralis*}, which lives in tropical forests and preys on ants, controlling the behavior of the ants to make them climb to a higher place, where the ant eventually dies.

The fungus can produce spores that are released from the dead ant's body to infect new hosts (EVANS et al., 2011). Ophiocordyceps also has some economically and medically important properties and is used in the treatment of some liver diseases. Some diseases that affect the respiratory and immune systems (SAMPLe et al., 2010).

Ophiocordyceps has the unique ability to infect and control the nervous system of ants, which helps the fungus position ants in a place that is favorable for the growth of the fungus. In addition to the unusual necrotrophic behavior of the fungus, which is one of the most remarkable examples of evolutionary novelty in the fungus kingdom, most people are unaware that this fungus is also threatened (ANDERSEN et al., 2009).

The microscopic habitats required for the fungus to survive are being destroyed and are disappearing with the increase in deforestation. Hence, universities in Brazil and Thailand initiated a project to conserve this species in sterile fungal banks, also safeguarding its natural habitat. Perhaps no fungus has excited and fascinated the sci-fi community more than *Ophiocordyceps unilateralis*, a parasitic fungus that infects an ant and modifies its behaviour significantly (HUGHES et al., 2011). However, there lies a legend, a scientific fact and a story about biological conservation. The tale begins in the Brazilian rainforest, where the scientists studying the unique fungus have observed a steady disappearance of the fungal colonies. Urban sprawl and deforestation have resulted in the loss of the shaded, humid pockets that the fungus needs to complete its lifecycle (STROBEL, 2003). To appreciate the organism's conservation value, we have to appreciate the fungus first.

The fungus extends a mycelium that covertly infects a worker ant. After a few days, it begins to alter the ant's behavior through some sophisticated chemical mechanisms, compelling it to ascend to the tops of branches and latch on to them in the notorious 'death grip'. It is here that, in a conducive microhabitat of ventilation and humidity, the fruiting body of the fungus grows from the ant's head and releases its spores downward to continue the cycle. When the researchers noticed the decline of the Ophiocordyceps, they started a conservation project that included three integrated phases (BEKKE et al., 2014):

1 – Collecting live strains from different regions. This was no easy task, as the fungus is found only in very small locations. However, the team managed to collect approximately 35 different strains, which were subsequently placed in specialized laboratories with constant humidity and partial darkness.

2 - Developing a laboratory environment that mimics a forest. One of the biggest challenges is that fungi do not grow on a traditional artificial medium like common laboratory fungi. Therefore, scientists used samples of tree bark, forest soil, and a precise simulation of night-day temperature variations (SMITH; ONIONS, 1994).

3 - Genetic Preservation and DNA Bank. Due to the unique nature of this fungus, living preservation was not enough. Gene banks were also established to preserve the DNA of the strains, preventing their loss in case the living colonies died. By 2020, the fungus had begun to reappear naturally in ecologically restored areas, and the project had successfully preserved one of the most unusual and complex fungi on Earth (HAWKSWORTH; TALBOT, 1970).

Conservation Strategies: Determine the harvest season to ensure spore dispersal table (LI et al., 2011). Monitor fungi density annually using field surveys. Encourage cooperative farms to reproduce fungi sustainably. The story of the ant fungus is not just a story of species preservation, but a story about understanding the balance between organisms and the role of fungi in shaping complex behaviors within ecosystems (HAWKSWORTH; TALBOT, 1970; ABDUL-HUSIN et al., 2026). In Nepal and Tibet, a "community-based management of mountain ranges" system has been implemented, which includes: Establishing official harvesting seasons and prohibiting the use of tools that damage larval-bearing soils. Imposing harvesting fees used to fund environmental monitoring (THAPA et al., 2021).

Laboratory Culture and Synthetic Alternatives: Research has made significant progress in cultivating Ophiocordyceps in bioreactors using plant or insect substrates, producing preparations with nutritional and medicinal value similar to the natural substance.

Government Regulations: China has adopted special systems for registering mushroom collectors and preventing unlicensed sales, thus mitigating unregulated practices (DAY; BRAND, 2005).

