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RESEARCH ARTICLE

HIGHLIGHTS ON AQUATIC FUNGI AND MUSHROOMS ECOLOGY AND BIOTECHNOLOGY, WITH DESCRIPTION OF THE RARELY ISOLATED AQUATIC MUSHROOMSPSATHYRELLA AQUATIC AS A NOVEL TAXON

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ABSTRACT

Mushrooms are macrofungi that exist everywhere around us. Theyhave significant roles in human life as source of nutrition and bioactive compounds. Many aquatic isolatedfungi and mushrooms have been reported as promising biotechnological tools for production of secondary metabolites of various biologically activities. Recently, Psathyrella aquatica has been discovered in Rogue River, Oregon, United States. Psathyrella aquatic represents a novel taxon within the family Psathyrellaceae in the large polyphyletic genus *Psathyrella*, and is considered asthe only reported aquatic gilled mushroom till now. Aquatic gilled mushrooms are especially interesting due to the rareness of Basidiomycetes that can grow underwater. In this review, the ecology, occurrence, of unique aquatic gilled mushroomsare described, and available information about the novel mushroom *P*. aquatica was highlighted.

INTRODUCTION

Fungi have a truly global distribution and can be found across the whole terrestrial biosphere, from bothpolar and hot deserts, to tropical rainforests and estuarine environments. The majority of described fungi inhabit the land (terrestrial) environments, but several fungal species live only in aquatic habitats. The majority of fungi have a saprobic lifestyle and live in either soil or dead organic matter, but many are symbionts of plants, animals, or other fungi, and all fungi have a key role in ecosystem functioning (Elkhateeb and Daba, 2018). Fungi, along with bacteria that are found in soil, are the primary decomposers of organic matter in terrestrial ecosystems.

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The decomposition of dead organisms is a crucial component of ecosystem functioning,returning nutrients to the soil and to theenvironment (Elkhateeb and Daba, 2018; Elkhateeb, 2005; Shearer *et al*., 2007; Zohri *et al*. 2014; Elkhateeb *et al*., 2016).However, fungi may have aquatic origins and indeed the earliest evidence for any fungi have been found in Canada, in strata representing estuarine environments and dated to1–0.9-billion years old. These earliest microfossils have been assigned to the species *Ourasphaira giraldae*and suggest an occurrence in estuarine settings although the fungus may also have been transported from land or deeper marine environments (Loron *et al.* 2019). Today, marine fungi appear ubiquitous and have been found in almost every habit that has been checked: from hydrothermal vents to deep sea sediments and arctic sea ice (Gladfelter *et al*. 2019). Marine fungi even infect primary producers, such as diatoms, and may be an important component of the global carbon cycle. Perhaps as little of 1% of marine fungi have been identified but of these (aside from yeasts), many marine fungal species belong to

Ascomycotina, Basidiomycotina, Mastigomycotina (zoosporic fungi), Deuteromycotina, and some Zygomycotina (Kohlmeyer, 1984; Richards *et al*. 2012; Kohlmeyer and Kohlmeyer, 2013; Gladfelter *et al*. 2019). Whether many marine fungi are truly amphibious is an unanswered question and indeed, many fungi can be found in habitats both above and below the high tide line. However there is evidence for, and an expectation that, some species may exist in water for their whole life-cycle, during a single stage of their life-cycle, or as a truly amphibious(Amend *et al*. 2019; Grossart *et al*. 2019). Indeed some fungi, identified as marine through detection of DNA, may actually be terrestrial and have arrived in an aquatic environment by wind or by flood water (Dix and Webster, 1995). In this review, an overview about mushrooms, aquatic fungi in general, and aquatic mushrooms in particular are detailed, and the ecology and occurrence of the unique rarely isolated aquatic gilled mushroomsare highlighted.

