EXPLORING MYCELIUM-BASED BIOMATERIALS: DEVELOPMENT FROM SELECTED MUSHROOMS AND LOCALLY LIGNOCELLULOSIC SUBSTRATES IN THAILAND

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DOCTOR OF PHILOSOPHY
IN
BIOLOGICAL SCIENCE

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THIS DISSERTATION IS A PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN BIOLOGICAL SCIENCE

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ABSTRACT

Mushroom mycelium-based biomaterials (MMBs) are sustainable alternatives to plastic- and foam-based materials and align with the principles of the circular economy. MMBs are developed using the mycelium of suitable fungal species and lignocellulosic substrates, derived from agricultural and forest by-products. This study has provided the first worldwide checklist of all fungal species within Basidiomycota, utilised in MMBs production and investigation, based on all the relevant published and available articles till 2024. The mushroom genera used in its development have also been presented according to hyphal system type. This study has summarised the wide range of MMB applications, mainly packaging, building, insulation, architectural designs, and leather. Additionally, it highlights key challenges in the MMB sector and explores potential solutions.

In this study, 15 fungal strains, *Coriolopsis brunneoleuca* (MFLUCC 24-0265), *Earliella scabrosa* (MFLUCC 24-0263), *Earliella scabrosa* (MFLUCC 24-0268), *Ganoderma australe* (MFLUCC 24-0262), *Ganoderma tropicum* (MFLUCC 24-0267), *Hexagonia tenuis* (MFLUCC 24-0266), *Hexagonia tenuis* (MFLUCC 24-0270), *Lentinus squarrosulus* (MFLUCC 24-0271), *Microporus xanthopus* (MFLUCC 24-0261), *Panus ciliatus* (MFLUCC 25-0173), *P. subfasciatus* (MFLUCC 25-0172), *Phlebiopsis friesii* (MFLUCC 24-0323), *Pleurotus ostreatus* (MFLUCC 24-0260), *Trametes polyzona* (MFLUCC 24-0269), and *Trametes sanguinea* (MFLUCC 24-0264), were used to develop MMB test samples. The fungal strains were identified through a combination of morphological characteristics and

phylogenetic analyses. MMB samples developed using mycelia of these species and locally-sourced rubber sawdust were comprehensively characterised for their physical, mechanical, hydrodynamic, and chemical properties. Additional analyses included FTIR spectroscopy, SEM analysis, thermogravimetric analysis, flammability testing, and soil burial degradability. Notably, Ashby's chart of mechanical properties showed the MMB could substitute synthetic foam. Soil burial of MMB for 90 days shows cumulative weight loss exceeding 60%, proving biodegradable. A new approach for mycelial viability maintenance is described and verified, addressing the challenge of maintaining vigorous mycelium. Notably, this study presents the first comprehensive report on the application of *Coriolopsis brunneoleuca*, *Ganoderma tropicum*, *Hexagonia tenuis*, *Microporus xanthopus*, *Panus ciliatus*, *P. subfasciatus*, *Phlebiopsis friesii*, *Trametes polyzona*, and *T. sanguinea* in MMB development, characterisation, and prototype development. Based on the material properties and successfully developed prototypes, the MMBs are potentially suitable for packaging, indoor use, construction, and insulation purposes, as an alternative to conventional synthetic materials. This study also reports three new fungal species, *Echinochaete thailandica*, *Phanerochaete brunneohyha*, and *Thelephora chiangmaiensis*, and four new geographical records, *Favolaschia variistipitata*, *Panus ciliatus*, *Podoscypha gillessi*, and *Trullella yunnanensis*, based on morphological characteristics and phylogenetic analyses (ITS and LSU).

This study provides an illustrated Fungalpedia, a compendium of fungi, fungus-like taxa that provide outlines and notes of genera and higher taxa, their applications, terminology, and definitions of terms used in mycology. It is published as a series. This study includes two sections: notes on 111 Basidiomycota genera and notes on 55 terminologies related to mushroom mycelium-based biomaterials. The remaining genera will be documented in further publications. Fungal genera and higher taxa entries comprise information on habit and habitat, classification, distinguishing morphological characteristics, genetic markers used, critical analysis of taxonomic placement, beneficial roles to humans and nature, and clarify discrepancies in the main fungal classification and nomenclature databases. Additionally, brief notes on fungal families related to the genera are provided. Line drawings of morphological

characters of all genera, except for a few that are unavailable, are provided with each entry to aid understanding. Notably, this study includes the first compilation of notes on terms commonly used in the mushroom mycelium-based biomaterials sector, featuring their definition, implications, and necessary diagrams. This effort contributes to the integration of mycology and mycelium-based biomaterials as innovative and sustainable materials.

Keywords: *Agaricomycetes*, Circular Economy, Fungal Application, Fungal Genera, Global Checklist, Hyphal System, Mushroom Species, Mycelium-Based Biomaterials, New Geographical Record, Phylogeny, New Species, Saprophytic Fungi, Sustainable Development, Taxonomy, White-rot

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ABBREVIATIONS AND SYMBOLS

%	percentage
=	heterotypic (taxonomic, facultative) a synonym
×	Magnification
≡	homotypic (nomenclatural, obligate), a synonym
°C	degree centigrade
µg	microgram
µl	microliter
µm	micrometer
BLAST	Basic Level Alignment Search Tool
cm	centimeter
diam.	diameter
e.g.	for example
et al.	et alia; and others
etc.	et cetera; and others
FAO	Food and Agriculture Organization
Fig.	Figure
gen.	genus/genera
h	hour
i.e.	that is
KOH	Potassium Hydroxide
MEGA	Molecular and Evolutionary Genetics Analysis
mg	milligram
min	minute
ML	Maximum Likelihood
mm	millimetre
NCBI	National Center for Biotechnology Information
No.	Number
nov.	novem (Latin for new thing)

ABBREVIATIONS AND SYMBOLS

PCR	Polymerase Chain Reaction
PP	Posterior Probabilities
RAxML	Randomized Axelerated Maximum Likelihood
SK	Sabin Khyaju
sp.	species
spp.	species (plural)
viz.	that is
vs.	versus
$\bar{x}$	average

CHAPTER 1

INTRODUCTION

1.1 Background of Mushroom Mycelium-Based Biomaterials

The world population is increasing rapidly, with a current population of 7.7 billion in 2019 from 6.8 billion in 2009 and an estimated 9.7 billion by 2050 (Maraveas, 2020). According to United Nations projects (2018), it is anticipated that by the year 2050, approximately 68% of the global population will reside in urban areas (www.un.org, accessed January 25, 2024). Annual waste generation is anticipated to escalate to 2.2 billion tons by 2025 and reach an imposing 3.40 billion tons by 2050, which implies that annual waste will increase to 2.2 billion tons by 2025 and a staggering 3.40 billion tons by 2050 (Chattopadhyay et al., 2008; Hoornweg & Bhada-Tat, 2012; Alemu et al., 2022a). According to the escalating waste landscape, synthetic plastics, which are non-biodegradable, have emerged as a significant source of environmental pollution (Holt et al., 2012; Lin et al., 2017). These plastic products are predominantly sourced from finite natural resources, posing sustainability challenges and obstructing the shift towards a circular economy. The manufacturing processes of extruded polystyrene and expanded polyethylene foams are sourced from petroleum-based origins, which involve significant energy consumption. So, the limited and non-renewable petroleum sources direct the world towards crises. There are substantial risks to human health, underscoring the pressing requirement for sustainable waste management solutions (Lopez Nava et al., 2016).

The rapidly growing population has increased the demand for food, leading to the generation of elevated agricultural by-products (Muchovej & Pacovsky, 1997). Global agricultural waste is estimated to increase to 2.2 billion tons annually by 2025 (Mulat et al., 2019). The by-product of one crop holds the potential to become a valuable asset for

another industry, facilitating the creation of sought-after products. Using agricultural waste as a construction material promises to substantially impact the release of greenhouse gas emissions into the atmosphere (Abhijith et al., 2018). Utilising biomaterials derived from mycelium and organic substrates exhibits favourable attributes for industrial applications. This implementation could revolutionise the linear economic paradigm, altering the current production and disposal model towards a circular economy. Mycelium-based biomaterials present an eco-friendly substitute for conventional materials, promote sustainability, and have the potential to biodegrade (Abhijith et al., 2018).

Mycelium-based biomaterials are safe for users. An alternative product, utilising mushroom mycelium, has emerged through advancements in science and research. Biomaterials derived from renewable mushroom mycelium offer a multitude of advantages, including energy-efficient production, cost-effectiveness, complete biodegradability, recyclability, potential for carbon dioxide sequestration, sustainable sourcing, lightweight characteristics, low density, robust strength, non-toxic properties, and remarkable suitability for the packaging and construction industries (Jiang et al., 2017; Abhijith et al., 2018; Islam et al., 2018; Fairus et al., 2022). Recently, the packaging industry has experienced a surge in market demand. Attias et al. (2019) reported that some primary materials are manufactured at an industrial scale by three leading companies: Ecovative Design LLC (www.ecovativedesign.com), Mycoworks Inc. (www.mycoworks.com), and Mogu (https://www.mogu.bio/). Jones et al. (2020) reported that the raw material cost of mycelium composites was assessed, demonstrating a production cost range. The cost is notably lower than the wholesale price of polystyrene, such as polystyrene (2.1–2.3 $US.kg^{-1}$), polyurethane (8.2–10.4 $US.kg^{-1}$), phenolic formaldehyde resin (1.7–1.9 $US.kg^{-1}$), foams and plywood (0.5–1.1 $US.kg^{-1}$), softwood (0.7–1.4 $US.kg^{-1}$), and hardwood (3–11 $US.kg^{-1}$) products.

Mushrooms are the fruiting bodies of fungi that grow above ground or on a substrate, primarily belonging to the phylum Basidiomycota. They include gilled fungi,

puffballs, bracket fungi, coral fungi, jelly fungi, and crust fungi (Rathore et al., 2019). Since ancient times, mushrooms have been widely used in food, medicine, and the extraction of secondary compounds (Rathore et al., 2019). They are an important source of bioactive and medicinal compounds, such as terpenoids, polysaccharides, proteins, and vitamins, and are known for their antioxidant, antimicrobial, anticancer, antitumor, and immunomodulatory properties. Among several applications of mushrooms, mushroom mycelium-based biomaterials (MMBs) are a novel class of sustainable, eco-friendly, and biodegradable materials.

Mycelium is a vegetative part of filamentous fungi composed of hyphae, which act as unit-binding agents among hyphae and between hyphae and substrates. It is a bonding agent or natural binder for bio-composite materials (Jiang et al., 2016; Abhijith et al., 2018). The mycelium binds with the fibrous inner core and the outer surface of the organic substrates to form a composite, which forms a compact layer termed fungal skin (Appels et al., 2019; Elsacker et al., 2020; Atiwesh et al., 2021). This distinctive hypha property is observed before transferring the mycelium-substrate mixture into the mould during bio-composite preparation. Based on the structure of mushroom mycelium, they are categorised into monomitic, dimitic, or trimitic hyphal systems comprised of generative, binding, and skeletal hyphae, which are distinguished by variations in cell wall thickness, internal structure, and branching characteristics (Jones et al., 2020). Numerous contemporary studies underscore the significance of wood-decaying mushrooms, primarily *Ganoderma*, *Pleurotus*, and *Trametes*, as essential components in the advancement of mushroom mycelium-based biomaterials (Aiduang et al., 2022a). Mycelium works as a stabilising compound for the fibres of the agricultural substrate (Almpani-Lekka et al., 2021). However, to achieve significant or dense mycelial growth with higher mechanical strength on substrates, mushrooms characterised by a trimitic hyphal system are preferred over monomitic or dimitic (Porter et al., 2023). Mycelium density, mycelium structure, and growth rate are important criteria for mushroom

species selection for biomaterial preparation (Alemu et al., 2022a). In terms of tensile strength performance, biomaterials derived from trimitic fungal species exhibit superior flexural strength (Butu et al., 2020; Manan et al., 2021; Aiduang et al., 2022b). The basic method of mushroom mycelium-based biomaterials is illustrated in Figure 1.1.

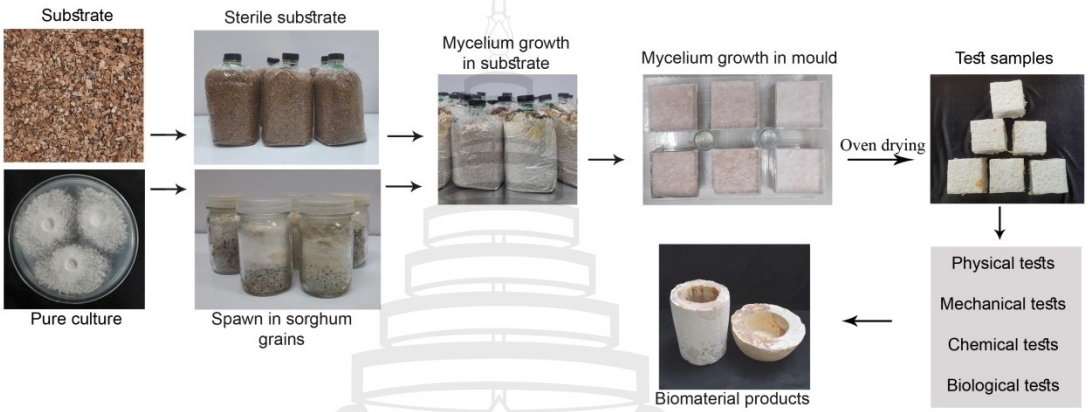


Figure 1.1 Overview of the preparation of mushroom mycelium-based biomaterials

1.2 Applications of Mycelium-Based Biomaterials

The utilisation of mushroom mycelium has expanded to a commercial scale across various industries (Dessi-Olive, 2022a). Mushroom mycelium-based biomaterial products have been successfully applied in several products, such as packaging, architectural and design work, building materials, thermal insulation materials, textiles, and leather (Joshi et al., 2020) (Figure 1.2). Mycelium-based biomaterials have been a miracle for the new era, suffering from non-degradable and non-sustainable products. Mushroom mycelium-based biomaterials are non-toxic and safe, offering a sustainable alternative to environmentally harmful, synthetic, and non-renewable plastics (Răut et al., 2021). The demand for mushroom mycelium-based biomaterials, along with their research and invention, is rising alarmingly. It is necessary to compile all recent updates on the applications of mushroom mycelium-based biomaterials. This review mainly comprises diverse uses of

mycelium-based bio-composites, based on recently published articles, focused on the following five main areas.

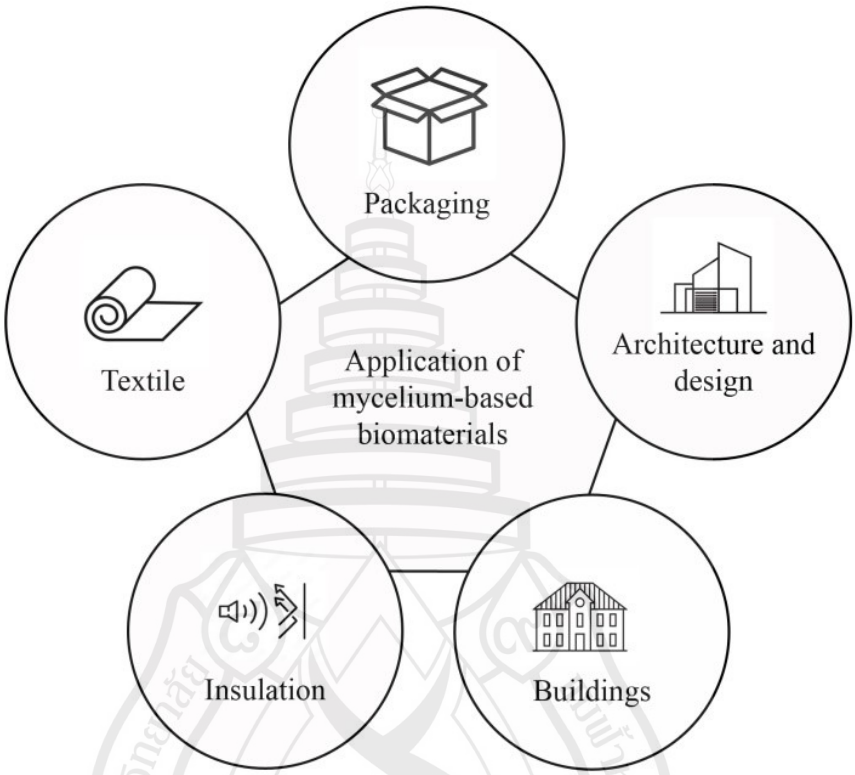


Figure 1.2 Application of mushroom mycelium-based biomaterials

1.2.1 Application of Mycelium-Based Packaging Products

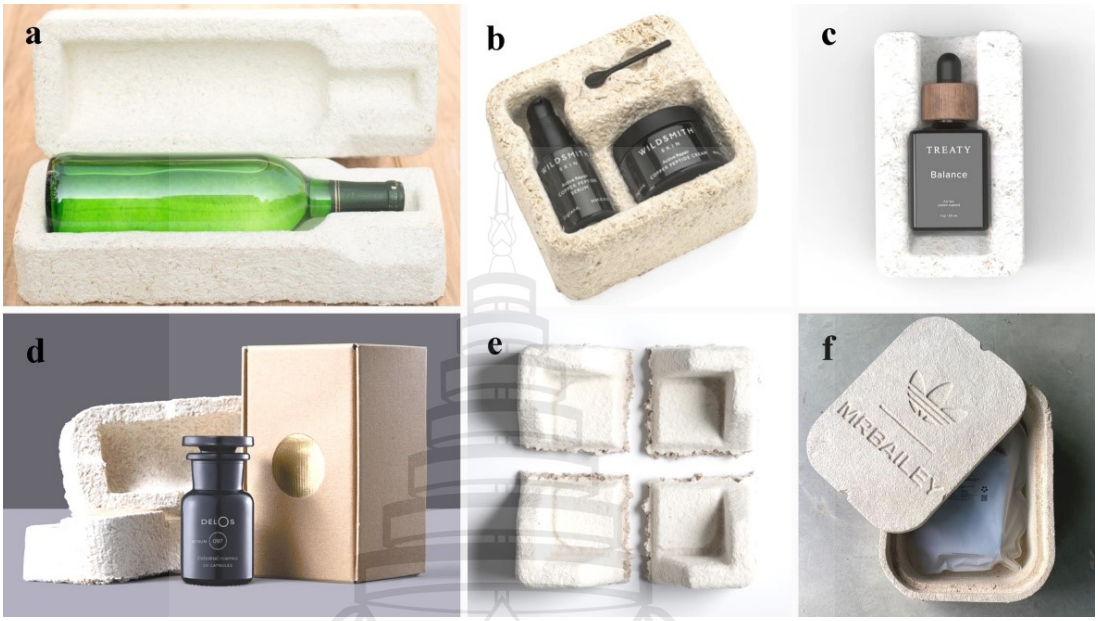
The utilisation of mushroom mycelium in packaging materials is a significant step toward sustainable practices, offering a biodegradable alternative to traditional plastics (Abhijith et al., 2018) (Figure 1.3). Mushroom mycelium-based packaging addresses environmental concerns, with its rapid growth, natural adhesiveness, and biodegradable properties providing a compelling solution to conventional packaging waste issues (Iordache et al., 2018; Kim & Ruedy, 2019). Research explores the potential of mycelium-based packaging in creating biocomposite materials as a viable alternative to traditional packaging (Abhijith et al., 2018; Vandelook et al., 2021). Polystyrene, or Styrofoam, is a major component in petroleum-based synthetic packaging products, which

pile up as pollutants in the environment (Abhijith et al., 2018). Most of the physical and mechanical properties of mushroom mycelium-based biomaterials showed similarity with polyimide and polystyrene foams (Aiduang et al., 2022c). With comparable mechanical strength to synthetic materials, mycelium-based packaging decomposes naturally, reducing non-biodegradable waste and aligning with consumer and corporate sustainability goals.

Sustainable packaging products have been in demand in the current context relating to environmental issues. Abhijith et al. (2018) reported that one-third of consumers favour environmentally labelled packaging. Biomaterials decompose faster through mushroom mycelium than plastic products. Mushroom mycelium-based biomaterials prepared from *Trametes versicolor* grown on hardwood chips and hemp on composting decomposed up to 70% after four months and were completely biodegradable (Zimele et al., 2020; Aiduang et al., 2022c). Plastic packaging has an extended degradation period, with plastic grocery bags taking 10–20 years, plastic sandwich bags requiring up to 1000 years, plastic straws (100–500 years), plastic bottles (450 years), disposable diapers (450 years), plastic coffee pods (150–500 years), and styrofoam cups (50 years) (Asore, 2021). Mushroom mycelium-based packaging products were guaranteed to be 100% biodegradable and renewable materials to reduce waste (Asore 2021).

Major corporations such as Dell, IKEA, and Ecovative Design have already integrated mushroom mycelium-based biomaterials into their products (Iordache et al., 2018). Specifically, Ecovative Design has demonstrated the EcoCradle^{TM}, a line of mushroom mycelium-based packaging products that serve as a sustainable substitute for expanded polystyrene (Holt et al., 2012; Vandelook et al., 2021). Dell Company has a larger plan to incorporate mushroom mycelium products as packaging for sustainable shipping purposes (Abhijith et al., 2018). Additionally, Rajendran (2022) reported that Ford Motor Company has decided to include mycelium-based foam in automotive parts. Mycelium Solutions Company is actively producing mycelium-based packaging materials

(Iordache et al., 2018). Consequently, mushroom mycelium-based packaging materials are emerging as the superior alternative in various industries.