Table 8. Effect of harvest management on *Ophiocordyceps sinensis*.
Tabela 8. Efeito do manejo da colheita sobre *Ophiocordyceps sinensis*.

Harvest Management Practice	Timing / Frequency	Impact on Yield	Environmental Impact	Notes
Manual selective harvesting	Early season, once per season	Maintains high yield, sustainable	Low disturbance to habitat	Recommended for sustainable collection
Intensive harvesting	Throughout the season, multiple times	May increase short-term yield	High soil and vegetation disturbance	Risk of overexploitation
Delayed harvesting	Late season	Reduced yield	Minimal environmental impact	Useful for natural regeneration
Controlled area rotation	Rotating harvesting zones annually	Stabilizes long-term yield	Promotes habitat recovery	Requires planning and monitoring
Mechanized harvesting	Any season	High yield in the short term	Significant habitat degradation	Not recommended due to ecological damage

6.5.11. Regeneration of mycorrhizal fungi in the Nakosa Grasslands Preserve, Illinois, USA. Background: Mycorrhizal fungi play a vital ecological role by forming symbiotic relationships with the roots of most terrestrial plants. These fungi contribute to improved nutrient and water uptake, increased plant resistance to pathogens, and enhanced overall plant survival, particularly in degraded ecosystems. Decades of changes in land use for farming, along with the deterioration of soil in the Nakosa Grasslands Preserve in Illinois and similar tall grass prairies, have caused considerable losses in the diversity of mycorrhizal fungi, which is damaging the critical ecological networks found in these grasslands (SMITH; RYAN, 2004; AL-SULTANY; JASSIM, 2016).

Mycorrhizal fungi are threatened by fungal diversity decline due to combining the native grasslands with agricultural fields by way of land conversion and tillage (WAGG et al., 2019). Soil compaction and the lack of soil nutrients lead to the loss of native plant assemblages that support the mycorrhizal networks. Without modification, these factors would have caused a long-term decline in native plant populations, given that mycorrhizal fungi are critical to plant survival and the functioning of ecosystems. The focus of the rehabilitation program was on integrated habitat restoration and the reintroduction of functional mycorrhizal networks. Controlled burns to stimulate soil microbes by imitating natural processes (MUELLER; SCHMIT, 2007).

Mycorrhizal soil inoculation: the addition of soil with mycorrhizal spores and fungal structures from a non-degraded reference site soil.

The restoration of native plant assemblages: sowing native plant seeds along with mycorrhizal soil inoculation, to promote the establishment of a plant-fungus network. Long-term assessment: Annual assessments of the success of restoration in plant survival, fungal diversity, and growth. The rapid restoration of mycorrhizal networks in soils that had previously been degraded. Restoration efforts have led to more successful plant survival and diversity as compared to unrestored areas (SMITH; RYAN, 2004). Evidence of functional recovery signs, such as restored mycorrhizal fungi, enhanced nutrient cycling and improved soil structure. These findings indicate that mycorrhizal fungi coupled with community management can even reinstate ecological functions in degraded areas.

IUCN Framework Relation: Although the project did not target any particular threatened fungal species, it aligns with the International Union for Conservation of Nature (IUCN) framework. Restoring the ecological functions of the ecosystem (the ecological approach). Preserving the diversity, both genetic and functional, of the fungi. Monitoring the ecosystem in the long run to set conservation priorities. This case serves as a successful example of ecosystem-level fungal conservation and underlines the role of fungi as a significant element in ecological conservation (DAHLBERG; MUELLER, 2011; RADHI et al., 2026).

6.5.12 INVAM Project – Conservation and reapplication of mycorrhizal fungi: Since your company plays an integral role in the support of ecosystem stability and the health of individual plants, your company acts to support the conservation of habitat, plant diversity, and the overall ecological balance of the world's ecosystems. Mycorrhizal Fungi (AMF) increase the ability of plants to absorb both nutrients and water, as well as provide a greater resistance to environmental stresses. Known as the 'living library of mycorrhizal fungi', the International Collection of Vesicular Arbuscular Mycorrhizal Fungi (INVAM) aims to assist with the collection, conservation, and provision of mycorrhizal species for scientific ecosystem restoration research (SMITH; RYAN, 2004; AL-AMERY et al., 2024).