Mushrooms: Mushrooms are the epigeous fruiting bodies of terrestrial fungi and as they lack cellulose and chlorophyll, they have a different lifestyle to other nonmotile life, such as plants. The inability to produce sugars through photosynthesis, creates a dependency onother plants or animals, either live or deceased, for the acquisition of nutrition. We usually only see a the above-ground parts of mushrooms –often liken to the shape of a tree or umbrella, although fruiting structures come in a whole plethora of shapes, colours and sizes. The most famous mushroom shapeis an umbrella-like structure appearing as a stem (stipe), carrying above it a cap (pileus), which carry the mushroom spores (Sridhar, 2020). The bulk of the fungi that gives rise to the mushroom is often dispersed over a relatively large area. Mushroom producing fungibelong to Basidiomycetes and Ascomycetes, including edible and non-edible species, and some mushroom fruiting body produces basidiospores at the tip of club like structures called basidia, which are arranged along the gills of the mushroom (Elkhateeb *et al*. 2019a; Elkhateeb, 2020; Elkhateeb and Daba, 2020; Kamalakannan *et al*. 2020). Mushrooms have been documented for centuries as use as food and medicine as they are generous sources of nutrients and biologically-active compounds that have various applications in agriculture, food, pharmaceuticals, cosmetics, andfood-related industries, amongst others(Cheung, 2010; Ali El-Hagrassi *et al*. 2020; Daba *et al*. 2020). Mushroom obtain their nutrition through being saprotrophs, parasites, or symbionts such as mycorrhiza. Mushrooms arethe reproductive phase (fruiting bodies) but they there is also a vegetative phase to these fungi (mycelia). Edible mushrooms areoften low in calories and can be healthy sources of proteins, flavonoids, metals, amino acids, minerals, volatile oils, carotenoids fats, phenolic compounds, and different vitamins and ergosterol that can be used as a source for vitamin D2 (Hobbs, 2002; Rathee *et al*. 2012; Ma *et al*. 2013; Xu and Beelman, 2015). Moreover, mushrooms have a long history of safe use in traditional Asian medicine for the treatment of different diseases (Halpern, 2007; Rahi and Malik, 2016; Elkhateeb *et al*. 2019b; Elkhateeb *et al*. 2020). Mushroom production is often observed as land-efficient and does not require high-value agricultural land and can be done on waste and unproductive land. Utilizing indoor cultivation methods, one can exploit vertical space for higher productivity. Agricultural/forest waste can be used as a substrate to produce quality food through mushroom production. Their legendary effects on promoting good health and vitality and increasing our body's adaptive abilities have been supported by recent studies.

The diversity of compounds extracted from mushrooms has attracted attention as a mine for novel compounds. Some compounds they contain have been classified as Host Defence Potentiators (HDP) which can have immune system enhancement properties(De Silva *et al*. 2013; Kamalakannan *et al*. 2020).Various compounds are responsible for different therapeutic activities of many mushrooms genera. Various biological activities have been reported such as anticancer, anti-inflammatory, hypoglycemic, antimicrobial, antioxidant, immunomodulatory, antiviral, hepatoprotective, anti-neurodegenerative, antiangiogenic, and hypocholesterolemic activities (Choi *et al*. 2010; Patel and Goyal, 2012; Sánchez, 2017; Elkhateeb *et al*. 2018).

Aquatic fungi: Freshwater fungiare commonly represented in genera belonging to Oomycota and Chytridiomycota, in addition tothe anamorphic forms of some Ascomycota and Basidiomycota (aquatic hyphomycetes) (Shearer *et al*. 2007; Shearer *et al*. 2004). Aquatic fungi are microscopic organisms with mostly mycelial growth and hyphae developing on or within the, typically submerged, organic substrates of plant or animal origin. Occupant aquatic fungi are able to complete their whole life cycle in freshwater and often have special adaptations for growth, sporulation, and dispersal in aquatic environments(Manoharachary *et al*. 2005). Hyde *et al*., (2007) have estimated that there are approximately 1.5 million fungal species on earth. Of these, only around 3000 species are known to be associated with aquatic habitats and only 465 species occur in marine waters. However, perhaps less than 1% of aquatic fungi have yet been discovered. Aquatic fungi are usually microscopic organisms, which usually do not produce visible fruiting bodies but grow asexually (anamorphic fungi) (Ali and Abdel–Raheem, 2003; Gulis *et al*. 2009).