Note a–d Cushioning packaging. e Breakaway corners. f Shoebox.

Source a, c, e Ecovative (2024), b Vandelook et al. (2021), d Hemptrain (2024), f MrBailey and Adidas (2024).

Figure 1.3 Packaging products using mushroom mycelium-based biomaterial

1.2.2 Application of Mycelium-Based for Architectural Works and Design

The non-degradable plastic products used in architecture and design have resulted in pollution in the environment (Oral et al., 2022). Almpani-Lekka et al. (2021) reported the potential use of fungal biomaterials in architectural works and design for the last ten years (Figure 1.4). New techniques such as laser cutting and hot and cold compression are used to get the desired shapes and structures of materials. Fibrous woven scaffolds are useful for growing large-scale mycelium structures (Özlü & Nicholas, 2021). The development of myco-material applications in architectural works and designs has been extensively used, and some of them are briefly presented here. Subsequently, numerous experiments have been undertaken to explore diverse architectural designs in this innovative field.

Various pioneering projects highlight the versatility of mycelium in architecture. For example, the Company New Heroes constructed the Growing Pavilion, which utilised biomaterial coatings to enhance water resistance (Almpani-Lekka et al., 2021). David Benjamin employed approximately 10,000 mycelium blocks to create the Hy-Fi pavilion (Almpani-Lekka et al., 2021). Block Research Group designed the MycoTree Pavilion, focusing on interior installations. The Shell Mycelium, designed by Studio Beetles 3.3 and Yassin Arredia Design, allowed on-site cultivation of the mycelium-substrate mixture (Almpani-Lekka et al., 2021). Phil Ross introduced Mycotectural Alpha, marking the inaugural architectural design showcased at Kunsthalle Düsseldorf (Modanloo et al., 2021). In Frankfurt, Germany, the Myco space 2021 by MT-CO-X was a collaborative project with dimensions of 5.2 × 6.0 × 3.0 m^3 (Almpani-Lekka et al., 2021). The El Monolito Micelio, designed by the Georgia Institute of Technology School of Architecture, featured vault-formed monolithic castings using 800 kg of mycelium-substrate composite mixture (Almpani-Lekka et al., 2021).

Moreover, the utilisation of myco-materials in 3D printing techniques has emerged as an innovative and attention-grabbing development (Goidea et al., 2020; Soh et al., 2020; Dessi-Olive, 2022a). Bio-welding or myco-welding has gained popularity as a method for design (Dessi-Olive, 2022a). Mushroom mycelium-based biomaterials exhibit plasticity, enabling their application in design and structural uses. The autonomous binding characteristic of mycelium allows for regrowth upon breakage, and these materials can be reinforced further with the addition of wood and metal connectors.

Note a Growing Pavilion. b Hy-fi tower. c The Mycotree Pavilion. d Shell Mycelium. e Mycotectural Alpha. f My-co space. g EI Monolito.

Source a, c–g Almpani-Lekka et al. (2021), b Modanloo et al. (2021).

Figure 1.4 Architectural designs using mycelium-based materials

1.2.3 Application of Mycelium-Based Building Materials

There is a growing demand for construction materials that are sustainable, environmentally friendly, and cost-effective. The average lifespan of buildings has decreased, with only 34 years in China and 25 years in Japan (Liu et al., 2014; Wuyts et al., 2019; Dessi-Olive, 2022). This trend contributes to an increased volume of waste in landfills, posing challenges for waste management. Mushroom mycelium-based

biomaterials have been applied to produce building components such as bricks, blocks, and panels (Figure 1.5). The mycelium-substrate mix is grown in bags and transferred into desired moulds to allow mycelium growth.

The incorporation of agricultural byproducts in the production process enhances the cost-effectiveness of the final product, making it suitable for widespread use. The application of mycelium and agricultural waste in creating low-energy construction materials has garnered attention from researchers and investors (Madurwar et al., 2013). By combining inexpensive agricultural waste with mycelium, various products like bricks, blocks, panels, and essential construction components can be manufactured, reducing overall production requirements (Holt et al., 2012; Jones et al., 2017).

The potential for creating interlocking blocks has expanded the application of biomaterials in construction, showcasing water and fire resistance. Sharma and Sumbria (2022) report that mycelium bricks display lower brittleness and higher ductile properties than materials without mycelium. Moreover, these biomaterials conform to international standards for thermal and acoustic insulation, dry density, and other construction material requirements (Saez et al., 2020). In contrast, mycelium-based composites pose specific constraints for constructing larger structures, necessitating scaffolds or comprehensive reinforcement systems (Dessi-Olive, 2019; Özdemir et al., 2022). Insufficient data is available regarding the impact of reinforcement with mushroom mycelium-based biomaterials. Notably, these composites exhibit hydrophilic properties compared to synthetic materials used on external building surfaces, presenting a potential recommendation challenge (Tsao, 2020). Additional research is essential to address the lack of tension and bending resistance in mycelium-based composites.

Figure 1.5 Mushroom mycelium pre-composite blocks prepared with different combinations of mushroom strains and substrates

1.2.4 Application of Mycelium-Based Materials as Insulating Materials

The shift towards using mushroom mycelium for insulation purposes represents a notable advancement in the construction and insulation industries, offering an eco-friendly alternative to traditional methods. Conventional insulation, often reliant on polystyrene foams, contributes to environmental pollution upon disposal and poses health risks due to its synthetic or petroleum-based nature, including carcinogenic properties (Sulong et al., 2019; Tsao, 2020). The innovation of incorporating mushroom mycelium with lignocellulosic substrates proves effective in acoustic absorption. Pelletier et al. (2013) reported that mycelium-based boards show promise as bio-based alternatives to synthetic foams for sound insulation. The inherent porous structure of mushroom mycelium-based biomaterials enhances their sound absorption properties, making them well-suited for applications in sound control.

The noise absorption capability of mushroom mycelium-based biomaterial panels is substrate-dependent (Meyer et al., 2020; Yang et al., 2021). In a compact form,

mycelium disrupts the path of sound waves, diminishing their amplitude and converting them into heat energy (Peters et al., 2013). It effectively absorbs low frequencies (below 1500 Hz), making it suitable for noise absorption applications, such as replacing ceiling tiles to mitigate noise pollution (Manan et al., 2021; Gou et al., 2021). This product serves as an environmentally friendly alternative to synthetic and non-degradable insulation materials (Vandelook et al., 2021).

Mycelium-based composites demonstrate satisfactory characteristics for thermal insulation (Elsacker et al., 2019; Elsacker et al., 2021). Jones et al. (2020) stated that the lower thermal conductivities indicate superior insulation materials. Mushroom mycelium-based biomaterials exhibit superior fire resistance compared to conventional building materials relying on polystyrene insulation and particle boards (Boyer, 2014; Silverman et al., 2020; Tsao, 2020; Oral et al., 2022). According to Tsao (2020), the thermal conductivity of mycelium-based foams ranges between 0.04–0.13 ($W.m^{-1}.K^{-1}$), slightly higher than conventional foams, which range between 0.03–0.04 ($W.m^{-1}.K^{-1}$). This development opens new possibilities for an industry focused on enhancing the fire safety of buildings.

In regions with temperate climates, effective wall insulation is crucial for maintaining comfortable temperatures indoors. The use of mushroom mycelium-based biomaterials in wall insulation can successfully preserve insulating properties. Ecovative Design, for instance, has developed a fire-retardant board called Greensulate, which has gained popularity as an effective insulating product (Casini, 2016; Abhijith et al., 2018; Rajendran, 2022).

1.2.5 Application of Mycelium-Based Textile as a Leather Product

Mushroom mycelium-derived leather stands out as an environmentally safe, green, and sustainable alternative compared to animal-sourced and synthetic products (Vandelook et al., 2021; Raman et al., 2022). In contrast, conventional leather production involves using numerous toxins and chemicals, including harmful substances (Silva, 2021).

Pure fungal materials for leather production can be obtained through completely degrading substrates or fungal mats from liquid or solid surfaces (Cartabia et al., 2021). Mushroom mycelium-based leather is considered safe for use due to its beneficial properties for human skin. German company ZVNDER conducted successful tests, demonstrating the positive effects of mycelium leather on an athlete's foot, with mycelium-based shoes offering advantages such as improved air circulation to prevent unpleasant odours (Gandia et al., 2021).

Furthermore, the Bolt Threads Company, renowned for producing the mycelium-based product Mylo, positions itself as an alternative to traditional leather (Iordache et al., 2018). Mushroom mycelium-based leather is lighter than traditional animal-based leather, providing advantages for both industries and consumers. This lightweight property makes it suitable for a diverse range of applications. The fashion industry has embraced mushroom mycelium-based biomaterials in producing sustainable alternatives for clothing, bags, and shoes, leading to the creation of luxury fashion items that contribute to a modern and sensual aesthetic.

Vasquez and Vega (2019) reported the preparation of myco-accessories, such as necklaces, crowns, and bracelets, using a thin layer of mycelium with a lamination technique, showcasing the artistic and decorative potential of mycelium-based materials. Moreover, mycelium-based materials have demonstrated utility in supporting electronic circuit boards (Vasquez & Vega, 2019; Vandelook et al., 2021), indicating their potential applications beyond fashion and accessories.

Conventional leather production involves the slaughter of animals, contributing to ethical concerns raised by animal rights activists (Gupta & Dave, 2021; Silva, 2021; Raman et al., 2022). Mushroom mycelium-based leather provides a cruelty-free alternative, eliminating the need for animal hides. One advantage of mushroom mycelium-based leather is its rapid growth, allowing it to be ready in a short period, contrasting with animal-derived leather, which requires years.

Consumers increasingly prioritise environmentally safe leather and fabric products. Mushroom mycelium-based leather offers a low production cost without the need for chemical processing. Certain plasticisers, such as glycerol, polyethylene glycol, PEG400, mono/di/oligosaccharides, lipid, and lipid derivatives, are employed to enhance desirable characteristics, reducing brittleness and hardness while increasing elongation and ductility (Janjarasskul & Krochta, 2010; Raman et al., 2022). Although mushroom mycelium-based leather has not fully matched the commercial success of traditional animal-sourced and synthetic leather, ongoing extensive research holds the promise of discovering better options for sustainable products. Companies like MycoWorks and MOGU Inc. have successfully utilised mycelium to develop synthetic leather (Rajendran, 2022).

This study provides a foundation for deepening the understanding of mushroom mycelium-based biomaterials and their significance as a sustainable, eco-friendly, cost-effective, and biodegradable alternative to the current world's problems posed by synthetic plastic- and foam-based materials.

1.3 Study on Pure Mycelium Mats Developed from *Phlebiopsis friesii*

Phlebiopsis Jülich (1978) (Phanerochaetaceae, Polyporales, Agaricomycetes, Agaricomycotina, Basidiomycota) is a white-rot fungus and is typified by *P. gigantea* (Fr.) Jülich (Jülich, 1978; Hyde et al., 2024a). This genus is distinguished by its combination of resupinate to effused-reflexed basidiomata, a membranous to subceraceous texture when fresh, not cracking when dry, a smooth to odontoid or poroid hymenophore, a monomitic hyphal system composed of simple septate generative hyphae, and smooth, thin-walled, cylindrical to ellipsoid basidiospores which are acyanophilous and inamyloid (Bernicchia & Gorjón, 2010; Xu et al., 2020a). Species of *Phlebiopsis* are widely distributed in all continents except Antarctica (Floudas & Hibbett, 2015; Miettinen et al., 2016a; Vu et al., 2019; Xavier de Lima et al., 2020; Chen et al., 2021). There are 42

records of *Phlebiopsis* in Index Fungorum (www.indexfungorum.org; accessed on 26 March 2025). To date, 22 species have been recognised in the genus worldwide (Jülich, 1978; Hjortstam & Ryvarden, 1980; Dhingra, 1987; Gilbertson & Adaskaveg, 1993; Ryvarden et al., 2005; Douanla-Meli & Langer, 2009; Bernicchia & Gorjón, 2010; Wu et al., 2010a; Floudas & Hibbett, 2015; Miettinen et al., 2016a; Zhao et al., 2019; Zhao et al., 2021).

Phlebiopsis species have been relatively underexplored in terms of their applications. Biomaterials derived from mushroom mycelium offer numerous benefits, including energy-efficient production, low cost, reduced carbon footprint, sustainable sourcing, lightweight properties, low density, low combustibility, complete biodegradability, and non-toxic characteristics (Jiang et al., 2017; Abhijith et al., 2018; Fairus et al., 2022). Mycelium-based leather (MBL), one of the applications of biomaterials, is a ground-breaking and sustainable alternative to plastic-based products, with potential applications in packaging, architectural design, construction, thermal and acoustic insulation, and textiles (Khyaju & Luangharn, 2024). Conventional leather production involves animal slaughter and contributes to significant environmental challenges (Gupta & Dave, 2021; Silva, 2021; Amobonye et al., 2023). In contrast, MBL is a sustainable, eco-friendly, and non-polluting alternative (Raman et al., 2022). With its emerging benefits, several prominent companies, including Ecovative (www.ecovative.com), Mycoworks (www.mycoworks.com), Bolt Threads (www.boltthreads.com), Mycel (www.mycelproject.com), and Mogu (www.mogu.bio), have scaled up production of mycelium-based biomaterials (Attias et al., 2020; Dessi-Olive, 2022b). However, research on MBL derived from diverse potential mushroom species remains limited. Additionally, a substantial portion of information on MBL development is confined by patents despite the numerous ongoing studies conducted worldwide. *Phlebiopsis* is also no exception, where mycelium mat applications are underexplored. Besides the usage of *P. gigantea* as a biological control agent in conifer root and butt diseases (Pratt et al., 2010) and in biological processing for the pulp

and paper industry (Blanchette et al., 1998), any application of *Phlebiopsis* species in MBL has not been reported yet.

Polyporales are recommended for producing superior-quality mycelium-based biomaterial (Cerimi et al., 2019; Raman et al., 2022). Based on this fact, *Phlebiopsis friesii* has been studied further. This is the first study to explore the use of *P. friesii* for mycelium-based biomaterial production. Pure mycelium mats derived from *P. friesii* were subjected to comprehensive analyses. Based on thorough morphological characteristics and phylogenetic analysis using internal transcribed spacer (ITS) and large subunit (LSU) sequence data, *P. friesii* has been revealed to be first reported from Thailand. Thus, this study aims to document a new geographical record of *P. friesii* in Thailand and characterise its potential as a sustainable resource for mycelium-based mat production.

1.4 Study on Mycelium-Based Biomaterials Developed from *Panus ciliatus* and *P. subfasciatus*

Panus Fr. (Panaceae, Polyporales) was described by Fries (1838), with *P. conchatus* (Bull.) Fr. as the type species. Members of this genus are wood-inhabiting saprobes distributed worldwide, particularly in subtropical and tropical regions (Kumla et al., 2024; Sousa-Guimarães et al., 2024). *Panus* species are characterised by a centrally to eccentrically stipitate basidiomata, infundibuliform to cyathiform pilei, a hymenophore with decurrent lamellae, free gills, ellipsoid, smooth, thin-walled, inamyloid basidiospores, thin to thick-walled cystidia, and a dimitic hyphal system with unbranched skeletal hyphae (Fries, 1838; Corner, 1981; Sousa-Guimarães et al., 2024).

Panus was treated as an infrageneric taxon of *Lentinus* Fr., and classified as *Lentinus* subg. *Panus* (Fr.) Pegler (Pegler, 1971, 1983). Subsequent molecular phylogenetic analyses supported its recognition as a distinct genus within the family Panaceae (Vinjusha & Kumar, 2021). Panaceae comprises only two genera, namely

Cymatoderma Jungh. and *Panus* (Liu et al., 2023a; Kumla et al., 2024). Index Fungorum has listed 255 records of *Panus* (https://www.indexfungorum.org/names/Names.asp, accessed 2025/09/29). However, only 20 species of *Panus* are recognised worldwide (He et al., 2019; Wijayawardene et al., 2022). Some species, including *P. conchatus*, *P. neostrigosus* Drechsler-Santos & Wartchow, *P. rudis* Fr., and *P. strigellus* (Berk.) Chardón & Toro, are considered edible (Vasco-Palacios et al., 2008; Vargas-Isla et al., 2015; Sharma et al., 2020).

Mushrooms are valued globally for their nutritional, medicinal, and functional properties, with growing production and economic importance (Niego et al., 2023). In recent years, mushroom mycelium has also been explored in material science, particularly in the development of mushroom mycelium-based biomaterials (MMBs). These materials are eco-friendly, sustainable, and biodegradable, which align with the principles of the circular economy or closed-loop system. Petroleum-based materials, such as plastics and foams, are environmental pollutants that are non-sustainable, non-biodegradable, and leave a significant carbon footprint (Holt et al., 2012; Khyaju & Luangharn, 2024). These materials pose threats to human health, as well as to marine and wildlife. Conversely, MMBs are cost-effective, energy-efficient, non-toxic, and non-polluting materials used as an alternative to plastic- and foam-based products (Abhijith et al., 2018; Fairus et al., 2022). Interestingly, these materials have been produced commercially to be applied in packaging, construction, insulation, architectural design, and leather (Khyaju & Luangharn, 2024). However, only a limited number of wood-decaying fungal species, belonging to the genera *Ganoderma*, *Pleurotus*, and *Trametes*, have been investigated and characterised for MBBs development (Aiduang et al., 2022b).

Among several orders of Basidiomycota, members of the order Polyporales are highly prioritised due to their inherent ability to produce superior-quality MMBs (Raman et al., 2022; Khyaju et al., 2025). *Panus*, like many other mushroom genera, remains underexplored in the context of MMB development, requiring its exploration. Interestingly, this genus meets the recommended fungal criteria for developing MMBs as

reported by Sydor et al. (2022), including a saprobic nature, white-rot decay, rapid hyphal growth, a dimitic hyphal system, and non-toxicity. Additionally, Hibbett et al. (1993) demonstrated that *Panus* mycelia grow effectively on sawdust under room temperature and moisture content (65%). In this study, wild strains of *Panus ciliatus* and *P. subfasciatus* collected from forests of Chiang Rai Province, Thailand, were identified through a combination of morphological and molecular phylogenetic analyses (ITS region). Subsequently, *Panus ciliatus* is reported as a new geographical record from Thailand. The pure mycelium from these species was used to develop MMBs, which were subsequently evaluated for their physical (moisture content, density, shrinkage), mechanical (compression, flexural, tensile, and impact strengths), hydrodynamic (water absorption, water contact angle), and chemical (pH, electrical conductivity, organic matter, organic carbon, nitrogen, phosphorus, and potassium contents) properties. This is the first report of MMBs produced from these fungi. Additional evaluations included Fourier-transform infrared (FTIR) spectroscopy, thermogravimetric analysis (TGA), flammability, soil burial degradability, and maintenance of mycelial viability. Additionally, MBB prototypic products were successfully developed, demonstrating their potential in the valorisation of lignocellulosic wastes and applications in packaging, construction, insulation, and indoor uses.

1.5 Study on Mycelium-Based Biomaterials Developed from Twelve Fungal Strains

Mushroom mycelium-based biomaterials, an innovative alternative to traditional plastics, offer a multitude of advantages, including energy-efficient production, cost-effectiveness, complete biodegradability, recyclability, potential for carbon dioxide sequestration, sustainable sourcing, lightweight, low density, robust strength, non-toxic, and remarkable suitability for the packaging and construction industries (Abhijith et al., 2018; Fairus et al., 2022). Utilising biomaterials derived from mycelium and agricultural

organic byproducts exhibits favourable attributes for industrial applications. Mycelium density, mycelium structure, and growth rate are important criteria for fungal species selection for biomaterial preparation (Alemu et al., 2022a). A limited number of fungal species are used in biomaterials, and research for unexplored mushrooms has to be carried out. Potential fungal species might not have been identified and investigated for mycelium-based biomaterials. This work utilises twelve fungal strains to identify, characterise, and examine the potential of mycelium-based biomaterial production in alignment with international standards for biomaterials.

1.6 Research Gaps

1.6.1 The study of mushrooms in relation to mycelium-based biomaterials is limited to a very few species, while numerous potential wild species have not yet been explored.

1.6.2 Although with a high diversity of mushrooms, they have not yet been identified, screened, and characterised for mycelium-based biomaterial. Research on mycelium-based biomaterial in Thailand is limited.

1.6.3 A comprehensive worldwide checklist of fungal species used in mycelium-based biomaterials is lacking.

1.6.4 Notes on fungal genera are scattered and unavailable. Notes on terminologies related to mycelium-based biomaterial are lacking.

1.7 Research Objectives

1.7.1 To identify fungal species and characterise mycelium-based biomaterials using selected mushrooms and lignocellulosic substrates (sawdust).

1.7.2 To provide a worldwide checklist of mushroom species used in mycelium-based biomaterials and discuss the challenges and opportunities.

1.7.3 To provide notes and illustrations of Basidiomycota genera and terminologies related to mycelium-based biomaterials.