Degraded ecosystems and global ecosystems also face the following threats: The conversion of major agricultural areas, compounded by overall land degradation, and diminished mycorrhizal soil diversity resulting from the excessive use of pesticides and chemical fertilizers. Surprisingly, scientific data about the mycorrhizal fungi of a given region, and the region's optimal growth conditions, are either limited or non-existent (MUELLER; DAHLBERG, 2011). As for the conservation of species and the mitigation of the application of conservation technologies, the INVAM project utilized breeding strategies of'species conservation to environmental application' in the collection and conservation of strains in the specialty laboratories.

Developing functional and genetic diversity: This includes initializing an interactive database that includes genetic and functional attributes and their interrelations with a diversity of plants.

Fungal application in ecological restoration (Tan; Stalpers, 1996): Fungal application in soil restoration of degraded lands, especially in degraded forests and rangelands, along with sowing of native plants, fusion with preservation and cultivation of fungi.

Education and knowledge dissemination: Morton; Redecker (2001) reported educating and training researchers and farmers on the use of fungi as a means to enhance the health of plants and the sustainability of ecosystems.

Outcomes: Detailed records of ecological and functional attributes were maintained for over 900 mycorrhizal fungal strains. Post-restoration, plant growth in areas with the application of preserved fungi, as compared to areas with unpreserved fungi, improved. Supported the scientific community in the study of the role of fungi in nutrient cycling and tolerance to abiotic stress, with the results being of global application (TAN; STALPERS, 1996; HASSAN et al., 2025). Linked with IUCN standards, the project supported the conservation of fungal genetic diversity. Supported the continuity of the ecological function of the ecosystem being restored. Supported the Delay of the Restoration response of the ecosystems being restored. The INVAM project exemplifies world-class fungal conservation by integrating laboratory conservation, ecosystem conservation, and documentation (WAGG et al., 2019).

6.5.13. Using Mycorrhizal fungi to support threatened plants in Hawaii: Mycorrhizal fungi play a crucial role in improving the survival of rare and threatened plants, especially in fragile ecosystems such as the Hawaiian Islands. Habitat loss, invasive plant populations, and genetic loss have reduced the chances of native plants surviving (HOMOLKA et al., 2001).

Threats: Decreased survival of native plants due to loss of fertile soil and natural habitats. Competition with invasive plants. Limited availability of seeds suitable for wild cultivation.

Conservation interventions: Inoculation of seedlings with mycorrhizal fungi before replanting them in the wild. Growing plants in greenhouses with micro-amended soil enhances their ability to adapt to natural soil upon transplanting. Follow up after reintroduction to monitor growth success and survival rate (SMITH; READ, 2008; SMITHSONIAN MAGAZINE, 2019).

Results:

- Increased survival rate of cultivated plants compared to untreated sites.
- Enhanced plant health, nutrient uptake, and tolerance to environmental stress.
- Provides a scientific model for applying fungi in practical conservation programs for threatened plants.
- Supporting the restoration of threatened plants as classified by the IUCN.
- Illustrating the importance of fungi in the conservation of threatened plant species and ecosystem functions.

6.5.14. Inclusion of fungi in national legislation – The Chilean Experience: In many countries, fungi are not typically included in biodiversity protection laws, despite their ecological and economic importance. Chile is a pioneer in including fungi in national legislation for their protection (HOMOLKA et al., 2001).

Threats: Indiscriminate harvesting of wild mushrooms. Degradation of natural habitats. Lack of regulatory policies to protect mushrooms. Conservation Interventions. Inclusion of specific mushroom species in the national environmental law. Establishment of a national red list of threatened mushrooms. Monitoring enforcement of laws and regulating mushroom harvesting to ensure sustainability (DAHLBERG; MUELLER, 2011). Results:

- Protection of 45 fungal species, including rare ones.
- Enhancement of environmental awareness among local communities and farmers.
- Provision of a model for implementing national fungal conservation policies with the potential for global expansion.
- Direct application of IUCN principles through species assessment and habitat protection.
- Supporting biodiversity and integrating fungi into environmental policies.