Aquatic fungi play key roles in aquatic ecosystems and in transition zones these may be similar to terrestrial fungi, such as nutrient cycling and the degradation of organic compounds alongside symbiotic associations with semi-aquatic plants. Elsewhere, from coral reefs to deep sea sediments, the function is less well understood but certainly fungi in these habitats have numerous and complex roles from the degradation of organic compounds to pathological associations with a range of organisms from mammals to algae. In the latter example, this pathogenesis may be a critical component of nutrient cycling within marine habitats (Gladfelter *et al*. 2019). Of topical interest is the fact that marine fungi may also represent a source fornovel secondary metabolites of specificmedical, industrial, or agricultural interest. Although most interest is focused around the identification of novel antibiotic or anticancer compounds, these fungi also appear to have the potential to contribute to bioremediation of different forms of pollutants in wastewaters and potentially even in the degradation of plastics which has the potential to address some of the greatest issues in the earths oceans(Zhang *et al*. 2015; Kan *et al*. 2015).Definitely fungi represent an important component of aquatic microbiota. Microbial ecologists are just starting to understand the contributions of aquatic fungi to biodiversity, ecosystem functions and services but there is much that remains unexplored(Ba¨rlocher and Boddy, 2016). Marine fungi can exist on sand grains, plankton, alae, sediments, plastisphere, and as mentioned before on estuarine plants and submerged wood (Kohlmeyer and Kohlmeyer, 1979; Jones, 2011; Overy *et al*. 2019). The submerged wood is usually a favourable environment for the growth of genera belonging to the family Halosphaeriaceae, and orders

Torpedosporales, and Lulworthiales exclusively in open oceans areas (Jones, 1995). Generally, marine fungi have developed several adaptation mechanisms to protect and succeed in dispersing their spores in such environment. One of the strategies is the absence of the central long necks in the ascomata of arenicolous marine fungi. Also, the ascospores are usually found trapped in sea foam. On the other hand, ascomata growing on submerged wood are found partly or completely immersed within the substrata (Kohlmeyer and Kohlmeyer, 1979). Furthermore, many ascomycotal fungi release their spores during low tide periods, which rest on the ascomata and become washed off into the water at the period of high tide. The produced ascospores are often with gelatinous sheaths (Dothideomycetes), appendages (Sordariomycetes), or, in some species, both to assist in attaching the spores to substrata (Jones, 2011). Similarly, ways of adaptation applied on some conidia (asexual spores) include being branched, ornamented, or extremely long in size in order to help in floatation and dispersal (Overy *et al*. 2014a). It should be noted that aquatic fungi represent a generous source for natural products existing mostly in their secondary metabolites. Genome mining was used to reveal the biosynthetic potentials of many marine members of ascomycetes, basidiomycetes, and Zoopagomycetes, and as a result they were nominated as rich sources of secondary metabolite (Arvas *et al*. 2007; Lackner *et al*. 2012).

Aquatic fungi as biotechnological tools for production of bioactive compounds: Till 2002, about 272 compounds originated from marine fungi were discovered, and characterized (Bugni and Ireland 2004; Overy *et al*. 2014b). After that, a dramatic increase in the number of discovered natural compounds took place to record over 1000 novel secondary metabolites, thanks to the development of extraction and identification techniques (Rateb and Ebel, 2011). Some of the natural compounds originated from marine ascomycetous fungi are aigialomycins A–G, aigialospirol and associated derivatives, and aigialone produced by an isolate of Aigialus parvus (Kohlmeyer *et al*. 1985; Alias *et al*. 1995; Tan *et al*. 1995; Isaka *et al*. 2002; Vongvilai *et al*. 2004; Isaka *et al*. 2009). Similarly, three new lipodepsipeptides, five new macrocyclic polyethers, and five new linear polyesters were produced by the marine ascomycete, Halorosellinia oceanica (syn. Hypoxylon oceanicum) (Abbanat *et al*. 1998). Alternaria alternata isolated from the soft coral Litophyton arboreum tissues was the source of 5 novel secondary metabolites (alternariol9methyl ether 3Osulphate, alternariol9methyl ether, alternariol, maculosin and maculosin5). Moreover, such compounds showed promising natural antimicrobial and anticancer activities besides a potent inhibitory effect against HCV NS3NS4A protease (Hawas *et al*. 2015; Hawas *et al*. 2016).