1.8 Expected Outcome

1.8.1 Identification of mushroom species, using both morphology and phylogeny, and developing and characterising mycelium-based biomaterials.

1.8.2 Worldwide checklist of mushroom species used in mushroom mycelium-based biomaterials and discussion on challenges and opportunities.

1.8.3 Notes and illustrations of Basidiomycota genera and mycelium-based biomaterials related terminologies (Fungalpedia).

1.8.4 Review on diverse use of mushroom mycelium-based biomaterials.

1.9 Thesis Outline

This dissertation comprises six chapters.

Chapter 1 provides a general introduction to mushroom mycelium-based biomaterials and their application. It includes historical perspectives of research and development in this field. The research gaps, objectives, expected outcome, and thesis outline are provided.

Chapter 2 includes materials and methods used in conducting reviews and experiments in mushroom mycelium-based biomaterials. The procedure of testing physical, mechanical, hydrodynamic, and chemical properties is presented. It also includes FTIR spectroscopy, scanning electron microscopy, thermogravimetric analysis, flammability testing, and soil burial degradability of the test samples.

Chapter 3 provides a study on selected fungal species and is divided into four sections. The first section covers *Phlebiopsis friesii* (Phanerochaetaceae, Polyporales) as a new geographical record in Thailand based on morphological and phylogenetic analyses (ITS and LSU). This study is also the first preliminary characterisation of its potential in mycelium mats, reporting thermogravimetric properties, Fourier-transform infrared (FTIR) spectroscopy profiles, scanning electron microscopy (SEM), and water contact angle (CA) measurements. The second section includes the first comprehensive characterisation of mycelium-based biomaterials developed from *Panus ciliatus* (MFLUCC 25-0173) and *P. subfasciatus* (MFLUCC 25-0172) (Panaceae, Polyporales). Physical, mechanical,

hydrodynamic, and chemical properties have been reported. Additionally, FTIR spectroscopy, thermogravimetric analysis, flammability testing, and soil burial degradability results based on the samples have been provided. Prototypic biomaterial products from these two species have also been presented. The third section provides a comprehensive characterisation of biomaterials from twelve Thai mushroom species, including two commercial and ten wild mushroom species. The results of physical, mechanical, hydrodynamic, and chemical properties are reported. The FTIR spectroscopy, scanning electron microscopy, thermogravimetric analysis, flammability testing, and soil burial degradability of the test samples are also reported.

Chapter 4 includes a global checklist of mushroom species that were undertaken for mycelium-based biomaterials field till 2024. The fungal classification of the mushroom species used in biomaterials is distributed among the orders *Polyporales* (67 species), *Agaricales* (20 species), *Hymenochaetales* (6 species), *Auriculariales* (2 species), *Russulales* (2 species), and *Gleophyllales* (1 species). Additionally, current challenges in research, development, and utilisation of mycelium-based biomaterials, along with the possible opportunities, are discussed.

Chapter 5 provides notes and illustrations of Basidiomycota genera. Fungal genus entries comprise data on habit and habitat, classification, distinguishing morphological characteristics, genetic markers used, critical analysis of taxonomic placement, and beneficial roles to humans and nature. Additionally, brief notes on families related to the genera are provided. Line drawings of morphological characters of all the genera are provided along with each entry. Notes on the most commonly used terminologies in the MMB sector, featuring their definition, implications, and necessary diagrams.

Chapter 6 includes the summary of collected fungal samples, description of new species and new geographical records of fungal species in Thailand. It includes morphology and phylogenetic analyses of the described fungal species, along with illustrations.

Chapter 7 provides an overall conclusion of characterisation of mushroom mycelium-based biomaterials of fifteen fungal strains, a global checklist of fungal species used in mycelium-based biomaterial research, notes on Basidiomycota genera and terms related to mycelium-based biomaterials, and a review of applications. It also highlights the research advantages, future work, and publications.

CHAPTER 2

MATERIALS AND METHODS

2.1 Collection, Isolation and Examination of Samples

Fresh mushroom specimens were collected from decaying logs in mixed deciduous forests in seven provinces in Thailand, Chiang Rai, Chiang Mai, Lampang, Phayao, Phrae, Chanthaburi, and Narathiwat (Figure 2.1). Macro-morphological characters were recorded from the fresh specimens in the field, which were then air-dried at 55°C for 48 h until completely dehydrated (Khyaju et al., 2025). The dried specimens were kept in paper bags and subsequently used for micro-morphological characterisation in the laboratory. Fresh specimens were also used for tissue isolation on potato dextrose agar (PDA) plates, which were incubated at 25°C in the dark. After 3–5 days of growth, cultures were sub-cultured onto a fresh PDA plate to obtain pure isolates. These pure cultures were maintained at 4°C for further studies.

Altogether 15 fungal strains were selected for investigating in mycelium-based biomaterials, based on criteria, including successful pure culture preparation, representative of different hyphal system types, previously studied and unexplored fungal strains, and saprobic nature. *Phlebiopsis friesii*, with a monomitic hyphal system type, was investigated to develop a pure mycelium mat and characterised for screening the optimal culture agar media, dry biomass, and density, thermogravimetric analysis, Fourier transform infrared spectroscopy, scanning electron microscopy, and water contact angle analysis. *Panus ciliatus* and *P. subfasciatus*, with a dimitic hyphal system type, were investigated to characterise and compare between species within the same genus. The study included testing the effects of culture media on mycelial growth, mycelial growth in lignocellulosic

substrate (sawdust), and evaluation of mycelium-based biomaterial samples for physical, mechanical, hydrodynamic, and chemical properties. Other analyses included scanning electron microscopy, thermogravimetric analysis, Fourier transform infrared spectroscopy, flammability, soil burial degradability, and viability maintenance of mushroom strains. Another experiment includes twelve fungal strains, with different hyphal system types, to compare the effects on mycelium-based biomaterials by different fungal genera. The test samples were characterised for physical, mechanical, hydrodynamic, chemical properties, and other properties, including scanning electron microscopy, thermogravimetric analysis, Fourier transform infrared spectroscopy, flammability, soil burial degradability, and viability maintenance of mushroom strains. Additionally, prototypic mycelium-based biomaterial products using those fungal strains were developed.

Macro-morphological characters were examined both in the field and the laboratory. Fresh specimens were photographed in the field using a Nikon SLR D3400 camera. Morphological descriptions followed the methods of Lodge et al. (2004), and colour codes and terms were noted according to the Methuen Handbook of Colour (Kornerup & Wanscher, 1978). Micro-morphological characters (basidia, basidiospores, cystidia, pileipellis, and hyphae) were observed using OLYMPUS BX-53 and Nikon Eclipse Ni compound microscopes. Freehand sections of dried specimens were treated with 5% KOH and then mounted in 1% Congo red. Additional sections were mounted in distilled water and/or 5% KOH to determine the presence of pigments or any colour reactions. Basidium length was measured excluding sterigmata. Thirty basidiospores were measured in side view to determine size ranges. The size and shape of basidiospores were expressed by the following Q = L/W ratio: L = mean length, W = mean width. Photomicrographs were taken with a camera attached to the compound microscope, and all microscopic measurements were taken using the Tarosoft® Image Framework program v.0.9.7. Dried specimens were deposited in the Fungarium of Mae Fah Luang University (MFLU), and the

pure cultures were deposited in the Mae Fah Luang University Culture Collection (MFLUCC).

Source Wikipedia Commons (accessed on 02 October, 2025)

Figure 2.1 Fungal sample collection sites in Thailand

2.2 DNA Extraction, PCR Amplification, and Sequencing

Genomic DNA was extracted from pure cultures of selected fungal strains using the High Pure PCR Template Preparation Kit (Roche) following the manufacturer's protocol. DNA quality and concentration were assessed using a NanoDrop One Microvolume UV-Vis spectrophotometer (Thermo Scientific, MA, USA). The ITS region was amplified using the primer pair ITS1/ITS4 and LROR/LR5 (White et al., 1990). Polymerase chain reaction (PCR) reactions were carried out in a total volume of 25 µL, containing 12.5 µL of 2× Power Taq PCR Master Mix, 1 µL of each primer (20 µM), 1 µL of genomic DNA, and 9.5 µL of deionised water. Amplifications were performed on an Eppendorf Mastercycler (Eppendorf AG 22331 Hamburg, Germany) with the following cycling program: initial denaturation at 94°C for 3 min, followed by 35 cycles of 95°C for 30 s, 55°C for 1 min, and 72°C for 1 min; and a final extension at 72°C for 10 min. PCR products were sequenced by SolGent Co., Ltd., Yuseong-gu, Daejeon, Republic of Korea.

2.3 Sequence Alignments and Phylogenetic Analyses

Sequence quality was assessed using BioEdit v.7.0.9 (Hall, 1999), and sequences were assembled using Geneious 9.1.2 (Kearse et al., 2012). The final consensus sequences were deposited in GenBank (www.ncbi.nlm.nih.gov/genbank/) to obtain accession numbers for the ITS region. To determine the closest matches, each sequence was compared against the National Center for Biotechnology Information (NCBI) database using the Basic Local Alignment Search Tool (BLAST). The ITS and LSU dataset includes newly generated sequences, closely related taxa, available sequences of other species within the genus, and outgroup sequences were used for phylogenetic analysis and reconstruction (Table 2.1, 2.2).

Taxa table for genera *Phlebiopsis* and *Panus* are shown in Table 2.1 and Table 2.2, respectively.

Sequence alignment was performed with MAFFT v7 (Katoh et al., 2019) using G-INS-I iterative refinement methods. Ambiguously aligned regions were removed using trimAl v1.4.1 (Capella-Gutiérrez et al., 2009), and Gblocks v0.91b (Talavera & Castresana, 2007) was used to refine alignment further, allowing smaller final blocks, gaps position within blocks, and less strict flanking positions. Single-gene phylogenetic analyses were performed for species delimitation. Maximum Likelihood (ML) analyses were conducted in RAxML-GUI v2.0 under the GTRGAMMA substitution model (Edler et al., 2021). ML analysis was conducted using the rapid bootstrap algorithm with 1,000 replicates. ML bootstrap percentages (MLB) of 70% or greater were considered significant. Gaps were treated as missing data. Bayesian Inference (BI) analyses were conducted using MrBayes v3.2.6 (Ronquist et al., 2012) with four Markov chain Monte Carlo (MCMC) chains run for 1,000,000 generations, sampling every 100th generation. The first 25% of trees were discarded as burn-in. Chain convergence was assessed using Tracer v1.5 (Rambaut et al., 2018), ensuring effective sample size (ESS) values >200. Posterior probability (BPP) values ≥0.90 indicate strong support. Phylogenetic trees were visualised in FigTree v1.4.4 (http://tree.bio.ed.ac.uk/software/figtree/) and edited in Adobe Photoshop v8.0 (Adobe Systems, USA). The fungal species description followed the guidelines of He et al. (2024).

Table 2.1 Fungal name, voucher, geographic origin, and GenBank accession numbers of the taxa used in the phylogenetic analysis of *Phlebiopsis*

Taxon	Voucher	Country	GenBank accession no.		References
			ITS	LSU	
Phlebiopsis alba	GC 1508-110	China	MZ637042	MZ637246	Chen et al. (2021)
P. alba	Wu 1809-270	China	MZ637044	MZ637248	Chen et al. (2021)

Table 2.1 (continued)

Taxon	Voucher	Country	GenBank accession no.		References
			ITS	LSU	
P. albobadia	He 5805	Sri Lanka	MT452526	−	Zhao et al. (2021)
P. amethystea	URM 84741	Brazil	MK993645	MK993639	Xavier de Lima et al. (2020)
P. amethystea	URM 92985	Brazil	MK993646	MK993640	Xavier de Lima et al. (2020)
P. amethystea	URM 93248	Brazil	MK993644	MK993638	Xavier de Lima et al. (2020)
P. brunnea	He 5822	Sri Lanka	MT452527	MT447451	Zhao et al. (2021)
P. brunneocystidiata	Chen 1143	China	MZ637048	MZ637249	Xavier de Lima et al. (2020)
P. brunneocystidiata	Chen 666	China	MT561707	GQ470640	Wu et al. (2010a); Zhao et al. (2021)
P. castanea	He 2489	China	−	MT447406	Zhao et al. (2020)
P. castanea	Spirin 5295	Russia	KX752610	KX752610	Miettinen et al. (2016a)
P. crassa	TNM:F33036	China	MZ637049	−	GenBank
P. crassa	He 5866	China	MT386376	MT447408	Zhao et al. (2021)
P. crassa	KKN-86-Sp	USA	KP135394	KP135215	Floudas and Hibbett (2015)
P. cylindrospora	He 5984	China	MT386404	MT447445	Zhao et al. (2021)
P. cylindrospora	He 6054	China	MT561716	MT598030	Zhao et al. (2021)
P. darjeelingensis	GC 1409-20	China	MZ637052	MZ637252	Chen et al. (2021)

Table 2.1 (continued)

Taxon	Voucher	Country	GenBank accession no.		References
			ITS	LSU	
P. flavidoalba	FD-263	USA	KP135402	KP135271	Floudas and Hibbett (2015)
P. flavidoalba	Otto_Miettinen 17896	USA	KX752607	KX752607	Miettinen et al. (2016a)
P. flavidoalba	URM 87826	Brazil	MK993648	MK995635	Xavier de Lima et al. (2020)
P. friesii	**MFLUCC 24-0323**	**Thailand**	**PQ569315**	**PQ569317**	**This study**
P. friesii	He 5722	Sri Lanka	MT452528	MT447413	Zhao et al. (2021)
P. friesii	He 5817	Sri Lanka	MT452529	MT447414	Zhao et al. (2021)
P. friesii	He 5820	Sri Lanka	MT452530	MT447415	Zhao et al. (2021)
P. galochroa	FP-102937-Sp	USA	KP135391	KP135270	Floudas and Hibbett (2015)
P. gigantea	CBS 935.70	Germany	MH860011	MH871798	Vu et al. (2019)
P. gigantea	FP-70857-Sp	USA	KP135390	KP135272	Floudas and Hibbett (2015)
P. lacerata Type	CLZhao 3692	China	MT180946	MT180950	Xu et al. (2020a)
P. lacerata	He 5734	Sri Lanka	MT561708	MT598032	Zhao et al. (2020)
P. lamprocystidiata	He 3874	China	MT386382	MT447418	GenBank
P. lamprocystidiata	He 5910	China	MT386383	MT447419	Zhao et al. (2021)
P. laxa	Wu 9311-17	China	MT561710	GQ470649	Wu et al. (2010a); Zhao et al. (2021)

Table 2.1 (continued)

Taxon	Voucher	Country	GenBank accession no.		References
			ITS	LSU	
P. magnicystidiata	He 5648	China	MT386377	MT447409	Zhao et al. (2020)
P. magnicystidiata	Wu 890805-1	China	MT561711	−	Wu et al. (2010a); Zhao et al. (2021)
P. membranacea	He 3842	China	MT386400	MT447440	Zhao et al. (2021)
P. membranacea	He 3849	China	MT386401	MT447441	Zhao et al. (2021)
P. membranacea	He 6062	China	MT386402	MT447442	Zhao et al. (2021)
P. odontoidea	GC 1708-181	China	MZ637054	MZ637255	Chen et al. (2021)
P. odontoidea	GC 1708-182	China	MZ637055	MZ637256	Chen et al. (2021)
P. pilatii	Dai 17041	China	KY971603	KY971604	Wu et al. (2017a)
P. pilatii	He 5165	China	MT386386	MT447422	Zhao et al. (2021)
P. sinensis	He 4295	China	MT386395	MT447433	Zhao et al. (2021)
P. sinensis	He 4665	China	MT386396	MT447434	Zhao et al. (2021)
P. sinensis	He 4673	China	MT386397	MT447435	Zhao et al. (2021)
P. yunnanensis Type	CLZhao 3958	China	MH744140	MH744142	Zhao et al. (2021)
P. yunnanensis	He 2623	China	MT386387	MT447423	Zhao et al. (2021)
P. yushaniae	Chen 1914	China	MZ637045	−	Chen et al. (2021)
P. yushaniae	Chen 2358	China	MZ637047	MZ637261	Chen et al. (2021)
Rhizochaete americana (Outgroup)	FP-102188	USA	KP135409	KP135277	Floudas and Hibbett (2015)

Note Newly generated sequences are indicated in bold.

Table 2.2 Fungal name, voucher, geographic origin, and GenBank accession numbers of taxa used in the phylogenetic analysis of *Panus*

Fungal Species	Voucher	Geographic origin	Accession no. (ITS)	References
Panus baishanzuensis	FJAU67793.1	China	PP273986	Yue et al. (2024)
P. baishanzuensis	FJAU67793	China	PP273985	Yue et al. (2024)
P. bambusinus Type	AK61b	India	MW453097	Kumla et al. (2024)
P. cf. tephroleucus	VOG36	Brazil	MT669124	Sousa-Guimarães et al. (2024)
P. ciliatus	**MFLUCC 25-0173**	**Thailand**	**PV393836**	**This study**
P. ciliatus	SP446150	Brazil	MT669118	Yue et al. (2024)
P. conchatus	KUMCC18 0047	China	MK192053	Luangharn et al. (2019a)
P. conchatus	CLZhao 1452	China	MG231758	Sousa-Guimarães et al. (2024)
P. conchatus	Inat36307978	USA	OM349507	Sousa-Guimarães et al. (2024)
P. conchatus	LE265028	Russia	KM411463	Zmitrovich and Kovalenko (2016)
P. conchatus	CBS 267.58	Germany	MH857778	Sousa-Guimarães et al. (2024)
P. conchatus	UOC-MINNP-M13	Sri Lanka	KP776992	Sousa-Guimarães et al. (2024)
P. conchatus	JZ30	India	MG719287	Sousa-Guimarães et al. (2024)

Table 2.2 (continued)

Fungal Species	Voucher	Geographic origin	Accession no. (ITS)	References
P. conchatus	A52	Philippines	OM102535	Sousa-Guimarães et al. (2024)
P. conchatus	UOC:SIGWI:S24	Sri Lanka	KR818817	Sousa-Guimarães et al. (2024)
P. fulvus	DS1687	Brazil	MT669122	Yue et al. (2024)
P. lecomtei	HHB 9614	USA	KP135329	Floudas and Hibbett (2015)
P. lecomtei	HHB-11042-Sp	USA	KP135328	Floudas and Hibbett (2015)
P. minisporus	FJAU67792	China	PP273980	Yue et al. (2024)
P. minisporus	FJAU67792.1	China	PP273981	Yue et al. (2024)
P. neostrigosus	LSPQ NSM 106	Canada	KU761234	Dufresne et al. (2017)
P. neostrigosus	LSPQ NSM 107	Canada	KU761235	Dufresne et al. (2017)
P. parvus	URM80840	Brazil	MT669125	Yue et al. (2024)
P. purpuratus	PDD 96130	New Zealand	MK404671	Kumla et al. (2024)
P. roseus	HKAS 94714	China	KY490136	Kumla et al. (2024)
P. rudis	ZJ1005DKJ02	China	KU863049	Luangharn et al. (2019a)
P. rudis	ZJ1005DKJ03	China	KU863050	Luangharn et al. (2019a)
P. similis	LE287548	Vietnam	KM411466	Zmitrovich and Kovalenko (2016)

Table 2.2 (continued)

Fungal Species	Voucher	Geographic origin	Accession no. (ITS)	References
P. similis	FJAU67794	China	PP273984	Yue et al. (2024)
P. sribuabanensis	SDBR-CMUNK0930	Thailand	OR447475	Kumla et al. (2024)
P. sribuabanensis	SDBR-CMUNK0924	Thailand	OR447474	Kumla et al. (2024)
P. strigellus	B6	Paraguay	MW407012	Kumla et al. (2024)
P. subfasciatus Type	MFLU 16 2129	Thailand	LT614958	Tibpromma et al. (2017)
P. tephroleucus	CMINPA 1860	Brazil	MN602052	Sousa-Guimarães et al. (2024)
P. velutinus	CM10	Brazil	MT669138	Sousa-Guimarães et al. (2024)
P. velutinus	VOG30	Brazil	MT669139	Yue et al. (2024)
P. strigellus	INPA222827	Brazil	JQ955722	Sousa-Guimarães et al. (2024)
P. subfasciatus	**MFLUCC 25-0172**	**Thailand**	**PV393835**	**This study**
Panus sp.	TAC2130a MO506033	USA	OR336204	GenBank
Panus sp.	G028	China	KJ195662	Sousa-Guimarães et al. (2024)
Cymatoderma elegans (outgroup)	Dai 17511	China	ON417155	Kumla et al. (2024)
Cymatoderma elegans (outgroup)	CBS 491.76	Japan	JN649340	Kumla et al. (2024)

Note Newly generated sequences are indicated in bold.

2.4 Evaluation of Culture Media for Optimal Mycelial Growth

Five agar-based media were tested: corn meal agar (CMA), malt extract agar (MEA), oatmeal agar (OMA), PDA, and yeast malt agar (YMA). All equipment and media were sterilised at 15 psi for 20 min at 121°C. Mycelial plugs (5 mm diameter) were taken from the actively growing edge of 10-day-old PDA cultures and inoculated onto the test media. Plates were incubated at 25°C in the dark for 12 days. The mushroom mycelium growth rate was recorded daily using the method described by Luangharn et al. (2019b). The mycelium density was scored as very scanty (1+), scanty (2+), moderate (3+), somewhat abundant (4+), or abundant (5+) (Luangharn et al., 2019b). The growth rate and density measurements were performed in five replicates.