Table 9. Comparative overview of successful fungal conservation case studies.
Tabela 9. Panorama comparativo de estudos de caso bem-sucedidos de conservação de fungos.

Case Study	Fungi / Ecosystem	Type of Conservation Success	Intervention / Approach	Outcomes	IUCN Relevance
Nachusa Grasslands, USA	Arbuscular Mycorrhizal Fungi in Tallgrass Prairie	Restoration of ecosystem function	Controlled burns, soil inoculation, reintroduction of native plants and long-term monitoring	Rapid re-establishment of fungal networks, increased plant survival and diversity, and functional ecosystem recovery.	supports functional restoration and fungal diversity; monitoring aligns with the IUCN ecosystem approach
INVAM – International Collection	Vesicular Arbuscular Mycorrhizal Fungi (AMF)	Ex-situ preservation and applied restoration	Collection and cryopreservation of fungal strains, genetic and functional documentation, soil inoculation in restoration projects	Over 900 strains preserved, enhanced plant growth in restored sites, and global research applications	Preserves genetic and functional diversity; informs IUCN conservation priorities
Endangered Plants in Hawai'i	Mycorrhizal fungi associated with endangered native plants	Assisted survival of threatened plants	Fungal inoculation of seedlings in greenhouses, reintroduction to natural sites and post-planting monitoring	increased plant survival, improved nutrient uptake and stress tolerance, a model for fungal-assisted restoration	Supports threatened species recovery per IUCN Red List criteria
Chile – Legal Protection	Various native fungi	Policy and legal protection	Inclusion of fungi in national environmental law, Red List assessment and regulated collection	Protection of 45 fungal species, increased public awareness and a framework for national fungal conservation	Direct application of IUCN Red List principles ensures habitat and species protection.
Black Truffle (Tuber melanosporum) – Europe	Ectomycorrhizal fungi	Sustainable cultivation and preservation	Managed cultivation under host trees, long-term monitoring, and farmer training	Sustainable truffle production, reduced pressure on wild populations, and improved genetic management	Reduces extinction risk for wild populations; links sustainable use to IUCN conservation goals

7. THE ROLE OF THE IUCN RED LIST IN ADVANCING FUNGAL CONSERVATION

The IUCN Red List of Threatened Species is the most important global framework for assessing the degree to which living species are at risk of extinction, and in recent decades it has formed the cornerstone in guiding environmental conservation policies globally ("SLOVENIAN RED LIST", 2010). Although animals and plants received the lion's share of these assessments, fungi remained largely out of the spotlight for a long time, despite their pivotal role in the sustainability of ecosystems.

This marginalization prompted the International Union for Conservation of Nature (IUCN) to establish a specialized program for fungal conservation through the IUCN Fungal Conservation Committee and launch the Global Fungal Red List Initiative, with the aim of formally integrating fungi into the global conservation system (EURONEWS, 2025; HASSAN et al., 2026).

The Red List of Fungi is based on standard IUCN criteria for assessment, which include: shrinking geographic range of the species, declining individual numbers or mycelium degradation, loss or degradation of natural habitats, severity of human pressures, and the impact of climate change. The importance of these standards lies in the fact that they transform environmental information into practical decision-making tools, allowing for the design of effective conservation strategies, which is clearly demonstrated in the success stories reviewed in this chapter. Recent assessments have shown that hundreds of wild species have been classified into different threat categories, such as Near Threatened (NT), Endangered (VU), and Critically Threatened (EN) (ONIONS, 1971). A notable example is wood-decaying fungi, which depend on old trees and dead wood.

The traditional focus on "forest cleanup" has led to the loss of their natural habitats, prompting the inclusion of several of them on regional red lists. This inclusion has contributed to changing forest management policies in some European countries, where the importance of dead wood as a key element in sustaining biodiversity has been re-recognized, leading to the recovery of entire wildlife communities within a few years (IUCN SSC, 2025). Another example is *Hericium erinaceus* (lion's mane fungi), which has been listed on national red lists in some European countries due to the deforestation of the old-growth forests it relies on. This classification has contributed to strengthening conservation programs within natural forests. In addition to conservation outside natural habitats via isolated banks and laboratory culture, it has made it a successful model combining in situ and ex-situ conservation, as reported in previous case studies in this study.