Zofimarin, the potent antifungal sordarin derivative was produced by an isolate of the marine fungus Zopfiella marina (Ogita *et al*. 1987; Konda *et al*. 1987). Recently, analogs and sordarin-inspired scaffolds are under in vivo investigations for their effectiveness against wide spectrum of susceptible pathogens (Chakraborty *et al*. 2016; Wu and Dockendorff, 2018). On the other hand, Aspergillus versicolor XZ-4 isolated from a Taiwan hydrothermal vent crab was the source of different metabolites as versicomides A–D, and the cyclopenin derivatives: 7-methoxycyclopeptin, 7-methoxydehydrocyclopeptin, 7-methoxycyclopenin, and 9-hydroxy-3-methoxyviridicatin (Pan *et al*. 2017).

The marine fungus, Phaeosphaeria spartinae isolated from the inner tissues of the marine alga, *Ceramium* sp., produced eight novel natural products including spartinoxide and spartinol C, which showed inhibition action on the human leukocyte elastase, and cystic fibrosis (Elsebai *et al*. 2009; Elsebai *et al*. 2010). Marine Asperigilli were reported as promising sources of biologically active metabolites. Preussins C-K produced by *Aspergillus flocculosus* 16D-1 showed antiinflammatory activity against Interleukin 16 (IL-16) (Gu *et al*. 2018). Asperversiamides B, C, F, G originated from *Aspergillus versicolor* exhibited activity against Inducible nitric oxide synthase **(**Li *et al*. 2018**).** Luteoride E; Lovastatin; Versicolactone G; Territrem A;Brasilanone A; Brasilanone E; and Methyl 3,4,5-trimethoxy-2- (2-(nicotinamido) benzamido)benzoate produced individually by two different **A.** terrus marine isolate exerted activity against **NO (**Liu *et al*. 2018; Wu *et al*. 2018**).** Moreover, several antiinflammatory compounds were identified from different Asperigillus Sp. such as Dihydrobipolaroxins B−D; Dihydrobipolaroxin; Aspertetranones A−D; Diorcinol; Cordyol C; and 3,7-dihydroxy-1,9- Dimethyldibenzofuran (Wang *et al*. 2015; Tian *et al*. 2015; Wang *et al*. 2016). Similarly, many marine originated species belonging to the genus Penicillium showed produced various compounds having promising biological activities such as methylpenicinoline; Citrinin H1; Penicillinolide A; Penstyrylpyrone; Chrysamide C; Viridicaol; Brevicompanines E and F (Lee *et al*. 2013a; Lee *et al*. 2013b; Chen *et al*., 2016; Ngan *et al*., 2017). Different other marine fungi were reported as producers of bioactive compounds including for example *Eurotium* Sp.; *Graphostroma* Sp.; *Chondrostereum* Sp.; *Hypocreales* Sp.; Phoma Sp.; *Acremonium* Sp.; and *Alternaria* Sp. (Belofsky *et al*. 2000; Kyoung-Su *et al*. 2013; Hong *et al*. 2013; Chen *et al*. 2015; Ko *et al*. 2016; Hsiao *et al*. 2017; Niu *et al*. 2018).

Aquatic gilled mushroomsas example of adaptation to the aquatic environment: Previously it has been observed that some aquatic ascomycetous fungi can form fruiting bodies on submerged wood and this has been noted in freshwater systems in Japan, Thailand and Costa Rica (Minoura and Muroi 1978, Pinruan *et al* 2004, Ferrer *et al* 2008).However, a recently discovered species of aquatic gilled mushrooms known as Psathyrella aquatic (Fig. 1), was describedin the mid-2000s and one of only a fewknown aquatic gilled fungi. The discovery is traced back to 2005, when researchers from Southern Oregon University, stumbled upon the mushrooms in the Rogue River, by chance. The appearance of a submerged and gilledBasidiomycetes, was unexpected and it appears that this structure in an aquatic environment is quite rare. The majority of underwater fungal species are members of Ascomycetes or Hypomycetes. The fruiting bodies of P.aquatica were found underwater and are usually growing on wood as a substrate, existing submerged in the water rather than the substrate of the water bed(Frank *et al*. 2010). The aquatic gilled mushrooms from southern Oregon appear to represent a novel taxon within the Psathyrellaceae in the large polyphyletic genus *Psathyrella*(Padamsee *et al*. 2008). Other Ascomycota fruit on submerged wood in lakes in Japan, Thailand and Costa Rica (Pinruan *et al*. 2004; Ferrer *et al*. 2008). However**,** P.aquatica is not the only species to form mushroom-like fruiting structures underwater. Another basidiomycete, this time with a smooth hymenium, *Gloiocephala aquatica* Desjardin, Martinez-Peck & Rajchenberg, that forms submerged basidiocarps has been reported from lakes and ponds in southern Argentina