2.5 Evaluation of Mycelial Growth in Lignocellulose Substrates

Rubber sawdust (≤2 mm particle size) was soaked in tap water overnight and subsequently drained to remove excess moisture. The sawdust was used as the primary substrate (80% w/w), supplemented with 10% rice bran, 4% yeast extract, 4% molasses, 1.5% calcium carbonate ($CaCO_3$), and 0.5% gypsum ($CaSO_4$ $2H_2O$). A 30 g portion of the prepared substrate mixture was transferred into glass plates, packed in a polypropylene bag, and sterilised at 121°C for 60 min. After cooling, 5 mm mycelial plugs from 10-day-old cultures of fungal species were inoculated at the centre of each plate, and incubated in the dark at 25°C. Each treatment was performed in five replicates. Mycelial growth diameter was measured every two days, beginning on day 2 post-inoculation, until complete colonisation of the substrate was observed. Mycelial density was recorded on day 14.

2.6 Preparation of Pure Mycelium Mat Samples

The pure mycelium test samples were prepared using three broth media, respectively, the best-performing media: malt extract broth (MEB), potato dextrose broth (PDB), and yeast malt broth (YMB). One centimetre diameter mycelial plug from a pre-grown culture was inoculated into 150 ml of broth prepared from the selected media. The cultures were incubated at 25°C for 30, 45, and 60 days in the dark, with three replications for each treatment. The test samples were prepared with modifications based on Raman et al. (2022).

For the treated samples, the harvested mycelium mats were rinsed in reverse osmosis (RO) water for 1–2 min to remove residual broth, immersed in 15% glycerol for 48 h, and then transferred to 5% tannic acid for 7 days. Following this, the mats were rinsed in RO water for 1–2 min, hot-pressed at 120°C for 20 min, and re-immersed in 15% glycerol for 48 h. The mats were then re-rinsed in RO water and dried in a hot oven at 60°C for 48 h. These treated samples were compared to control samples, which underwent no additional processing. For the control, pure mycelium mats were harvested after each incubation period, rinsed in RO water to remove broth residues, and dried at 60°C for 48 h or until a consistent dry weight was achieved.

2.7 Preparation of Mycelium-Based Biomaterials Test Samples

Test samples were developed from selected fungal species through a series of steps, including spawn preparation, substrate bag formulation, mycelium-based biomaterial fabrication, and denaturation, as described below.

2.7.1 Preparation of Spawn

Spawn preparation followed the method described by Aiduang et al. (2022b) with modifications. Sorghum grains (*Sorghum bicolor*) were thoroughly washed and

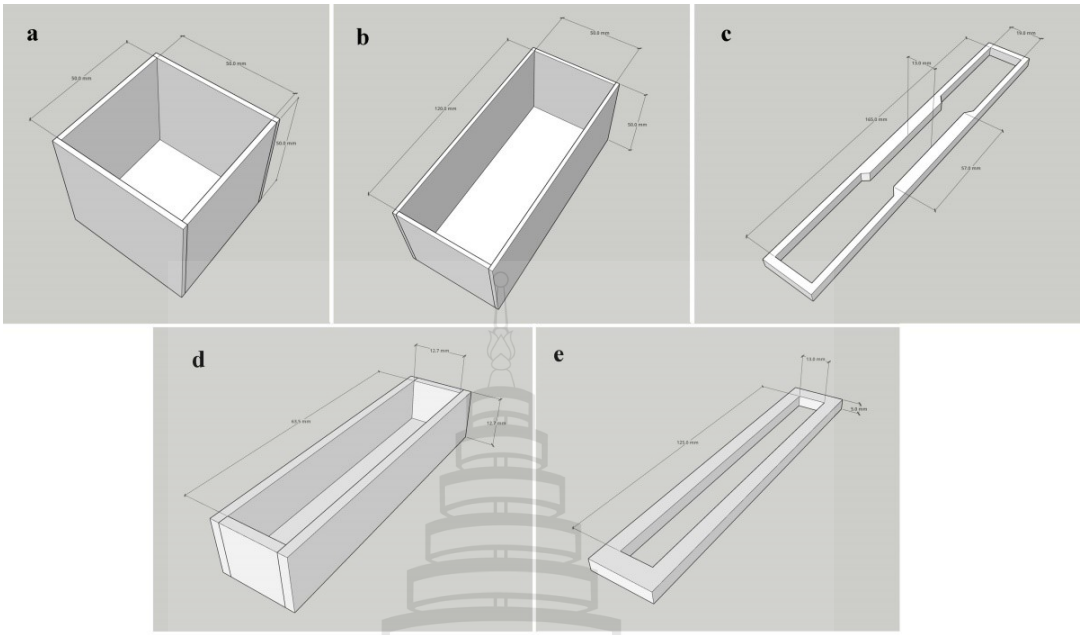
soaked in tap water overnight, then boiled for 15 min. After cooling and air-drying at room temperature, 150 g of grains were transferred into sterile glass bottles and autoclaved at 121°C for 30 min. Once cooled, mycelial plugs of the mushroom strains were aseptically inoculated into the bottles. The inoculated bottles were incubated in the dark at 28°C for 25 days or until the grains were fully colonised by mycelium.

2.7.2 Preparation of Mycelium Substrate Bags

Bag preparation followed the method described by Luangharn et al. (2017) with modifications. The rubber sawdust was used as the primary substrate (80% w/w), supplemented with 10% rice bran, 4% yeast extract, 4% molasses, 1.5% calcium carbonate, and 0.5% gypsum. The ingredients were manually mixed to achieve a moisture content of 55–60%. A 700 g portion of the mixture was packed into polypropylene bags, sealed with a plastic ring and lids, and sterilised in an autoclave at 121°C for 60 min. After cooling to room temperature, 20 g of prepared spawn was aseptically inoculated into each bag. The inoculated bags were incubated in the dark at 25 ± 1°C until complete colonisation.

2.7.3 Preparation of Moulds

The mould designs for performing tests are shown in Figure 2.2. For the compression strength test, moulds were designed from acrylic transparent sheets that were cut into a cubic shape (5 × 5 × 5 cm), following the method by Özdemir et al. (2022). The moulds for the tensile and impact tests were designed into a dumbbell-shaped segment (165 × 19 mm, neck 57 × 13 mm) and a cuboid shape (63.5 × 12.7 × 12.7 mm), respectively, following American Society for Testing and Materials (ASTM) standards (Aiduang et al., 2022c). For the flexural strength test, the moulds were prepared into a cuboid shape (12 × 5 × 5 cm). Glass Petri-dishes (diam. 9 cm) were used to prepare circular samples for FTIR spectroscopy.



Note a Sample for moisture content, compression, and water absorption tests. b Sample for density, flexural strength, SEM, chemical, and soil burial biodegradability tests. c Sample for tensile strength test. d Sample for impact strength test. e Sample for flammability test. Figures were generated using SketchUp online software (https://sketchup.trimble.com/en/products/sketchup-for-web?srsltid=AfmBOooktqmmGypuCyXg51tYY75e2Rc7DboJBvrthMHPxsEhkmCmJTZS).

Figure 2.2 Moulds designed to develop test samples

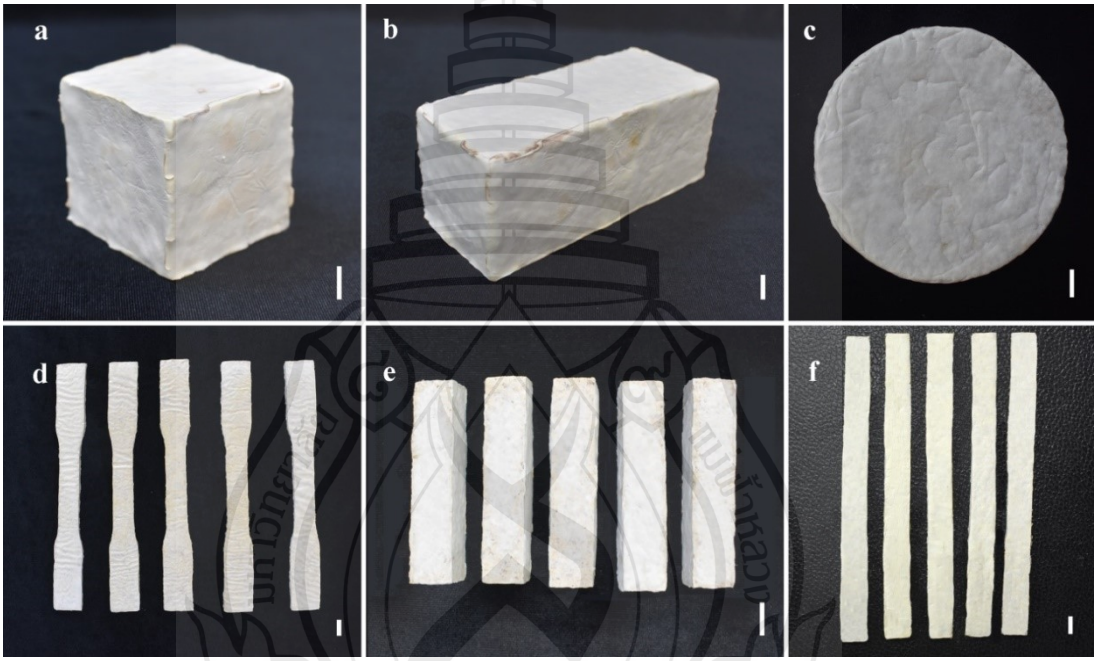
2.7.4 Fabrication of Mycelium-Based Biomaterials

Once the sawdust substrate in the bag was fully colonised, the mycelial-substrate mass was broken apart, transferred, and manually pressed into a sterile acrylic mould to form test samples. The moulded mycelium-substrate mixture was incubated for 4–7 days to grow within the mould, then unmoulded and incubated for an additional 4–7 days to allow mycelial growth on surfaces previously in contact with the mould. All the equipment was thoroughly washed in tap water

and sterilised by heat treatment in a hot air oven at 60ºC overnight. The procedures were conducted under sterile conditions in a laminar hood to prevent contamination.

2.7.5 Denaturation

The fully colonised mycelium-based composite samples were deactivated by drying in a hot-air oven at 60°C for 2 days (Ly & Jitjak, 2022). After cooling to room temperature, the samples were subjected to analyses of physical, mechanical, hydrodynamic, and chemical properties (Figure 2.3).



Note a Sample prepared for testing moisture content, dry density, volumetric shrinkage, compression strength, and water absorption. b Sample for flexural strength, SEM microscopy, TGA, chemical analyses (pH, organic matter, organic carbon, NPK), and soil burial degradability. c Sample for FTIR spectroscopy. d Sample for tensile strength and water contact angle. e Sample for impact strength. f Sample for flammability. Scale bars = 1 cm.

Figure 2.3 Test samples of MMBs developed from *Panus ciliatus* (MFLUCC 25-0173) and sawdust

2.8 Evaluation of Physical Properties of Mycelium-Based Biomaterial

2.8.1 Biomass of Mycelium Mats

The biomass of mycelium mats was determined by harvesting pure mycelium mats grown in the selected best-performing three media, rinsing in RO water for 1–2 min, and drying in a hot air oven at 45°C for 24 h until a constant weight was achieved (Rizal et al., 2016). The dry weight of the oven-dried mycelium was measured on days 30, 45, and 60.

2.8.2 Moisture Content and Dry Density

The dry density of the mycelium-based biomaterials (MMBs) was determined in accordance with ISO 9427:2003. Density was calculated as the ratio of oven-dry mass to volume. Test samples were prepared in the form of cubes with dimensions of 5 × 5 × 5 cm. The test was conducted in five replicates.

2.8.3 Volumetric Shrinkage

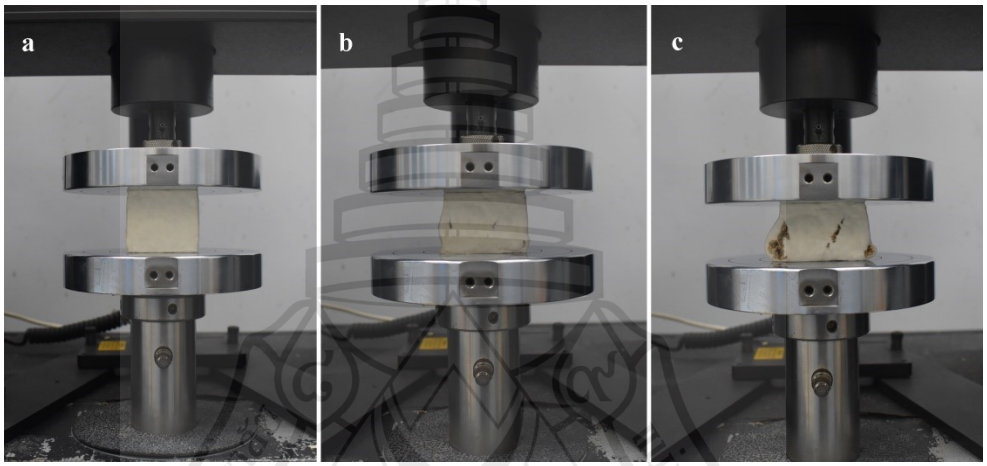
Fully colonised MMB cubes (5 × 5 × 5 cm) were used to calculate volumetric shrinkage following the method described by Elsacker et al. (2019). Shrinkage percentage was calculated as: shrinkage (%) = $(V_1-V_2)/V_1 \times 100$, where V_1 = moist volume of sample and V_2 = dry volume of sample. The test was conducted in five replicates.

2.9 Evaluation of Mechanical Properties of Mycelium-Based Biomaterial

2.9.1 Compression Strength

Compression strength was measured according to ASTM D3501-94, following the procedure described by Elsacker et al. (2019), using a Universal Testing Machine (UTM; Instron Model 5566, Instron Corporation, Norwood, MA, USA) (Figure 2.4). The test was conducted with a 10 kN capacity load bench and a

10 kN load cell, operated under ambient conditions at 25°C, with ~50% relative humidity. Tests were performed under displacement control at a rate of 5 mm min^{-1}, with five replicates per sample. Compression strength was expressed in kilopascals (kPa) and calculated from the load-displacement data using the following formulas: compressive stress (σ) = F/A and strain (ε) = ($\Delta L/L_o$), where F = compressive force (N), A = original cross-sectional area (m^2), ΔL = displacement of the loading surfaces (m), and L_o = original height of the specimen (m).

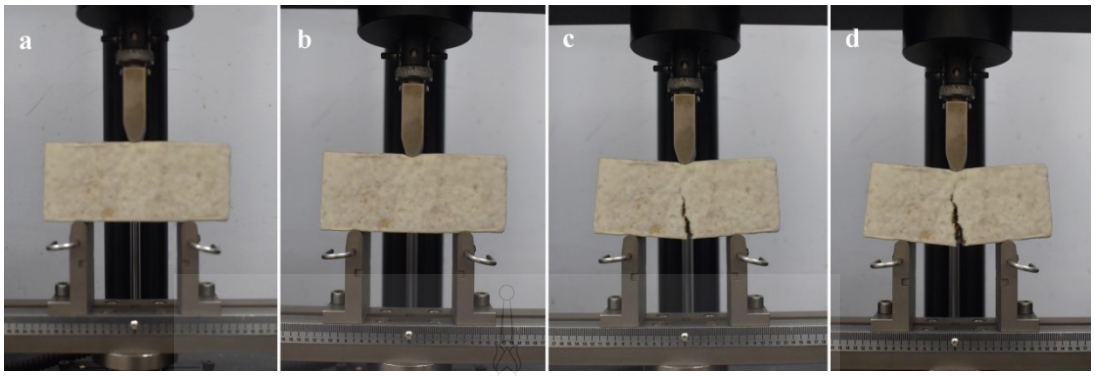


Note a Sample before testing. b Bulging during compression. c Cracking

Figure 2.4 Compressive strength test of MMB developed from *Panus ciliatus* (MFLUCC 25-0173) and sawdust

2.9.2 Flexural Strength

Flexural strength was conducted according to ASTM D790-10, following the procedure described by Appels et al. (2019), using a Universal Testing Machine (UTM; Instron and Model 5566) (Figure 2.5). The test was performed with a cross-head speed of 2 mm min^{-1} and a clamp support span of 100 mm. Each strain was tested in five replications. Flexural strength was expressed in kilopascals (kPa) and calculated from the load-displacement data using the formulas: flexural stress (σf) = $3FL/(2bd^2)$, where F = applied load at fracture (N), L = support span (m), b = specimen width (m), and d = specimen thickness (m).

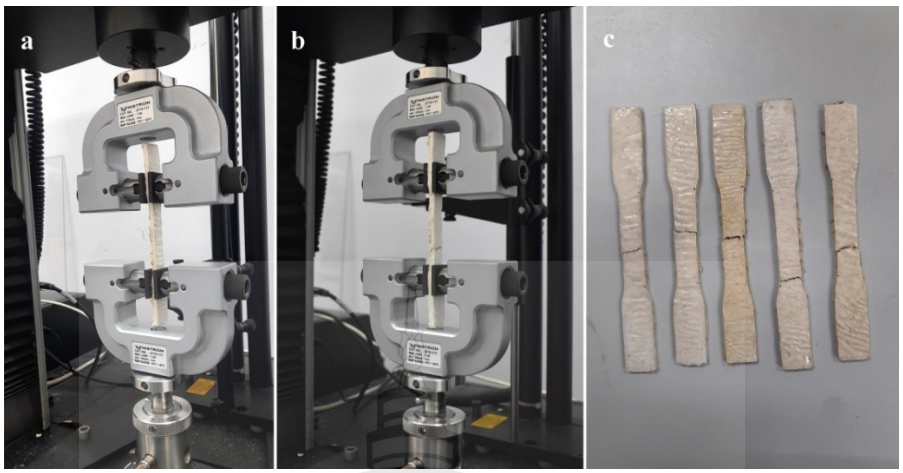


Note a Sample before testing. b Bending under load. c Initial crack formation. d Complete crack.

Figure 2.5 Flexural strength test of MMB developed from *Panus ciliatus* (MFLUCC 25-0173) and sawdust

2.9.3 Tensile Strength

Tensile strength was measured according to ASTM D638-14, following the procedure described by Appels et al. (2019), using a Universal Testing Machine (UTM; Instron Model 5566). Tests were operated at a crosshead speed of 2 mm min^{-1} and a maximum load capacity of 1 kN, under ambient conditions at 25°C, with ~50% relative humidity (Figure 2.6). Samples were held in the grips of the tensile testing machine and pulled until fracture occurred. Tensile stress was recorded in relation to strain and plotted as a stress-strain curve. Each strain was tested in five replicates. Tensile strength was expressed in kilopascals (kPa) and calculated from the load-displacement data using the formulas: tensile stress (σt) = F/A, where F = maximum tensile force at fracture (N) and A = original cross-sectional area of the specimen (m^2).



Note a Application of tensile force on the sample. b Beginning of a crack on the sample. c Sample after crack

Figure 2.6 Tensile strength test of MMB developed from *Panus ciliatus* (MFLUCC 25-0173) and sawdust

2.9.4 Impact Strength

Impact strength was measured using the Charpy impact test according to ASTM D256, following the procedure described by Aiduang et al. (2022c), using an Impact Pendulum Machine (Instron; Model CEAST 9050). Samples were loaded in the testing machine and subjected to a pendulum strike until fracture occurred. Each strain was tested with five replicates. Impact strength (IS) was calculated as: $IS = K/A$, where K = energy required to fracture the sample (kJ) and A = cross-sectional area of the sample (m^2).

2.10 Evaluation of Hydrodynamic Properties of Mycelium-Based Biomaterial

2.10.1 Water Absorption

Water absorption rate was measured following ASTM C272/C272M-18, as described by Attias et al. (2019), by partially submerging the MMB samples in water

at room temperature (25°C, 50% RH). The water absorption rate was determined based on the change in weight relative to the initial dry weight.

2.10.2 Water Contact Angle

The water contact angle (CA) was measured using a contact angle meter (Kino SL200KS, Puditec, Bangkok, Thailand) following the procedure described by Antinori et al. (2021). A 5 μL droplet of deionised water was statically deposited on the sample surfaces of each sample, and side-view images of the droplets were captured at 10 and 60 s. Each treatment was replicated 15 times.

2.11 Evaluation of Chemical Properties of Mycelium-Based Biomaterial

The MMB samples were ground into a powder form using a blender and sieved to obtain particles smaller than 2 mm. The pH of the samples was determined following Alemu et al. (2022a) by mixing 5 g of each sample in 50 mL Milli-Q water for 1 h and measuring with a calibrated pH meter. Electrical conductivity (EC) was measured using a conductivity meter. Organic matter (%) and nitrogen (%) contents were determined following the Walkley-Black method (Sánchez & Montoya, 2020) and the Kjeldahl method (Attias et al., 2017), respectively. Organic carbon (%), phosphorus (%), and potassium (%) were measured using a total organic carbon analyser, a spectrophotometer, and a flame photometer, respectively.

