



'Tyger! Tyger! burning bright' – but fungi are out of sight

T.S. Suryanarayanan

Vivekananda Institute of Tropical Mycology (VINSTROM), A Research Unit of Ramakrishna Mission Vidyapith, Chennai, 600004, India

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ABSTRACT

Governments, nature conservation and civil society organizations worldwide are doing commendable service in protecting species and their habitats. However, they focus more on charismatic species such as tigers, elephants and whales. Microorganisms, especially the fungi, are not given the due attention despite their ecological importance. Because of their unique lifestyle and relatively less investigations on them, serious exploration efforts on fungi are bound to reveal many new species housing novel genes which could aid in managing current global crises including antibiotic resistance, fuel crisis and negative effects of climate change on crops. This is urgent since loss of habitats, invasion by exotic species, pollution, and anthropogenic changes cause extinction of fungal species as well. Apart from emphasizing these points, this article alludes to a rapid and less expensive method of collecting fungi using a crowdsourcing model and the importance of including information about traits to the cultures deposited in the culture collection centers.

1. Introduction

Conservation efforts are focused on charismatic animals like tiger and blue whale. The IUCN report which declares that 26 % of mammals, 14 % of birds and 41 % of amphibians are under threat, hardly mentions the fungi (Kasson et al., 2022). Fungi invariably draw bad press as causal organisms of various diseases in humans, animals and crops. The fact that we know only around 150,000 of the 2 to 11 million species of fungi estimated to exist today (Phukhamsakda et al., 2022) underscores the urgent need to consider them seriously in this regard. Their unique lifestyle and inadequate critical investigations on them are bound to reveal many new species housing novel genes which could aid in managing current global crises including antibiotic resistance, fuel crisis and negative effects of climate change on crops.

To the general public 'fungi' means only the mushrooms as they are visible to the unaided eye. But then mushrooms constitute only a miniscule group of fungi. There are numerous fungal species whose existence is overlooked because they are invisible to the unaided eye. Till recently, studies on such microfungi were more basic and concentrated on identifying and naming new species thus limiting the interest on fungi to a select group of biologists. Even the advanced molecular and genetic studies address only a select few species. Studies on a broader perspective on fungi are mostly with an anthropocentric perception addressing methods to manage diseases caused by them in crops and humans.

2. Uniqueness of fungi

Fungi are one of the evolutionarily most successful organisms and are critical in the healthy functioning of ecosystems due to their role as recyclers of nutrients. The part played by fungi is major due to the panoply of their unique extracellular enzymes which target recalcitrant macromolecules such as lignin, chitin, cellulose and tannins. Fungi improve plant performance and aid inter-plant communication by forming a mycorrhizal network with their roots (Song et al., 2010). Some microfungi establish symptomless symbiosis with plants of all ecosystems and taxonomic groups and survive inside their tissues as non-disease causing endosymbionts. Termed the endophytes, their constant and universal association enhances the plants' tolerance to abiotic and biotic stresses (Chitnis et al., 2020), improves their competitive ability (Zhou et al., 2018), and increases their nutrient acquisition (Jahn et al., 2021) and probably their photosynthetic abilities (Suryanarayanan et al., 2022). It is now obvious that a plant's performance is a reflection of the interactions it has with its associated organisms and the environment. With reference to fungi in this context, only the plant pathogenic and mycorrhizal forms have been investigated in detail.

3. Growth, nutrient acquisition and reproduction

The mycelial forms of fungi exhibit tubular hyphal growth to maximize nutrient acquisition and minimize competition among them (Nagy

E-mail address: t_sury2002@yahoo.com.

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et al., 2020). This growth pattern is most suited for rapid exploration and colonization of environment for the saprotrophic fungi. Fungi acquire their nutrition by an absorptive mechanism whereby hyphal tubes secrete enzymes which degrade recalcitrant macromolecules outside into smaller absorbable nutrients. Such nutrient 'creation' by fungi enables colonization of the niche by other microbes otherwise incapable of surviving there. Investigating the interactions of fungi with co-occurring microbes in less-studied habitats could reveal novel metabolites of technological use (Zheng et al., 2015).

Many fungi exhibit both sexual and asexual reproduction. In most fungi, the hyphae are multinucleate which are identical due to their mitotic origin; however, mutations could occur during genome duplication resulting in nuclear differences known as heterokaryosis. In such heterokaryons, the less adapted nucleus can disappear due to selection of nuclei supporting a certain trait thus reducing the need for frequent sexual reproduction to eliminate deleterious mutations (Nieuwenhuis and James, 2016). Furthermore, fungi exhibit mitotic recombination (parasexual cycle) which allows them to combine the advantages of both diploid and haploid states at the somatic level. Haploid nuclei in the mycelium fuse to form vegetative diploid nuclei. Diploid nuclei can produce diploid recombinants by mitotic crossing-over and resulting in the production of spores exhibiting better fitness adaptation (Schoustra et al., 2007). Hence, although produced asexually, all the spores of a fungal thallus need not be genetically identical. Many fungi which reproduce asexually are similar to r-selected species and produce numerous spores within a short period of growth. Given the genetic variability among the spores produced due to the parasexual cycle, fungi could adapt to colonize newer habitats. Thus, terrestrial fungi such as *Aspergillus* spp. also occur commonly in different marine substrates (Gonçalves et al., 2022), as endophytes of seaweeds (Suryanarayanan et al., 2010), and in salterns (Suryanarayanan and Ravishankar, 2023); similarly, entomopathogenic (Vega et al., 2008) and plant pathogenic fungi (Suryanarayanan and Murali, 2006) could grow as endophytes. It is not known if such extensive niche switching in these fungi is enabled by genetic variability among them.