Amanita caesarea is also a clear example of a food mushroom of cultural and economic value that has been included in local red list assessments in the Mediterranean region due to overexploitation and habitat loss (ONIONS, 1971). This classification has led to restrictions on commercial harvesting, the launch of awareness campaigns, and the inclusion of mushrooms in environmental monitoring programs, which have contributed to the stabilization of their populations in some protected areas (HAWKSWORTH, 2001; YOUSEF; JASSIM, 2026). The importance of the Red List of Fungi extends beyond individual species, guiding success stories in the conservation of entire ecosystems. For example, the inclusion of mycorrhizal fungi within functional conservation frameworks has helped support programs for restoring degraded lands. This is evident in rangeland and forest restoration projects, where lab-preserved fungi have been reintroduced to support the stability of plants and the entire ecosystem (GLOBAL FUNGAL RED LIST INITIATIVE, 2025).

Thus, the Red List of Fungi is not merely a scientific classification of their status as endangered, but a pivotal strategic tool that underpins many success stories in fungal conservation, whether through protecting natural habitats, regulating human exploitation, establishing genetic and fungal banks, or supporting environmental legislation; this aligns directly with the primary objective of this chapter. This highlights how science, when supported by global assessment mechanisms such as the Red List, can translate into tangible achievements in preserving one of the most important and least visible components of biodiversity.

8. CHALLENGES AND OPPORTUNITIES IN FUNGAL CONSERVATION

Despite progress in the field of fungal conservation, several key challenges require continued attention.

- Lack of data and documentation: Many fungal species have not yet been accurately documented scientifically, which hinders threat assessment and conservation planning (HAWKSWORTH, 2001). A study of *Ophiocordyceps sinensis* showed that the density of the fungus varies annually according to environmental conditions, making surveys incomplete if they are not carried out over long periods (LI et al., 2011).

- Difficulties in Cultivation and Reintroduction: Some microfungi cannot be easily cultured outside their natural environment, such as *Ophiocordyceps sinensis*, which is host-dependent (LI et al., 2011). Reintroducing fungi to their natural environment after *ex-situ* preservation requires careful planning to avoid disrupting the ecological balance.

- Human pressure: Intensive commercial exploitation of economically important fungi threatens the sustainability of natural species, as in the cases of Morchella spp. and Amanita caesarea. Deforestation and overgrazing threaten the natural habitats of some fungi, such as *Hericium erinaceus* and *Ganoderma lucidum*.

- Legislation and Policies: The absence of clear laws in some countries hinders effective protection. There is a need for legislative coordination between local communities and governments to ensure the sustainable protection of fungi.

- Opportunities: Integrating fungi into environmental education programs enhances community awareness (EURONEWS, 2025). The most comprehensive solution is developing ex situ and in situ programs in parallel. Due to the international nature of research, there is collaborative knowledge sharing on best practices in conservation (BERTZ et al., 2013). Fungal conservation is multifaceted. Previous studies have identified the need for a composite approach, which includes the following. In situ conservation: monitoring and protecting the indigenous environment of the fungi, and the sustainable resource of which the fungi are a part.

- *Ex-situ* conservation: sustainable cultivation of and the use of cryopreservation on reference populations.

- Community education and awareness: education of community members on the environmental and economic value of fungi and their roles as monitors.

- Legislation: the formulation of laws to manage the economic harvest and trade, with mechanisms to monitor compliance.

9. COMPARATIVE ANALYSIS OF CONSERVATION SUCCESS FACTORS

The case studies presented here show that successful fungal conservation cannot be achieved through one approach, but through the integration of multiple complementary strategies. The case studies are varied in their geographical location, the fungal groups they target and their conservation objectives, but they display a number of common factors that are consistently associated with successful conservation outcomes. One of the most important factors is the establishment of a strong scientific basis, through fungal inventory, taxonomy and biodiversity assessment.