2.12 Scanning Electron Microscopy

Samples (5 × 5 mm) were cut using a dissecting blade, mounted on stub adapters with double-sided carbon tape, and gold-coated for 2 min under high vacuum, following Aiduang et al. (2022c). Surface morphology was observed using a scanning electron microscope (SEM; TESCAN MIRA, 4th Generation, Tescan

Orsay Holding, Brno-Kohoutovice, Czech Republic) operated at 5 kV with TESCAN's Essence™ software. The surfaces and cross-sectional characteristics of the biomaterials were examined.

2.13 Thermogravimetric Analysis

Approximately 8 mg of pure mycelium from fungal species were analysed using a thermogravimetric analysis (TGA) with a thermal analyser (Mettler Toledo, TGA/DSC3+ HT, Mettler Toledo, Greifensee, Switzerland), following Cartabia et al. (2021). Samples were heated from 25°C to 900°C at a scanning rate of 20°C min^{-1} under a constant nitrogen purge flow of 25 mL min^{-1}.

2.14 Fourier Transform Infrared Spectroscopy

FTIR spectroscopy was performed to characterise the chemical composition of the pure mycelium samples using attenuated total reflectance (ATR-FTIR) spectroscopy (Nicolet iS50, Thermo Fisher Scientific Inc., Madison, WI, USA), following Raman et al. (2022). Spectra were recorded in the range of 4000−400 cm^{-1} with a resolution of cm^{-1}.

2.15 Flammability

Flammability testing followed the UL-94 standard for horizontal and vertical burning (Suthatho et al., 2024). Samples (125 × 13 mm) were tested in both orientations. In the horizontal burning test, each sample was held horizontally and exposed to a 20 mm high Bunsen burner flame for 30 s, and the flaming duration and burning length were recorded. In the vertical burning test, the sample was positioned vertically, and the flame was applied to the bottom for 10 s, and flame duration and

burning characteristics were recorded. Each test was replicated five times per species.

2.16 Soil Burial Degradability

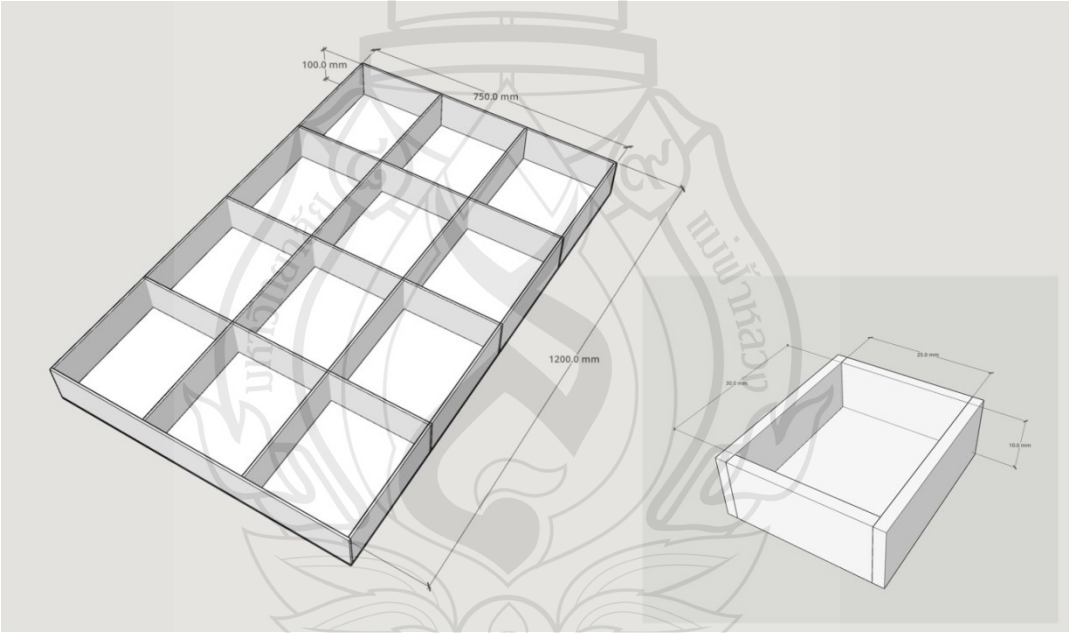
A biodegradability test was performed under soil burial conditions (ISO 846/2000) using fine-grained active soil from forest areas in Chiang Rai Province, Thailand. The soil was sieved to obtain particles smaller than 2 mm (Aiduang et al., 2022c). Test samples were wrapped in synthetic netting and buried in soil for 90 days. Five replicates were prepared per treatment. Samples were removed at 15, 30, 45, 60, 75, and 90 days, cleaned, and dried at 60°C to constant weight. Weight loss was calculated using the formula: WL (%) = $(W_i\text{-}W_t)/W_i \times 100$, where WL = the percentage of weight loss (%), W_i = initial weight (g), W_t = weight after the specified time (g).

2.17 Viability Maintenance of Fungal Strains

The viability of fungal strains was maintained through basidiomata formation, following the method described by Aiduang et al. (2024). Fresh basidiomata were produced using the same substrate composition as in the test sample preparation. Cultivation bags were incubated in the dark at 25°C, and then transferred to a fruiting chamber at 25 ± 1°C, 75–80% relative humidity, with illumination. The resulting basidiomata were used for isolation and preparation of a pure culture for further study. Five cultivation bags were used for each species.

2.18 Developing Prototypic Product

The mushroom mycelium and sawdust substrate mixture was used to develop a biomaterial prototypic insulation wall (Figure 2.7). The blocks were developed following the procedure of the test sample development. The completely colonised blocks by mycelium were dehydrated at 60°C for 5 days until the dried weight became stable. Individual blocks (30 × 25 × 10 cm) were placed into a large panel framework (120 × 75 × 10 cm) made of transparent acrylic sheets. Similarly, various constructions, household, and decorative items, such as vases, bowls, and blocks, were also designed and fabricated.



Note Figures generated using SketchUp online software (https://sketchup.trimble.com/en/products/sketchup-for-web?srsltid=AfmBOooktqmmGypuCyXg51tYY75e2Rc7DboJBvrthMHPxsEhkmCmJTZS)

Figure 2.7 Main framework and individual mould for preparing an insulating wall

2.19 Data Collection and Statistical Analysis

Data analysis was performed using the statistical software SPSS v.16.0. Data on mycelial growth rate, dry biomass, physical, mechanical, hydrodynamic, chemical tests, flammability tests, and soil burial biodegradability test were analysed using one-way analysis of variance (ANOVA). An independent samples t-test was performed to compare the means of two independent groups. The multiple comparisons of means were deployed when significant differences were found (p<0.05) using Duncan's Multiple Range Test (DMRT).

CHAPTER 3

RESULTS AND DISCUSSIONS: EXPLORING MYCELIUM-BASED BIOMATERIALS USING SELECTED FUNGAL STRAINS AND SAWDUST

3.1 Study on Pure Mycelium Mats Developed from *Phlebiopsis friesii*

3.1.1 Taxonomy

Phlebiopsis friesii (Lév.) Spirin & Miettinen Figures 3.1, 3.2

Index Fungorum number: IF 817924; *Facesoffungi number*: FoF 16523

Basidiomata 3−7.5 cm in length and 3−4 cm in width, up to 1.5 mm thick, annual, effused-reflexed, thin, flattened, connected to the substrate by the side but can be separated, concentrically furrowed, not cracked when dried; *Surface* strigose, spongy; sordid grey, zoned violet-purple from the base to the edge, turning purple in KOH. *Hymenium* 162−199 µm, glabrous, waxy, brown (8E5–8). *Margin* distinct, strigose, spongy, wavy, lilac (16B4). *Subiculum* fairly uniform, compact texture with parallel hyphae, light brown (7D5–6). *Subhymenium* thin. *Stipe* absent. *Odour and taste* not noted.

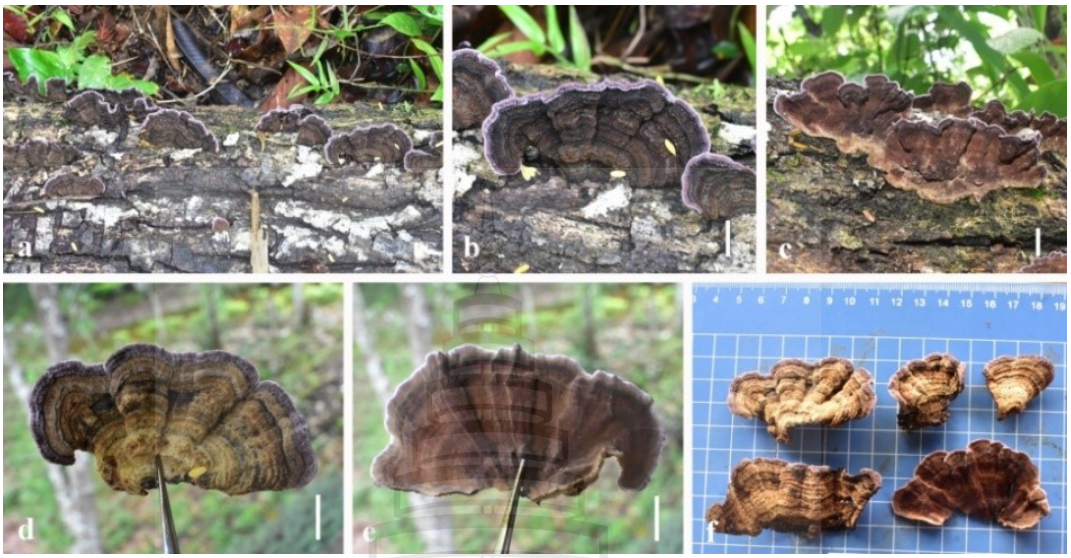
Basidiospores (3.8–)4.1–6.5(–6.8) × (3.5–)3.8–4.9(–5.2) µm, L = 4.9 ± 0.6 µm, W = 4.1 ± 0.4 µm, Q = 1.18 ± 0.17 (n = 30), globose, hyaline, smooth. *Basidia* up to 27.5 × 5.6 µm, clavate to subcylindrical, hyaline. *Sterigmata* up to 4.5 µm, four-spored. *Lamprocystidia* up to 77 × 18 µm, larger, thick-walled, scattered, conical, apically encrusted with small crystals. *Pileipellis* hypha 12.4–24.3 × 4.4–7.3 µm, septate, hyaline. *Hyphal system* monomitic; generative hyphae 3–6.7 µm, simple septate, hyaline. *Culture characteristics* white, thin, and non-fluffy.

Habitat: on a decaying log, mixed deciduous forests.

Material examined: THAILAND, Chiang Mai Province, Mae Taeng District, N 19° 7' 7", E 98° 43' 59", Alt. 919 m, 22 July 2023, Collector Sabin Khyaju, SK205, living culture MFLUCC 24-0323, MFLU24-0306.

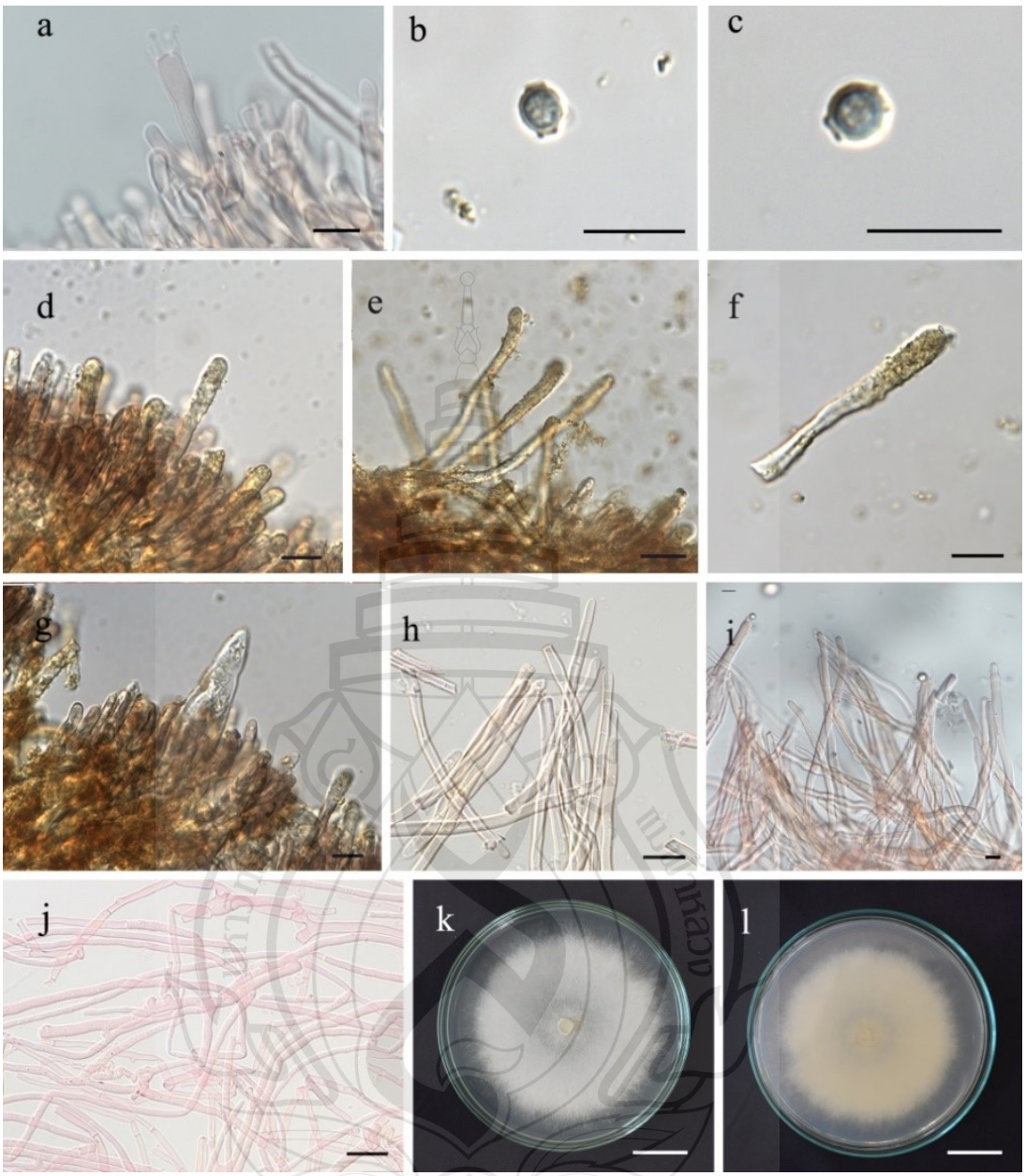
GenBank accession numbers: ITS: PZ569315, LSU: PQ569317.

Known distribution (based on molecular data): Sri Lanka (Zhao et al., 2021) and Thailand (this study).



Note a–f Fresh basidiomata growing on a host. Scale bar: a−e = 1 cm

Figure 3.1 Basidiomata of *Phlebiopsis friesii* (MFLU24-0306)



Note a Basidia. b–c Basidiospores. d–f Cystidia with encrustation. g Lamprocystidia. h Pileipellis. i Hyphae in trama. j Hyphae in PDA culture. k Culture in PDA medium, upper view after incubating at 25°C for 7 days. l Culture in PDA, bottom view after incubating at 25°C for 7 days. Bar: a−d, f−g, i = 10 µm; e, h, j = 20 µm; k−l = 2 cm

Figure 3.2 Micro-morphology of *Phlebiopsis friesii* (MFLU24-0306)

Notes: The morphological characteristics of our specimen align with the original description of the holotype, which was characterised by an agglutinated lower

subiculum, well-developed upper subiculum, simple septate and parallel hyphae, and larger, conical, encrusted lamprocystidia (Zollinger, 1854; Hjortstam & Ryvarden, 1990). In addition, basidiomata are sessile, flattened, effused-reflexed, laterally connected to the substrate, concentrically furrowed, spongy, and the hymenophore turns purple in KOH (Hjortstam & Ryvarden, 1990).

3.1.2 Phylogenetic Inferences

Phylogenetic analyses were inferred from the combined ITS and LSU sequences, comprising 49 taxa, including our species, 23 *Phlebiopsis* species, and one outgroup species, *Rhizochaete americana* FP 102188 (Figure 3.3). The final dataset comprised 1408 total characters, including gaps: 876 characters for ITS and 875 characters for LSU. The dataset comprised 1408 characters, of which 1176 were constant, 151 variable characters were parsimony-informative, and 81 characters were parsimony-uninformative. The best-scoring ML tree is shown in Figure 3.3, with an optimal log-likelihood value of -4650.709782. The proportion of gaps and undetermined characters was 7.01%. Estimated base frequencies were A = 0.250195, C = 0.204722, G = 0.274387, T = 0.270695; substitution rates AC = 0.962009, AG = 4.418854, AT = 2.027812, CG = 0.512010, CT = 7.467033, GT = 1.000000; and the gamma distribution shape parameter α = 0.076105. Phylogenetic analyses indicated the placement of our isolate within the *Phlebiopsis friesii* clade with strong support (ML = 99%, MP = 98%).

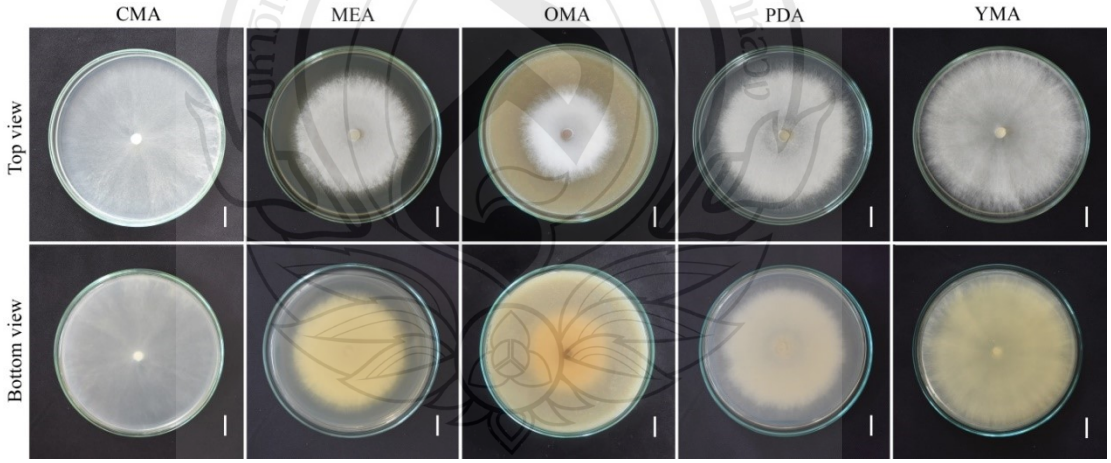
Note Phylogenetic tree (RAxML) obtained from the DNA sequence data of the ITS and LSU datasets. Bootstrap values (BS) from maximum likelihood (ML, left) and maximum parsimony (MP, right) greater than 70% are indicated above the nodes. The tree is rooted with *Rhizochaete americana* FP 102188. Newly geographically recorded species are indicated in red bold.

Figure 3.3 Phylogenetic tree of *Phlebiopsis*

3.1.3 Screening the Optimal Culture Agar Media, Dry Biomass, and Density of Mycelium

Five agar media tested, MEA, PDA, and YMA cultures exhibited favourable growth characteristics (Figure 3.4, Table 3.1). Mycelium in all five media was white to pale white. However, they differed in mycelium growth rate, dry mass, and density. An increase in the diameter of the mycelial plug was observed starting from day 2. Mycelium growth on CMA and YMA covered the agar in the first 7 days. The mycelium colony density was observed to be somewhat abundant (4+) in MEA, OMA, PDA, and YMA, while scanty (2+) in CMA. The highest mycelium dry biomass was obtained in OMA, followed by PDA, MEA, YMA, and CMA.

Although the mycelial dry mass in OMA was the highest (0.1886 g), it was not selected due to its slowest growth rate (3.77 mm/day). Conversely, while CMA exhibited a rapid growth rate (5.71 mm/day), it was excluded due to its scanty mycelial density (2+). Both CMA and YMA allowed rapid surface coverage; however, YMA had a higher mycelial dry mass (0.1114 g) and demonstrated a somewhat abundant (4+). Based on a comprehensive evaluation of growth rate, dry biomass, and colony density, MEB, PDB, and YMB were selected for further tests.



Note Cultures were incubated on different agar media at 25°C for 7 days. Scale bars = 1 cm.

Figure 3.4 Mycelial characteristics of *Phlebiopsis friesii* (MFLUCC 24-0323)

Table 3.1 Effect of different agar media on the mycelial growth rate, dry mass, and mycelium density of *Phlebiopsis friesii* evaluated after incubation at 25°C for 12 days

Culture agar media	**Mycelium growth rate (mm/day)**	**Mycelium dry mass (g)**	**Mycelium density (day 7)**
CMA	5.71 ± 0.00^{a}	0.0483 ± 0.0243^{d}	2+
MEA	4.47 ± 0.50^{c}	0.1424 ± 0.0255^{bc}	4+
OMA	3.77 ± 0.27^{d}	0.1886 ± 0.0113^{a}	4+
PDA	4.83 ± 0.38^{b}	0.1662 ± 0.0579^{ab}	4+
YMA	5.63 ± 0.22^{a}	0.1114 ± 0.0195^{c}	4+

Note Within a column, values with the same letter are not significantly different ($p < 0.05$) by Duncan's Multiple Range Test

3.1.4 Preliminary Characterisation of Mycelium-Based Biomaterials

Pure mycelium mats were grown in MEB, PDB, and YMB for 30, 45, and 60 days (Figure 3.5). All treated mats exhibited light brown to brownish skin, while the control mats were white to greyish-white. Pure mycelium mats were thicker with an increased cultivation period. However, mycelium mats in YMB in all three growth periods had a translucent layer at the centre. Furthermore, due to hot pressing, the treated mats had a smoother surface compared to the control mats with fluffy mycelium skin.