(Desjardin *et al*. 1995). Basidiocarps of 11 species of homobasidiomycetes occur in marine ecosystems (Hibbett and Binder, 2001; Larsson and Örstadius, 2008; Jones, 2000).

***Psathyrella aquatic* (Frank *et al*. 2010) as a novel aquatic gilled mushroom taxon:** The precise description of that *Psathyrella aquatica* was havingbasidiomata 4.5–10 cm alta, immersa. Pileus 0.8–1.5 cm latus, brunneolus vel brunneigriseus. Basidioporae ellipsoideae, leves, brunneae, 10–14 × 6–8 µm, poro germinali. Cystidia hymeniales: cheilocystidia pleurocystidiaque similaria, ventricosa, 25–45 × 10–18 µm. Lamellae adnatae. Stipes textura porrecta.

***Psathyrella aquatica* macromorphology:** Basidiomata immersed, 4.5–10 cm tall; pileus 0.8–1.5 cm diam, broadly parabolic to campanulate, light brown to brownish gray, sometimes with central orange-brown disk, sometimes mottled or striate, smooth, hygrophanous; pileus context thin above gills, light tan to orange-brown; odor not distinctive; lamellae adnate, thin, light tan, densely speckled with dark brown spores, extending to pileus margin, lamellulae in two ranks and extending from one-half to one-fourth of the radius; stipe 4.0–9.5 cm long, diameter expanding from 1.0–2.2 mm at apex to 1.8–3.2 mm at base, white to pale yellow, hollow, lacking annulus, fibrous, surface fibrillose covered with wefty white to gray-white mycelium, and with cottony rhizomorphs and mycelial tomentum emanating from base.

Fig. 1. Psathyrella aquatica **taken by Jonathan Frank, Locality, Jackson, upper Rogue river, Oregon, United States, hosted by http://mycoportal.org)**

***Psathyrella aquatica* micromorphogy:** Basidiospores 10–14 × 6–8 µm, ave. 12.3 × 6.9 µm, elliptical with a germ pore, smooth, dark reddish brown in water and in Melzer's, fading to gray-brown in KOH and to lilac in H_2SO_4, spore print purple-black; basidia 4-spored, clavate, 32–40 × 10–13 µm, hyaline; cheilocystidia 25–45 × 10–18 µm ventricose, apex subacute to elongate, thin walled, colourless, hyaline; pleurocystidia 25–40 × 10–13 µm, ventricose, apex subacute, scattered, thin-walled, colourless, hyaline; caulocystidia 32–40 × 10– 13 µm, cylindrical to ventricose, in fascicles, apex obtuse; pileipellis cellular, suprapellis a single layer of spherical to isodiametric, inflated cells, 25–35 µm diam, on 30–50 × 3–5 µm peduncles that extend into the pileus trama, clamp connections absent; pileus trama thin-walled hyphae 8– 15 µm diam, interwoven; stipe hyphae 35–70 × 8–14 µm, parallel; clamp connections present in mycelium at stipe base, absent elsewhere.Because the mycelium of Psathyrella aquatica inhabits river substrates, the fruiting body of the mushroom is fully submerged under the water. This leads scientists to speculate about how the spores of this underwater mushroom are dispersed.

Conclusion

Fungi are found everywhere on earth where there exists a carbon and water source.From ancient caves, to polar deserts, tropical rainforests, and also in saline and freshwater aquatic environments. Discovering rare mushrooms in unusual environments such as saline habitats can change our ideas about the capabilities of fungi to withstand and exist in different systems and under different pressure. Moreover, such rarely isolated mushrooms can represent unique sources for novel metabolites that may contribute in treatment of currently untreated diseases or have other promising applications that help in serving humanity.

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