The Egyptian case study shows how extensive documentation of fungal diversity and the use of IUCN Red List criteria provided a basis for national conservation planning (ABDEL-AZEEM; SALEM, 2017). Similarly, field studies conducted in Mediterranean forests in Spain demonstrated that many fungal species remain poorly documented, emphasizing the importance of continued taxonomic research and ecological surveys (DAHLBERG; MUELLER, 2011; POLEMIS et al., 2020).

Another recurring theme is the complementary use of *in-situ* and *ex-situ* conservation strategies. Therefore, it is crucial to continue protecting habitats for the conservation of ecological interactions that are impossible to re-create in laboratory conditions, especially for mycorrhizal and saprotrophic fungi, which depend on specific host plants and environmental conditions (GIROMETTA et al., 2020; LAZAREVIĆ; MENKIS, 2020). In parallel, culture collections, fungaria, cryopreservation and gene banks provide long-term safety for the genetic resources of fungi and are a support for research, biotechnology and future restoration programmes (HAWKSWORTH, 2001; MCCLUSKEY; WIEST, 2011).

The case studies analyzed also underline the importance of community participation and environmental education. The experience from the Middle East and North Africa (MENA) region indicates that the efforts for fungal conservation can be significantly improved by raising public awareness, promoting citizen science, and strengthening collaboration between researchers and local communities (ECCF, 2010; MOHAMED et al., 2021). Also, in several areas, economically important fungi have been conserved through sustainable harvesting practices and community involvement.

The case studies also show the importance of community participation and environmental education. Experience from the Middle East and North Africa (MENA) region shows that public awareness raising, citizen science and improved collaboration between researchers and local communities can greatly enhance efforts for fungal conservation (ECCF, 2010; MOHAMED et al., 2021). In addition, sustainable harvesting practices and community involvement have conserved economically important fungi in several areas.

Despite these successes, a number of shared challenges exist across all case studies. These include habitat loss, climate change, lack of long-term ecological monitoring, limited financial resources, absence of mycological expertise in many regions and underrepresentation of fungi in biodiversity conservation policies. Greater international collaboration, increased investment in fungal research, expansion of fungal conservation networks and a greater inclusion of fungi into programs of ecosystem restoration and environmental management are needed to address these needs.

The evidence reviewed here suggests that successful fungal conservation requires the integration of scientific investigation, habitat protection, ex situ conservation, policy development, institutional commitment and community engagement. These complementary approaches provide a practical framework for conservation of fungal biodiversity and preservation of its ecological, economic and biotechnological value for future generations.

10. CONCLUSIONS

This review highlights that effective fungal conservation requires an integrated approach combining *in-situ* and *ex- situ* conservation, scientific research, public policy, and community engagement. The case studies presented demonstrate that successful conservation is supported by accurate biodiversity documentation, habitat protection, long-term monitoring, and well-managed fungal collections.

Despite recent progress, fungal conservation continues to face important challenges, including habitat loss, climate change, limited taxonomic knowledge, and the underrepresentation of fungi in biodiversity conservation policies and Red List assessments. Addressing these challenges requires stronger international collaboration, expanded fungal inventories, improved conservation infrastructure, and greater public awareness.

Future efforts should focus on integrating fungi into biodiversity management and ecosystem restoration programs while strengthening research and conservation networks to ensure the long-term protection of global fungal diversity.

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Acknowledgments: The authors extend their sincere thanks and appreciation to Prof. Dr. Ahmed Abdel-Azeem for his valuable encouragement and inspiration to the authors to choose the topic of this review, and for his role in consolidating their interest in mycology.

Author Contributions: Y.A.J.: methodology, investigation or data collection, writing (original), writing (review & editing); S.M.H.Al-A.: methodology, investigation or data collection, writing (original); A.N.H.: methodology, investigation or data collection, writing (original); B.M.H.Al-A.: methodology, investigation or data collection, writing (original); E.F.A.A.: conceptualization, methodology, investigation or data collection, administration or supervision, writing (original), writing (review & editing). All authors have read and agreed to the published version of the manuscript.

Data availability: Data from this study can be obtained via email upon request to the corresponding author.

Conflict of interest: The authors declare no conflicts of interest.