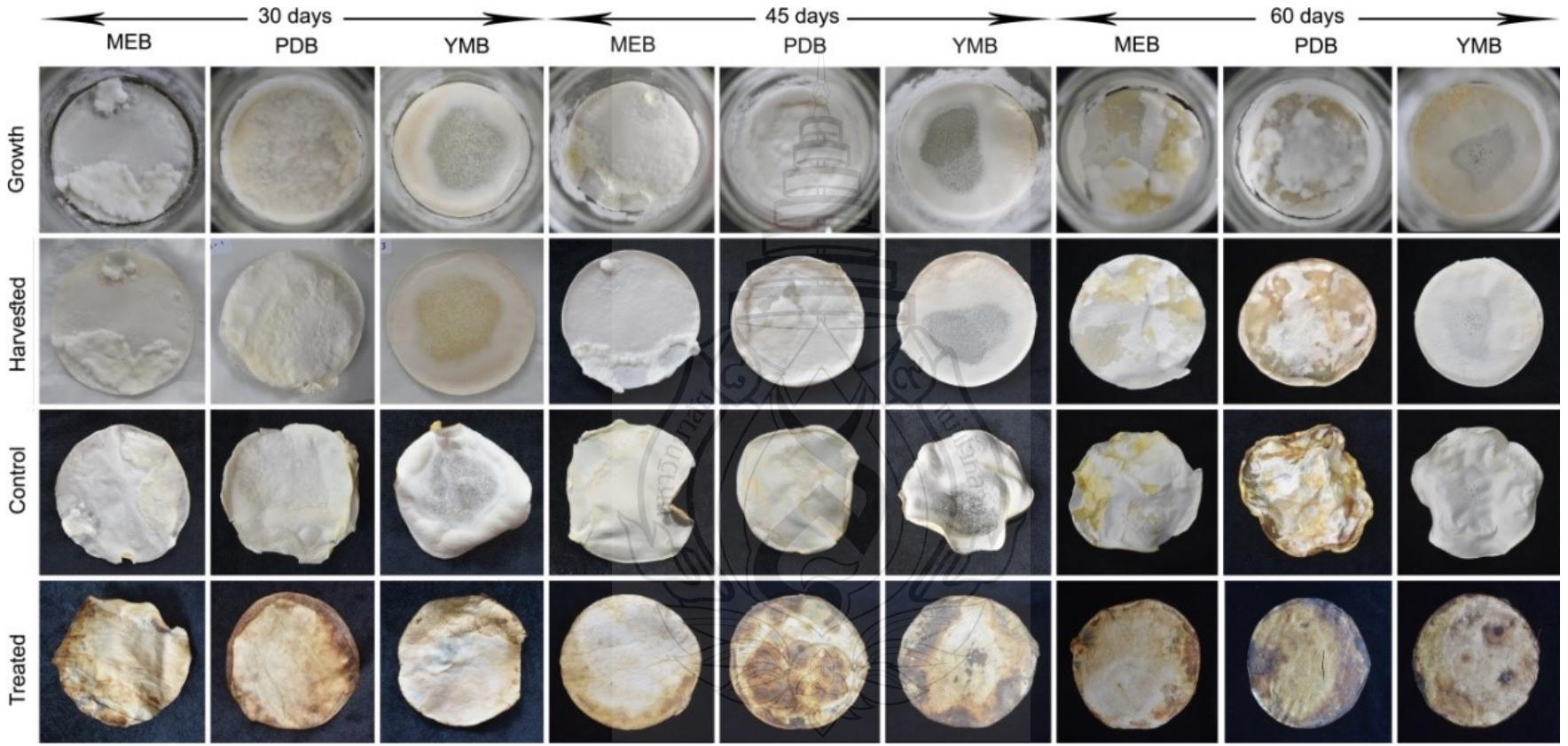


Figure 3.5 Pure mycelium mats grown of *Phlebiopsis friesii* (MFLUCC 24-0323) in different media on days 30, 45, and 60

3.1.4.1 Biomass of Mycelium Mats

The mycelium grown in MEB, PDB, and YMB exhibited increasing biomass yield in all three growth durations (days 30, 45, and 60) (Table 3.2). Among the three media, the biomass yield was highest in YMB, followed by PDB and MEB. For instance, the dry mycelium mat harvested from the YMB had the highest weight at 0.72 ± 0.02 g, and MEB had the lowest weight at 0.35 ± 0.05 g on day 30.

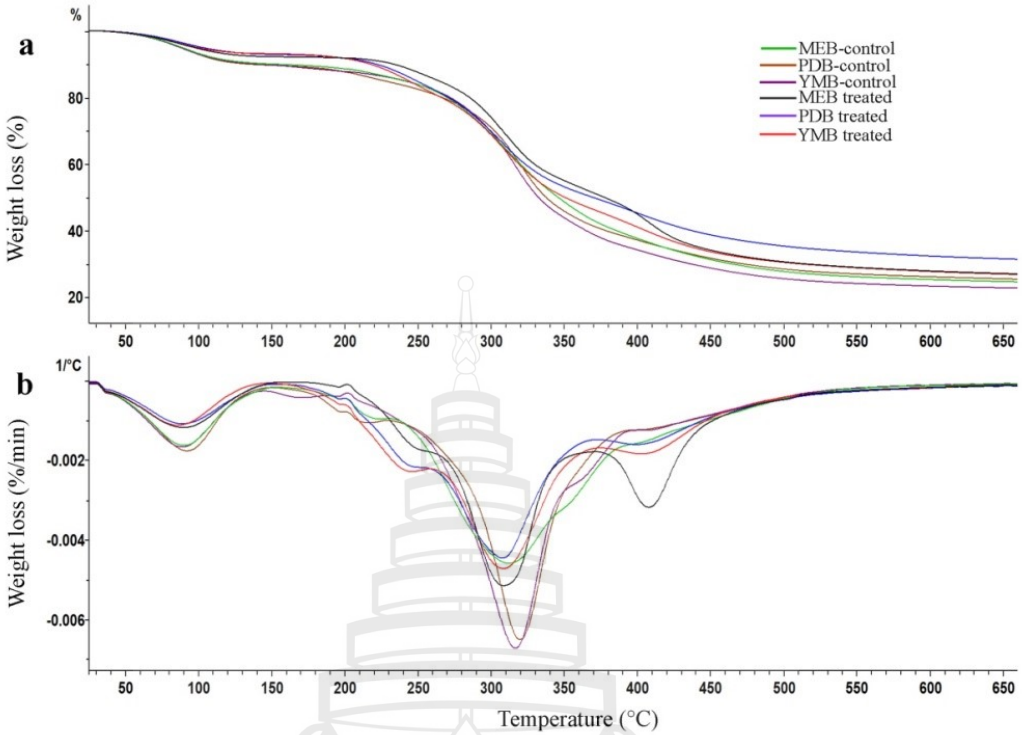
Table 3.2 The yield of mushroom mycelium dry biomass measured after incubation in different media at various periods

Culture agar media	**Mycelium dry biomass (g)**		
	day 30	**day 45**	**day 60**
MEB	0.35 ± 0.05^{c}	0.43 ± 0.06^{c}	0.50 ± 0.08^{c}
PDB	0.60 ± 0.02^{b}	0.63 ± 0.02^{b}	0.65 ± 0.02^{b}
YMB	0.72 ± 0.02^{a}	0.75 ± 0.02^{a}	0.77 ± 0.01^{a}

Note Within a column, values with the same letter are not significantly different ($p < 0.05$) by Duncan's Multiple Range Test.

3.1.4.2 Thermogravimetric Analysis

Thermal analysis data, represented by TGA curves and the first derivative of TGA curves (DTGA), are shown in Figure 3.6. All the mats demonstrated similar thermal degradation behaviour in all three test stages. The first event was observed below 95°C, resulting in an 8.51% weight loss. The first event peaked at around 90°C for the control, with a 10.09% weight loss, and at 87°C for the treated sample, with a 6.93% weight loss. In the second event, the degradation peak temperature was approximately 316°C for the control samples, resulting in 65.13% weight loss, and 308°C for the treated samples, with 55.5% weight loss. The third event (decomposition) is associated with non-degraded wastes and impurities, with 24.04% in control samples and 28.32% in treated samples. Water content was higher in control samples (9.78–10.53%) than in treated samples (6.47–7.32%), as shown by the weight loss at 89°C.

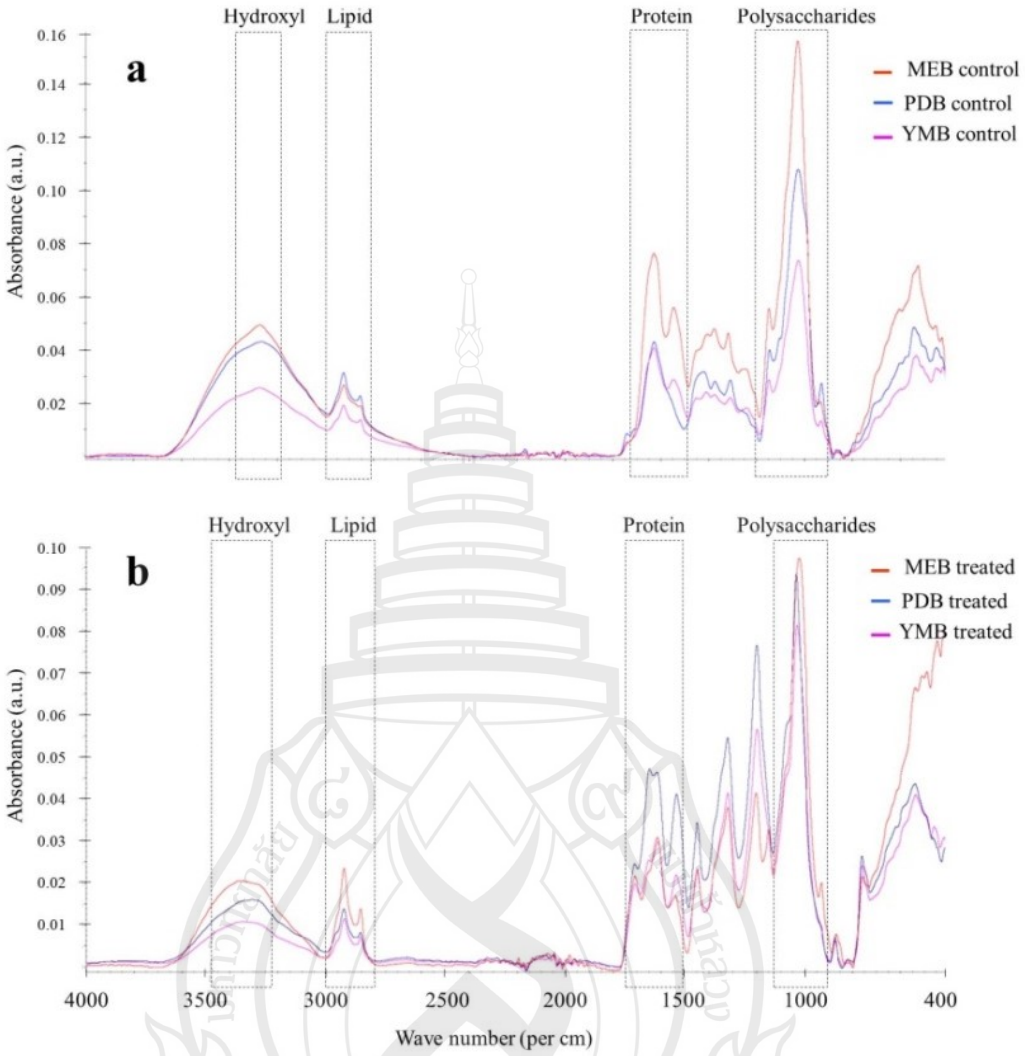


Note The different colour lines represent control and treated mycelium mats. a TGA. b DTGA.

Figure 3.6 Thermal analysis of pure mycelium mats of *Phlebiopsis friesii* (MFLUCC 24-0323)

3.1.4.3 Fourier Transform Infrared Spectroscopy

The FTIR spectroscopy of the treated and control mycelium mats grown for 45 days is shown in Figure 3.7. The analysis shows representative spectra of the mycelium mats developed on MEB, PDB, and YMB. Chemically significant regions in the spectra mainly fatty acid region dominated by C–H (3350–3150 cm^{-1}), amide region dominated by C=O amide I and N–H amide II bands of proteins and peptides (1700–1500 cm^{-1}), mixed region (1500–1200 cm^{-1}), polysaccharides region (1200–900 cm^{-1}), and true fingerprinting region (900–700 cm^{-1}) were identified. Details of the obtained bands are provided in Table 3.3.



Note The major absorption bands indicating the mycelium cell wall components are labelled. a control. b treated.

Figure 3.7 FTIR spectra of mycelium mats developed using *Phlebiopsis friesii* (MFLUCC 24-0323)

Table 3.3 FTIR spectra (4000−400 cm^{-1}) analysis of the mycelium mat from *Phlebiopsis friesii* (MFLUCC 24-0323) grown in various media

Spectra	Wavenumbers (cm^{-1})						
	Control			Treated			Components
	MEB	PDB	YMB	MEB	PDB	YMB	
O−H stretching	3272.5	3261.67	3271.42	3361.23	3342.57	3307.53	Polysaccharides
CH_2 asymmetric stretching	2920.67	2922.2	2922.08	2921.73	2921.41	2922.51	Lipids
CH_2 symmetric stretching	−	2853.88	2859.29	2852.5	2852.32	2853.31	Lipids
Ester C=O stretching	−	−	−	1706.15	1706.51	1707.73	Lipids
amide I (β-turn)	1626.45	1624.95	1625.68	1612.47	1610.08	1645.95	Proteins
amide II (β-sheet)	1543.31	−	1544.12	1537.76	1533.9	1533.05	Proteins
CH_2 bending	−	1417.87	1407.88	1446.53	1445.27	1445.48	Lipids
C−H bending	1374.46	1372.08	1373.54	1318.21	1317.96	1318.74	Chitin
$PO2^-$ asymmetric stretching	1244.05	−	1239.82	−	−	−	Nucleic acids

Table 3.3 (continued)

Spectra	Wavenumbers (cm^{-1})						Components
	Control			Treated			
	MEB	PDB	YMB	MEB	PDB	YMB	
C−C stretching + C−O stretching + C−H deformation	−	−	1145.87	1200.42	1195.98	−	Polysaccharides
C−O…H stretching	1146.02	1143.7	−	−	−	−	Polysaccharides
C−C stretching	1026.08	1024.78	1023.07	1020.23	1028.11	−	Polysaccharides
Glucan β-anomer C−H bending	−	−	−	866.31	870.08	871.13	Polysaccharides
Mannan band	523.88	540.57	531.87	755.25	756.67	757.75	Polysaccharides

Note "–" = not available

3.1.4.4 Scanning Electron Microscopy

The scanning electron microscopy (SEM) images of pure mycelium mats obtained by growing in PDB, MEB, and YMB resulted in similar hyphal morphology of the mats (Figure 3.8). The upper surfaces of the mats were generally hairy (fluffy) or loosely interwoven hyphae, while the lower surface was smooth, dense, and flattened. In treated samples, the upper and lower surfaces were smooth, dense, and flattened, which was not present in the control samples. Many anastomoses among hyphae were observed in treated mycelium mats compared with the control.

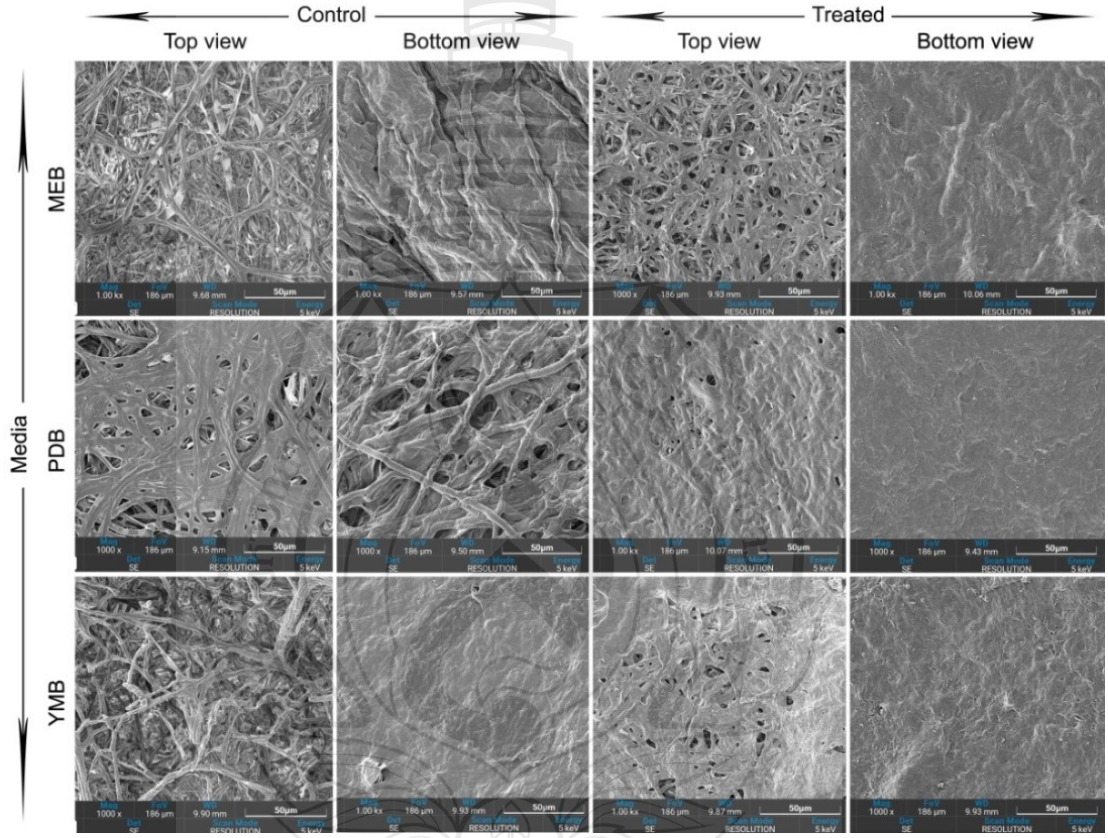


Figure 3.8 Scanning electron microscopy of control and treated pure mycelium mats of *Phlebiopsis friesii* (MFLUCC 24-0323)

3.1.4.5 Water Contact Angle Analysis

The water contact angle (WCA) of the pure mycelium mats, both control and treated (glycerol, tannic acid, and hot pressed), was compared (Figure 3.9, Table 3.4). The WCA values for the control sample, at 10 and 60 sec, exhibited a hydrophobic nature above 90°. In contrast, the WCA values for treated samples at 10

and 60 sec were close to or below 90°, indicating hydrophilic behaviour. Water absorption up to 60 sec was negligible for both control and treated samples, showing similar behaviour.

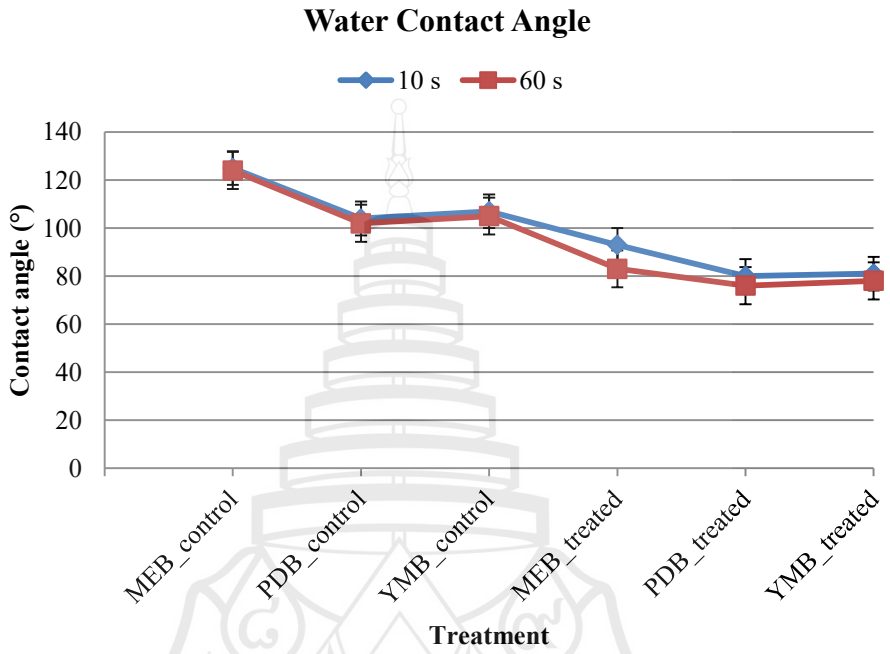


Figure 3.9 Water contact angle values of *Phlebiopsis friesii* (MFLUCC 24-0323) pure mycelium mats measured at 10 sec and 60 sec

Table 3.4 The water contact angle values of pure mycelium mat samples measured at 10 and 60 seconds

Samples	**Contact angle value (°)**	
	at 10 sec	**at 60 sec**
MEB, control	124.86 ± 5.04[a]	123.96 ± 5.92[a]
PDB, control	104.08 ± 8.51[b]	101.63 ± 10.01[b]
YMB, control	107.46 ± 4.88[b]	104.51 ± 8.03[b]
MEB, treated	93.21 ± 2.93[c]	83.29 ± 14.68[c]
PDB, treated	79.87 ± 5.04[d]	75.52 ± 8.66[d]
YMB, treated	81.47 ± 8.28[d]	78.44 ± 9.51[cd]

Note Within a column, values with the same letter are not significantly different ($p < 0.05$) by Duncan's Multiple Range Test.