4. To motivate fungal conservation

Although conservation of species should not be linked with their uses to humankind, it would be a good strategy to highlight some unique features of fungi that make them attractive candidates for technological use. This is essential to attract resources for conservation exercise and to counter the current pervasive notion that fundamental research is economically wasteful. Interestingly, secondary metabolite genes occur as clusters (Biosynthetic Gene Clusters) in fungi which expand their chemodiversity (Rokas et al., 2020) and makes it easier for genetic manipulation (Hoffmeister and Keller, 2007). Fungal genomes undergo major and rapid changes including gene loss and horizontal gene transfer resulting in the evolution of many phenotypic variants over short evolutionary time scale; this, along with convergent evolution enable fungi to elaborate many novel secondary metabolites (Naranjo-Ortiz and Gabaldón, 2020). The alteration of genotype by environment/habitat is another facet which should encourage conservation of fungi. The endophytic form of a given fungal species has more metabolic gene cluster diversity compare to nonendophyte (Scott et al., 2023). With such attributes and expanding gene manipulation methods (Shi et al., 2024), fungi could contribute to the management current global challenges - evolution and spread of antibiotic resistance among pathogenic microbes, the ever increasing energy demand and the negative effects of climate change on crop production.

Being absorptive heterotrophs, fungi are highly efficient in secreting proteins and have evolved very efficient mechanism of post-translational modification of proteins to regulate the secreted proteins' activities (Wang et al., 2020). Thus, fungi could be cell factories for heterologous protein expression and secretion.

5. An unopened treasure box is as good as not having it

The presence of numerous singletons in environmental DNA samples and in fungal inventories suggests that there are many undiscovered fungal species (Cazabonne et al., 2024). Though loss of habitats, invasion by exotic species, pollution, climate change and anthropogenic changes cause extinction of fungal species, this phenomenon was not focused upon until recently. The International Union for Conservation of Nature (IUCN) Red List of Threatened Species provides a global list of species, their conservation status, distribution, habitat, and threats. It functions as a base for framing conservation policies, to identify protected areas, and decide fund sharing (Lughadha et al., 2020). Though the IUCN started its Red List of Threatened Species in 1964, fungal species were hardly included until 2015 (Mueller et al., 2022); currently, of the more than 166,000 species assessed for Red List, lesser than 850 fungal species have been assessed for this (IUCN, 2024). This is due to 'the paucity of taxonomic, ecological, and distributional data and an initial misconception that a rigorous assessment of the conservation status of fungi was not feasible due to the fact of their unique biology' (Mueller et al., 2022). Furthermore, these lists pertain to macrofungi. Difficulties in methodologies required to effectively interpret the observations is a major hurdle in including microfungi in this list (Mueller et al., 2022). However, new insights into their roles in maintaining the ecology and the potentially technologically exploitable unique genes they carry makes it mandatory that microfungi are given due importance while designing exploration and conservation strategies. Being microbes, it is an immensely difficult process to characterize fungi from various ecological niches. This difficulty can be reduced by focusing on less-studied and extreme environments in tropical and subtropical regions so that fungi possessing unique traits may be captured (Suryanarayanan and Hawksworth, 2005). Though this statement aligns well with ecological findings so far, neither the governments nor the environmental programmes consider fungi which are an integral part of the ecosystem. Furthermore, strict laws prevent scientists from collection of samples from protected areas to study fungi. Apart from modifying laws to permit judicious sample collection from protected areas, government and other agencies which fund research related to conservation, bioeconomy, strategies to manage current health and environmental issues should mandatorily include studies on fungi as a research theme.

Evolution of the fungal genomes was not sudden but involved gene loss, turnover and many large duplication events such that a species defined by traditional taxonomy could house different cryptic species (Ekanayaka et al., 2025). This implies that culture collection centers which store cultures mainly based on traditional taxonomy are inadequate genetic resources. Moreover, most collection centers do not have a query field to search for a particular trait of the cultures thus being of little value to bioprospectors and those interested in applying the fungi to some end utility. Adding traits to cultures is bound to attract international bodies such as the Convention on Biological Diversity (CBD) dedicated to promoting sustainable development to focus attention on fungi. Considering the limited number of biologists interested in fungi and the numerous ecosystems/niches, it is impracticable to increase the number of cultures in the repositories. Here, a crowdsourcing model suggested by Suryanarayanan and Gopalan (2014) and Suryanarayanan (2024) involving students, faculty, research labs and industries could be followed to speed up and reduce the cost of isolating fungi and to increase the genetic resource and bioeconomy of the country. Briefly, college/university students as well as interested non-academic people are trained in isolating fungi from different habitats; after sometime, this exercise would result in a collection of different fungal strains. Since hardly 8 % of the estimated 2.2–3.8 million fungal species are known to science (Hawksworth and Lücking, 2017), this crowdsourcing model would help identifying several new species of fungi in a short time. Additionally, the participants could be trained to do simple bioassays for detecting strains which produce technologically useful

metabolites/enzymes. Such strains could be taken up for more detailed studies by industries for realizing their technological potential. Apart from training students, this model thus could enrich national microbial repositories rapidly at minimum cost.

To conclude, scientists, governments, national and intentional bodies, and voluntary organizations concerned with species conservation, environmental protection and ecosystem restoration should pay special attention to fungi before losing permanently some of them due to the ever increasing anthropogenic impact on environment.

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Declaration of competing interest

I, T. S. Suryanarayanan, declare that there is no conflict of interest.

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