3.1.5 Discussion

Mycelium-based biomaterials provide an eco-friendly, sustainable alternative to traditional animal-based leather (Raman et al., 2022). Despite the abundance of mushroom species in nature, only a few have been studied for the development and characterisation of pure mycelium materials. Among these, mushroom species from Polyporales have demonstrated promising characteristics essential for advancing mycelium-based biomaterial research (Cerimi et al., 2019; Attias et al., 2020; Bae et al., 2021). In this study, the mushroom specimen collected from Thailand was identified as *Phlebiopsis friesii* through a combination of morphological characteristics and phylogenetic analyses, establishing a new geographical record for Thailand. The phylogenetic analyses based on two loci (ITS and LSU) placed our specimen within the *Phlebiopsis friesii* clade with ML = 99% and MP = 98% support, including strains obtained from Sri Lanka (MT452528, MT452529, MT452530).

The mushroom mycelium was cultured on five different agar media to determine the most suitable for mycelium cultivation. Based on factors such as growth rate, dry mass, and density, MEA, PDA, and YMA were determined to be the most effective. Although CMA had the fastest growth rate (5.71 mm/day), it exhibited the thinnest culture density (2+) and the lowest mycelial dry mass, which led to its exclusion from further tests.

This study presents the first preliminary characterisation of pure mycelium mats from *Phlebiopsis friesii* worldwide. From the previous studies, broth media were recommended for the development of higher-quality mycelium mats (Bae et al., 2021; Raman et al., 2022). Kniep et al. (2024) also reported lower contamination rates and faster growth in liquid-state surface fermentation (LSSF) compared to solid-state fermentation (SSF). In this study, pure mycelium mats of *P. friesii* were cultivated in nutrient broths (PDB, MEB, and YMB) and subjected to heat denaturation after growth. The properties of the treated mats (glycerol, tannic acid, and hot-pressed) were compared with those of the untreated control mats across different media and growth durations. The treated samples exhibited more favourable characteristics, indicating their potential for mycelium mat production. Glycerol, a widely used plasticiser, enhanced the flexibility and hydrophobicity of the mats (Sejidov et al., 2005; Janjarasskul & Krochta, 2010; Haneef et al., 2017). Tannic acid facilitated

cross-linking between the hyphae, improving the mechanical properties of the mats. Among the three media, YMB yielded the highest biomass at 30, 45, and 60 days, followed by PDB. This suggests that the incubation period had a significant impact on the yield of mycelium biomass. The nutrient content, particularly glucose, likely played a critical role in influencing mycelium behaviour.

The TGA and DTGA of both control and treated pure mycelium mats demonstrated similar thermal behaviour at all three stages (Figure 3.6). The lower water content in the treated sample is due to the incorporation of glycerol. Moreover, heat pressing during treatment removed the moisture from the samples. The lower temperature value is attributed to the removal of free and chemically linked water (Joseph et al., 2003; Bruscato et al., 2019). In addition, the treatment caused crosslinking between hyphae, resulting in increased enzymatic stability and reduced water content (d'Errico et al., 2024). The hyphal cell wall enhances the thermal stability of the mycelium mats at higher temperatures (Cartabia et al., 2021). The reduction in mycelium mat mass with increasing temperature reflects the decomposition of inherent organic compounds. In addition, the changes in the curves of the treated samples around 325°C and 400°C might be due to the response of tannic acid and glycerol, respectively. This stage relates to the thermal degradation of lignocellulosic components (i.e., cellulose, hemicellulose, and lignin), which occurs between 220 and 410°C (Kim et al., 2006; De Rosa et al., 2010; Borsoi et al., 2013; Bruscato et al., 2019). The third event (decomposition) is associated with non-degraded waste and impurities (Hammoui et al., 2015; Bruscato et al., 2019).

The FTIR of control and treated pure mycelium mats of *P. friesii* (Figure 3.7) demonstrated their chemical constituents. The FTIR spectral bands correspond to the natural vibrations of the infrared-active molecular bonds (Bustillos et al., 2020). FTIR of control samples exhibited a higher contribution of lipids and polysaccharides than treated mats grown in all three media. In treated mats, the shoulder peak is around 1700 cm^{-1}, and the sharp peak at 1200–1300 cm^{-1} might be attributed to C=O stretching and C–O stretching of tannic acid. This phenomenon indicates the crosslinking between hyphae caused by tannic acid and heat press (Wahyono et al., 2019; d'Errico et al., 2024). The differences in peak heights were due to the effect of the growth media.

The SEM analysis revealed detailed information about the mycelial microstructure but did not address chemical composition. Pure mycelium mats derived from the three broth media exhibited similar hyphal morphology under SEM. However, treatments with glycerol, tannic acid, and hot-pressing resulted in a smoother, more condensed, and flattened surface morphology (Cartabia et al., 2021). These modifications improved the consistency and structural integrity of the mycelium mats, enhancing their suitability for practical applications.

The WCA is significantly influenced by the surface topography of the samples (Sun et al., 2020; Antinori et al., 2021; Raman et al., 2022). Control samples exhibited higher hydrophobicity, whereas the treated samples exhibited similar or lower WCA values, indicating hydrophilic behaviour. This shift is likely due to additives such as glycerol, which enhance water absorption (Asadollahzadeh et al., 2022). However, further research is necessary to better understand these properties and optimise the final mycelium products. For instance, tensile strength measurements were not feasible due to the brittleness of the treated mycelium mats.

3.2 Study on Mycelium-Based Biomaterials Developed from *Panus ciliatus* and *P. subfasciatus*

3.2.1 Taxonomy

Panus ciliatus (Lév.) T.W. May & A.E. Wood, Figure 3.10

≡ *Lentinus ciliatus* Lév. *Annls Sci. Nat.*, Bot., sér. 3 2: 175

Index Fungorum number: IF 413663; *Facesoffungi number*: FoF 17547

Basidiomata small, stipitate, leathery, solid, and dry, with a densely ciliated margin. *Pileus* 1.7–2.8 cm in diameter, infundibuliform, shallow and concentrically furrowed, membranous. *Pileus surface* tomentose, almost uniformly thick, greyish-orange (6B5–6), brown bristles (7E7), and context negative to KOH. *Margin* entire, incurved, thin, densely ciliated. *Stipe* up to 1.8–5.5 cm long, 3.6–7.2 mm in diameter, cylindrical, tough, almost woody, concolourous with the lamellae, covered with very short hairs. *Lamellae* up to 0.2 mm broad, densely crowded, decurrent, vinaceous (8B4), with 3–4 tiers of lamellulae. *Odour and taste* not distinct.

Basidiospores (3.79–)4.27–6.42(–6.73) × (2.87–)3.67–4.95(–5.04) µm (n = 30/2), Lm = 5.62 µm, Wm = 4.29 µm, Qm = 1.31; ellipsoid to cylindric, thin-walled, with few contents. *Basidia* 15–27 × 4–6 µm, clavate, thin-walled, 4-spored, with sterigmata up to 6 µm long; clamps connections present at the base. *Lamella edge* sterile, with abundant cheilocystidia. *Hyphal pegs* present on the lamellar walls, up to 135 µm in diameter, up to 35 µm in length. *Cheilocystidia* 18–24.4 × 5.2–6.4 µm, clavate, hyaline, thin-walled. *Sclerocystidia* abundant on the gill sides, 21.9–32.3 × 3.7–6.7 µm, clavate, hyaline, thin-walled. *Pileipellis* brownish, slightly thick-walled, cylindrical; generative hyphae 4.3–6.1 µm wide, with clamp connections. Context generative hyphae 4.4–5 µm wide, hyaline, thin-walled, with clamp connections. Context skeletal hyphae 5.1–5.9 µm wide, cylindrical, hyaline, slightly thick-walled.

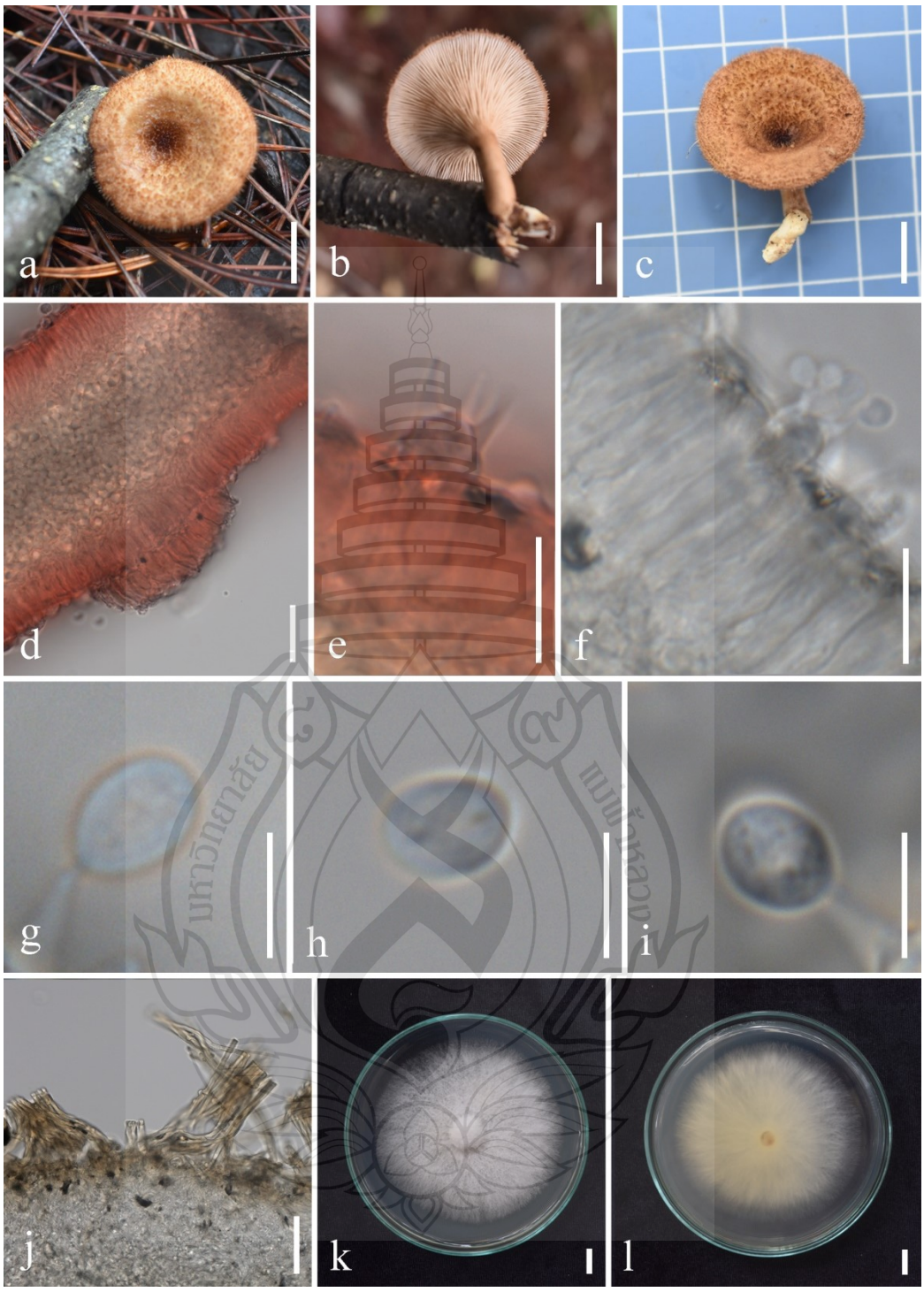
Habitat: On decaying branches in a mixed deciduous forest.

Material examined: Thailand, Chiang Rai Province, N 20°9'59", E 99°37'2", alt. 1200 m, 12 June 2024, S. Khyaju, SK288, MFLUCC 25-0173, MFLU 25-0108.

GenBank Number: ITS: PV393836.

Known distribution (based on molecular data): Brazil, China, India, Indonesia, Pakistan, Philippines, Singapore, Sri Lanka, the USA, Vietnam (Sousa-Guimarães et al., 2024), and Thailand (this study).

Notes: The morphological characteristics of our specimen are similar to the original description of the holotype from Maluku, Indonesia, which is characterised by its leathery, infundibuliform pileus, concentrically furrowed, tomentose, brown bristles, and sharply defined, densely ciliated margin (Léveillé, 1844). However, hyphal pegs were not observed in the descriptions of either the holotype or the Brazilian specimen (SP446150) (Sousa-Guimarães et al., 2024).



Note a–c Basidiomata. d Hyphal peg outgrowth in the hymenium. e–f Hymenium showing Basidia. g–i Basidiospores. j Pileipellis hyphae. k Culture (top view). l Culture (bottom view). Scale bar: a–c, k–l = 1 cm, d = 20 µm, e–f = 10 µm, g–i = 5 µm, j = 50 µm.

Figure 3.10 Morphological characteristics of *Panus ciliatus* (MFLUCC 25-0173)

Panus subfasciatus Thongbai, Karun., C. Richter & K.D. Hyde, Figure 3.11

Index Fungorum number: IF 552827; *Facesoffungi number*: FoF 02915

Basidiomata small, stipitate, leathery, solid, and dry. *Pileus* 2–4.5 cm in diameter, thin, coriaceous, and infundibuliform, reddish-brown (8D6–7) to brownish-violet (11D6) when young. *Pileus surface* brown (7D5–6), velvety with numerous hispid squamules forming erect hairs or appearing hispid-strigose, context negative with KOH. Margin entire, incurved, hispid, densely ciliated. *Stipe* 2–5 cm long, 2.7–4.2 mm in diameter, cylindrical, entirely covered with dense, short, soft hairs; dull red (9C4) to greyish-red (9C5) when young, concolourous with the pileus. *Lamellae* up to 0.2 mm broad, with 3–5 tiers of lamellulae, deeply decurrent, brown (7D7), and moderately crowded. *Context* white to light brown (7D5) with purplish shade, composed of a dimitic hyphal system with skeletal hyphae. *Odour and taste* not distinct.

Basidiospores (5.55–)6.38(–7.40) × (3.73–)4.00(–4.40) µm (n = 30/2) L_m = 6.38 µm, W_m = 4.00 µm, Q = (1.49–)1.60(–1.68), Q_m = 1.60 µm; ellipsoid to elongate, hyaline, thin-walled, with few contents. *Basidia* 20–24 × 3–5 µm, clavate to elongate-clavate, mostly 4-spored, occasionally 2-spored, with sterigmata up to 5 µm long; clamps connections present at the base. *Lamella* edge sterile, with abundant cheilocystidia. *Cheilocystidia* 14–18 × 4–6 µm, clavate, hyaline, thin-walled. *Sclerocystidia* abundant on the gill sides, 23–35 × 5–8 µm. *Pileipellis* interwoven, brownish, slightly thick-walled; generative hyphae 3.0–5.8 µm wide, branched, with clamp connections. *Generative hyphae* included generative hyphae 1.7–3.1 µm wide, hyaline, thin-walled, and branching with clamp connections. *Skeletal hyphae* 2.9–3.7 µm wide, cylindrical, hyaline, and slightly thick-walled.

Habitat: On decaying branches in a mixed deciduous forest.

Material examined: THAILAND, Chiang Rai Province, Muang Chiang Rai District, N 20°3'6", E 99°53'30", alt. 422 m, 20 November 2022, S. Khyaju, SK49, MFLUCC 25-0172, MFLU 25-0107.

GenBank number: ITS: PV393835.

Known distribution (based on molecular data): Cameroon, China, India, Sri Lanka, the USA (Sousa-Guimarães et al., 2024), and Thailand (Tibpromma et al., 2017; this study).

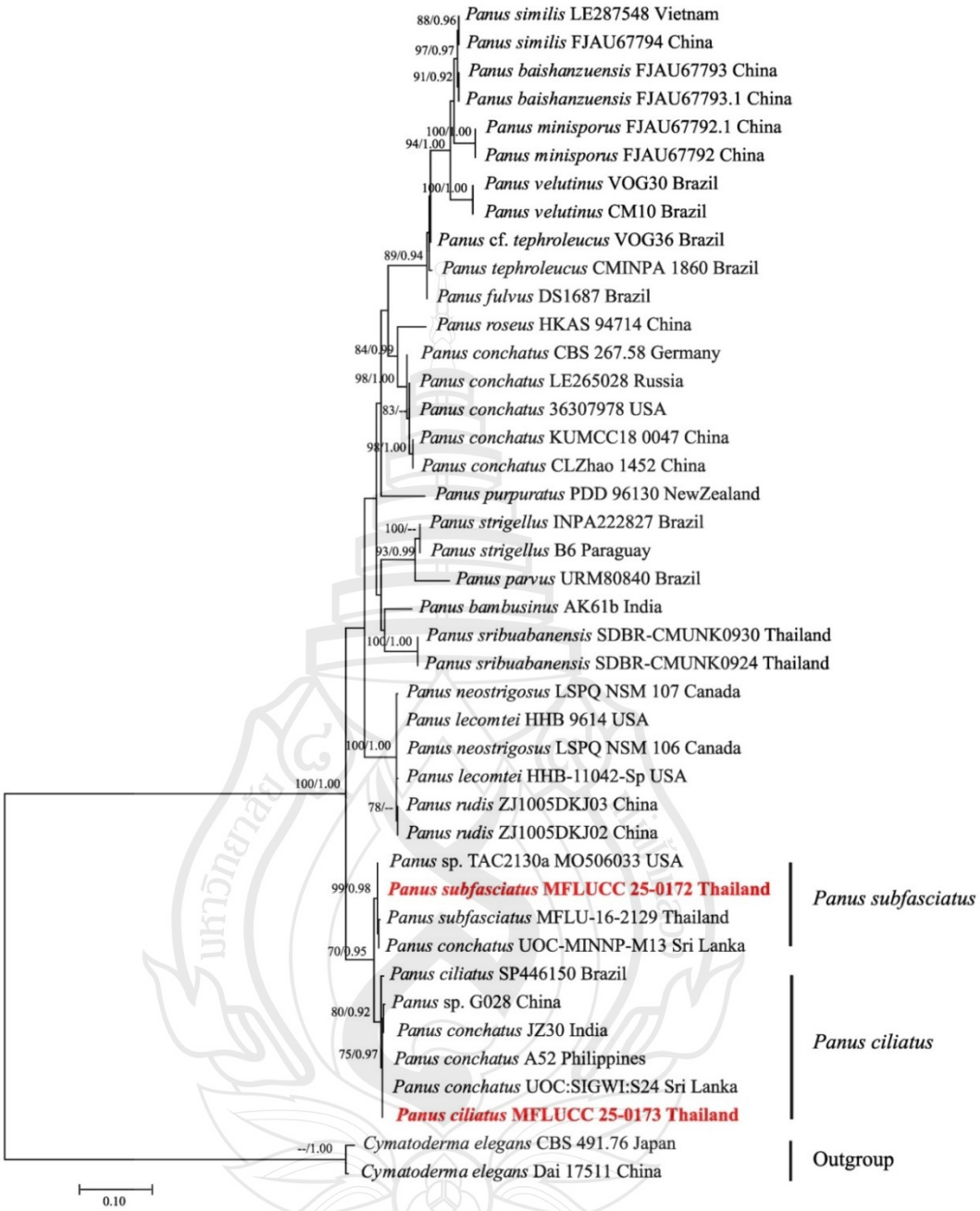
Notes: The morphological characteristics of our specimen are consistent with the original description of the holotype from Thailand, which is characterised by brownish-violet to purplish-brown basidiomata when young, later turning greyish-ruby, leathery, solid, dry, and fully covered with brownish-grey hairs (Tibpromma et al., 2017). Micro-morphological features of our specimen also range within the description of the holotype; however, the cheilocystidia and pleurocystidia in our collections are smaller than those reported for the holotype.

Note a–b Basidiomata. c Hymenium showing basidia and basidiospores. d Basidiospores. e Hymenium with pleurocystidia. f Hymenium with Cheilocystidia. g Pileipellis hyphae. h Culture (top view). i Culture (bottom view). Scale bar: c, e–f = 20 µm, d = 5 µm, g = 50 µm, h–i = 1 cm.

Figure 3.11 Morphological characteristics of *Panus subfasciatus* (MFLUCC 25-0172)

3.2.2 Phylogenetic Inferences

Phylogenetic analyses were conducted based on ITS sequences, comprising 42 taxa, including our specimens, additional *Panus* species, and two outgroup taxa: *Cymatoderma elegans* (Dai 17511) and *C. elegans* (CBS 491.76). The final dataset consisted of 581 total characters, including gaps. The best-scoring ML tree is shown in Figure 3.12, with an optimal log-likelihood value of -2872.843714. The alignment contained 2.54% gaps and undetermined characters. Estimated base frequencies were A = 0.241696, C = 0.219979, G = 0.225115, T = 0.313210; substitution rates AC = 0.668485, AG = 2.660522, AT = 2.057754, CG = 0.741111, CT = 5.494471, and GT = 1.000000. The gamma distribution shape parameter (α) = 0.333169. Phylogenetic analyses placed our sequences of *P. subfasciatus* (ML = 99%, BPP = 0.98) and *P. ciliatus* (ML = 80%, BPP = 0.92) in a well-supported clade. The isolates of both specimens used in this study, collected from Thailand, are presented in bold red.



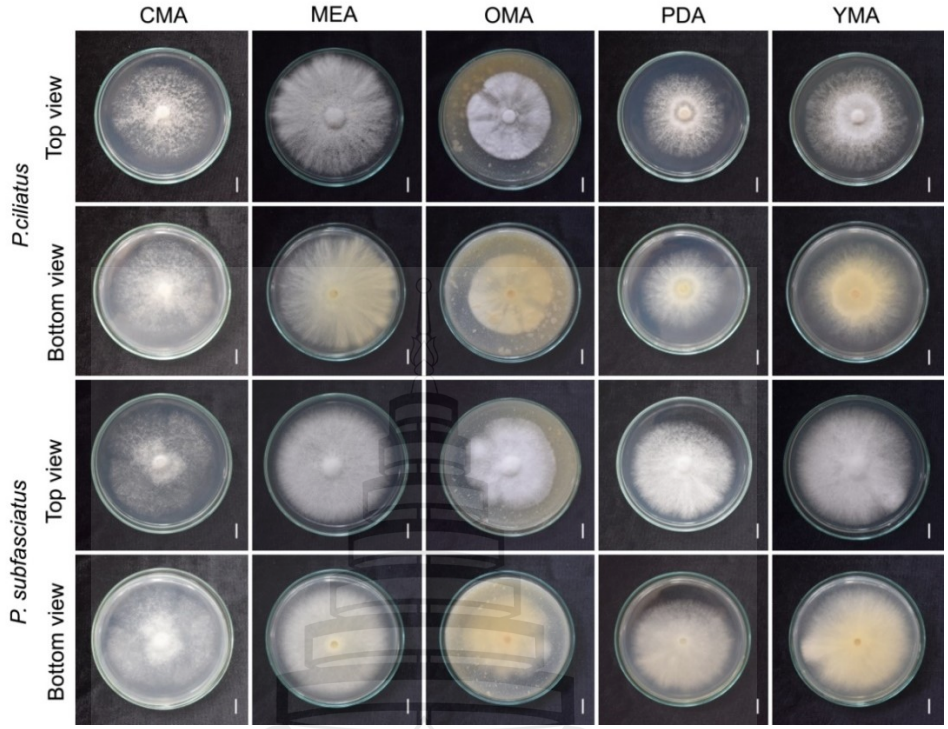
Note Phylogenetic tree (RAxML) obtained from the DNA sequence data of the ITS dataset. Bootstrap support values (BS) for maximum likelihood (ML, first value) equal to or greater than 70% and Bayesian posterior probabilities from MCMC analyses (BPP, second value) equal to or greater than 0.90 are given above the nodes. The scale bar indicates expected changes per site. The tree is rooted with *Cymatoderma elegans* (Dai 17511) and *C. elegans* (CBS 491.76). Newly generated sequences are indicated in bold red.

Figure 3.12 Phylogenetic tree of *Panus*

3.2.3 Effect of Culture Media on Mycelial Growth

The evaluation of mycelium grown in five different agar media was compared in terms of mycelium morphology, density, and growth rate (mm/day). Among the tested media, MEA exhibited the most favourable growth (Figure 3.13, Table 3.5). The mycelium of both species appeared white (6A1) across all media. Colony formation was observed by day 10, with notable differences in density and morphology. For *P. ciliatus*, somewhat abundant growth (4+) was observed on MEA, while CMA and PDA produced a scanty, cottony colony (2+). For *P. subfasciatus*, somewhat abundant growth (4+) occurred on both MEA and YMA, whereas CMA yielded scanty, cottony colonies (2+). Morphologically, *P. ciliates* produced uniformly thick mycelium on MEA and OMA, granular mycelium on CMA, and colonies with thicker centres and thinner edges on PDA and YMA. In *P. subfasciatus*, all media exhibited uniformly thick mycelium except CMA, which showed a granular texture.

Mycelium plug expansion began on day 2. The rapid growth of *P. ciliates* was on MEA (8.24 ± 0.61 mm/day) while *P. subfasciatus* grew most rapidly on both MEA (8.08 ± 0.14 mm/day) and YMA (8.07 ± 0.20 mm/day), covering the entire plates. OMA yielded the slowest growth in both species, *P. ciliatus* at 5.55 ± 0.12 mm/day and *P. subfasciatus* at 6.26 ± 0.14 mm/day.



Note Scale bars = 1 cm

Figure 3.13 Morphological characteristics of *P. ciliatus* (MFLUCC 25-0173) and *P. subfasciatus* (MFLUCC 25-0172) grown on different agar media at 25°C for 10 days

Table 3.5 Effect of different agar media on the mycelial growth rate and mycelial density of *P. ciliatus* (MFLUCC 25-0173) and *P. subfasciatus* (MFLUCC 25-0172) incubated at 25°C for 10 days

Culture agar media	Mycelium growth rate (mm/day)		Mycelium density	
	P. ciliatus	***P. subfasciatus***	***P. ciliatus***	***P. subfasciatus***
CMA	7.07 ± 0.14^{b}	7.77 ± 0.13^{b}	2+	2+
MEA	8.24 ± 0.61^{a}	8.08 ± 0.14^{a}	4+	4+
OMA	5.55 ± 0.12^{d}	6.26 ± 0.14^{c}	3+	3+
PDA	6.45 ± 0.06^{c}	7.70 ± 0.34^{b}	2+	3+
YMA	7.15 ± 0.28^{b}	8.07 ± 0.20^{a}	3+	4+

Note Within a column, values followed by the same letter are not significantly different ($p < 0.05$) by Duncan's Multiple Range Test.

3.2.4 Mycelium Growth in Lignocellulose Substrate Media

The mycelium of both *P. ciliatus* and *P. subfasciatus* was observed to be white and exhibited a regular growth pattern. Colony diameters were measured on alternate days starting on day 2 for cultures grown on rubber sawdust. The average mycelial growth rates were 4.70 ± 1.35 mm/day for *P. ciliatus* and 6.07 ± 0.89 mm/day for *P. subfasciatus* (Figure 3.14). On day 14, the mycelial density in the plates of *P. subfasciatus* was abundant (5+) compared to *P. ciliatus,* with somewhat abundant (4+) (Figure 3.15).

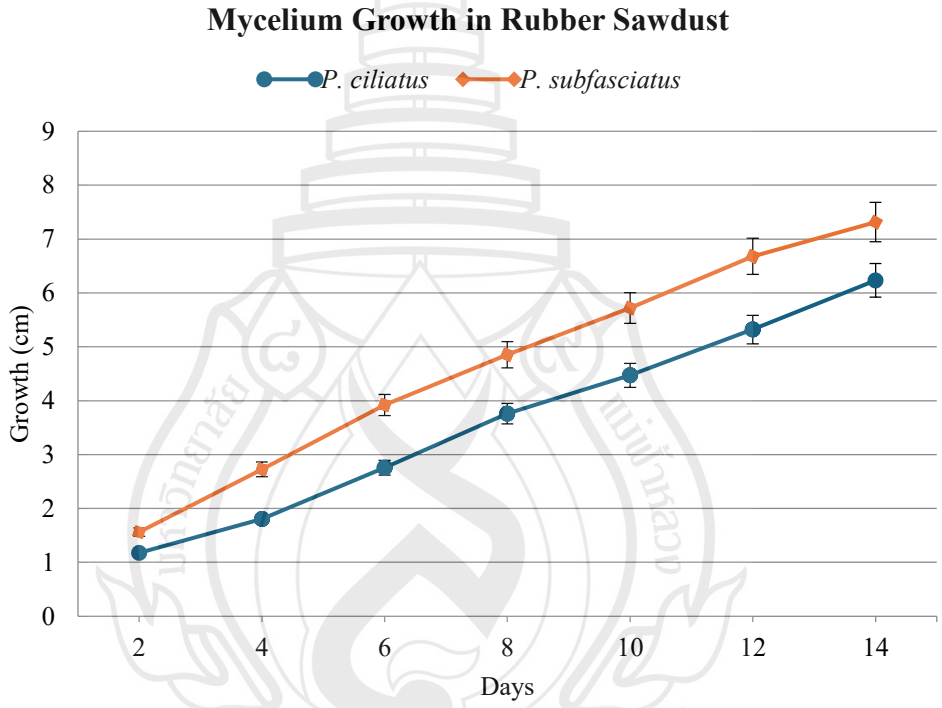
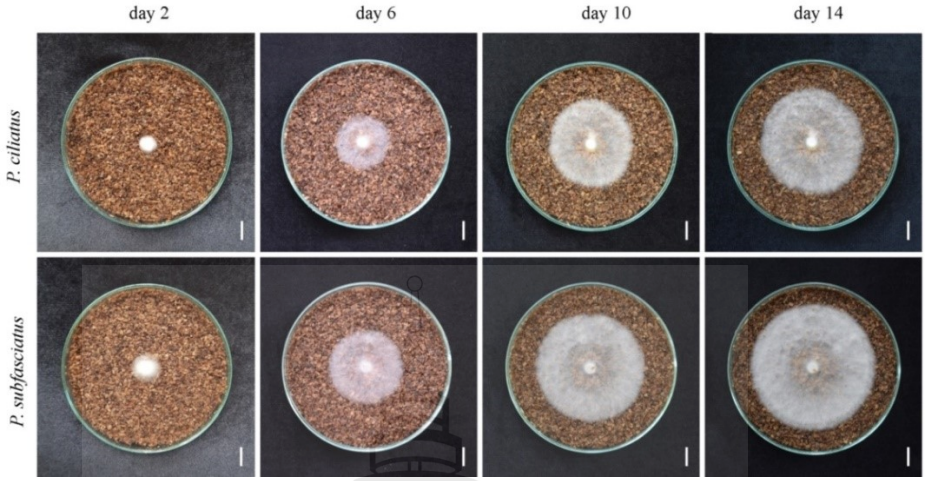


Figure 3.14 Mycelium growth rate of *P. ciliatus* (MFLUCC 25-0173) and *P. subfasciatus* (MFLUCC 25-0172) on rubber sawdust



Note Scale bars = 1 cm

Figure 3.15 Morphological characteristics of *P. ciliatus* (MFLUCC 25-0173) and *P. subfasciatus* (MFLUCC 25-0172) incubated on rubber sawdust with supplements at 25°C for 14 days

3.2.5 Evaluation of Physical Properties of MMBs

3.2.5.1 Moisture Content and Dry Density

The moisture content of the cube test samples before deactivation was 55 ± 0.51% for *P. ciliatus* and 54.14 ± 0.43% for *P. subfasciatus*. The dry densities of samples from both species were similar, at 272.99 ± 4.44 kg/m^3 and 273.45 ± 4.87 kg/m^3, respectively (Table 3.6).

Table 3.6 Moisture content, dry density, and volumetric shrinkage of MMB samples obtained in this study

Parameter	***P. ciliatus* (MFLUCC 25-0173)**		***P. subfasciatus* (MFLUCC 25-0172)**	
	95% Confidence interval	**Average**	**95% Confidence interval**	**Average**
Moisture content (%)	54.38, 55.63	55 ± 0.51	53.61, 54.67	54.14 ± 0.43
Dry density (kg/m^3)	267.48, 278.51	272.99 ± 4.44	267.41, 279.50	273.45 ± 4.87
Volumetric shrinkage (%)	7.60, 9.49	8.54 ± 0.76	6.88, 10.22	8.55 ± 1.35

Note Values represent mean ± standard deviation. Within a row, means are not significantly different ($p > 0.05$) by the independent samples t-test.

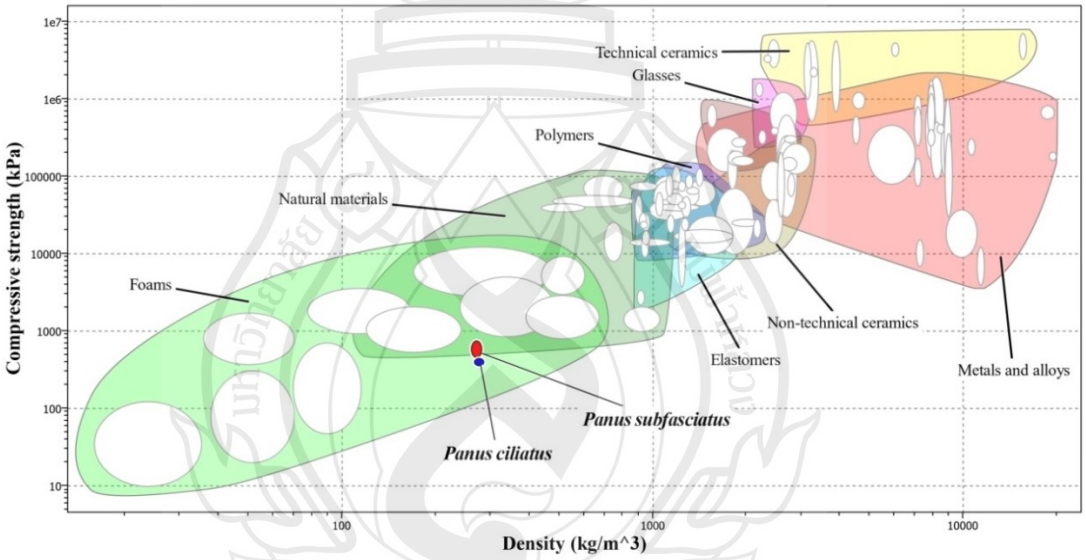
3.2.5.2 Volumetric Shrinkage

The volumetric shrinkage of cube test samples was 8.54 ± 0.76% for *P. ciliatus* and 8.55 ± 1.35% for *P. subfasciatus* (Table 3.6).

3.2.6 Evaluation of Mechanical Properties of MMBs

3.2.6.1 Compression Strength

The compressive strength of MMB samples developed from *P. ciliatus* ranged from 370 to 440 kPa, whereas samples from *P. subfasciatus* ranged from 470 to 730 kPa. On average, MMB from *P. subfasciatus* showed significantly greater compressive strength (604 ± 99 kPa) than MMB from *P. ciliatus* (412 ± 27 kPa) (Figure 3.16, Table 3.7).



Note The members of each class are enclosed in envelopes. The image was generated using CES EduPack 2014 v14.3.5.

Figure 3.16 Material property chart (Ashby) comparing MMB samples from *P. ciliatus* (MFLUCC 25-0173) and *P. subfasciatus* (MFLUCC 25-0172) to typical materials families in terms of compressive strength against density

Table 3.7 Compressive, flexural, tensile, and impact strengths of MMB samples obtained in this study

Parameter	*P. ciliatus* (MFLUCC 25-0173)		*P. subfasciatus* (MFLUCC 25-0172)	
	95% Confidence interval	**Average**	**95% Confidence interval**	**Average**
Compressive strength (kPa)	377.55, 446.46	412 ± 27.75[a]	479.96, 728.04	604 ± 99.90[b]
Flexural strength (kPa)	1113.90, 1538.10	1326 ± 170.82[a]	737.30, 862.70	800 ± 50.50[b]
Tensile strength (kPa)	859.34, 1117.95	988.65 ± 104.14	–	–
Impact strength (kJ/m^2)	0.08, 0.17	0.13 ± 0.04[a]	0.06, 0.12	0.09 ± 0.03[a]

Note Values represent mean ± standard deviation. Within a row, values followed by the same letter are not significantly different ($p < 0.05$) by the independent samples t-test. "–" not available.

3.2.6.2 Flexural Strength

The flexural strength of MMB samples developed from *P. ciliatus* ranged from 1110 to 1560 kPa, whereas those from *P. subfasciatus* ranged from 720 to 860 kPa. On average, *P. ciliatus* samples exhibited significantly higher flexural strength (1326 ± 170 kPa) compared to *P. subfasciatus* (800 ± 50 kPa) (Table 3.7).

3.2.6.3 Tensile Strength

Tensile strength values ranged from 825 to 1106 kPa for *P. ciliatus*, with the average noted to be 989 ± 104 kPa (Table 3.7).

3.2.6.4 Impact Strength

The impact strength of MMB samples from *P. ciliatus* ranged from 0.09 to 0.16 kJ/m^2, while *P. subfasciatus* ranged from 0.06 to 0.13 kJ/m^2. On average, *P. ciliatus* exhibited similar impact strength (0.13 ± 0.03 kJ/m^2) compared to *P.*

subfasciatus (0.09 ± 0.03 kJ/m^2) (Table 3.7).

3.2.7 Hydrodynamic Properties

3.2.7.1 Water Absorption

The maximum water absorption of cube test samples after 96 h was 242.49% for *P. ciliatus* and 181.41% for *P. subfasciatus* (Figure 3.17). The water absorption was the highest in the first 24 h, with 113.71% for *P. ciliatus* and 74.52% for *P. subfasciatus*. Overall, *P. ciliatus* exhibited a higher water absorption than *P. subfasciatus*.

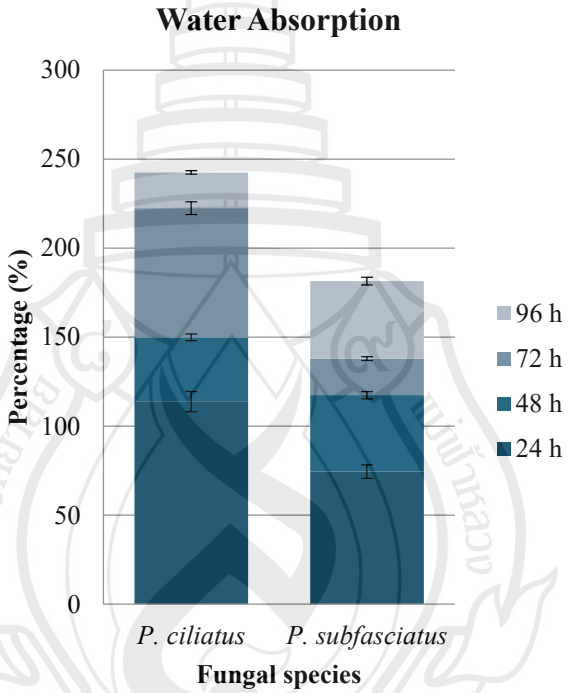


Figure 3.17 Water absorption of MMB samples from *P. ciliatus* (MFLUCC 25-0173) and *P. subfasciatus* (MFLUCC 25-0172).

3.2.7.2 Water Contact Angle

Water contact angle (WCA) measurements of MMBs developed from *P. ciliatus* and *P. subfasciatus* indicated a hydrophobic behaviour, with WCA values exceeding 90° at both 10 and 60 s (Figure 3.18). At 10 s, WCA was 111° for *P. ciliatus* and 120° for *P. subfasciatus*. In the 60s, the CA values slightly decreased to 107° and 118°, respectively.

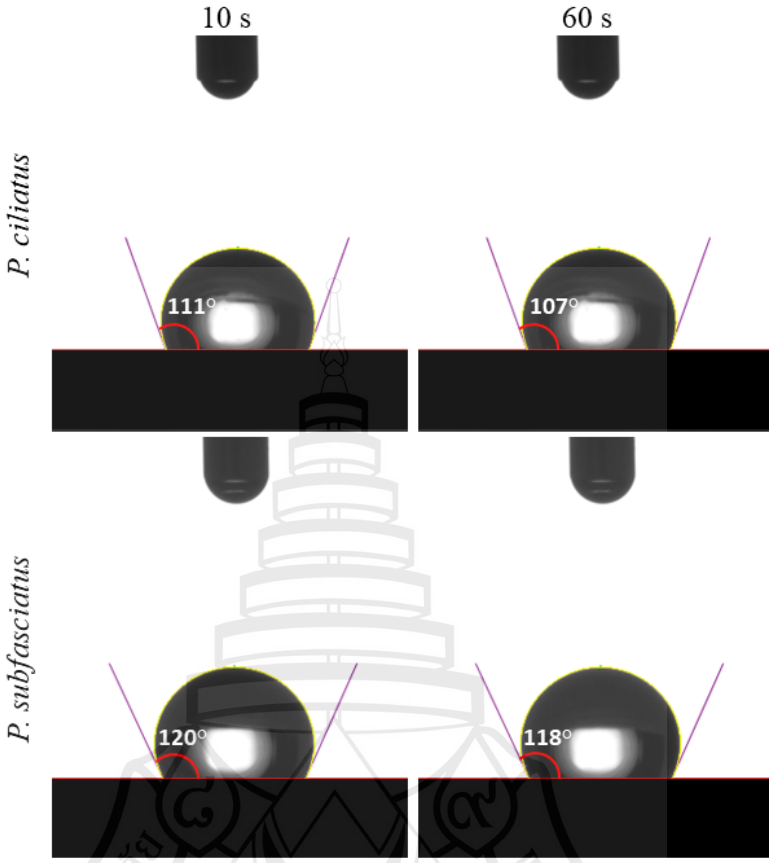


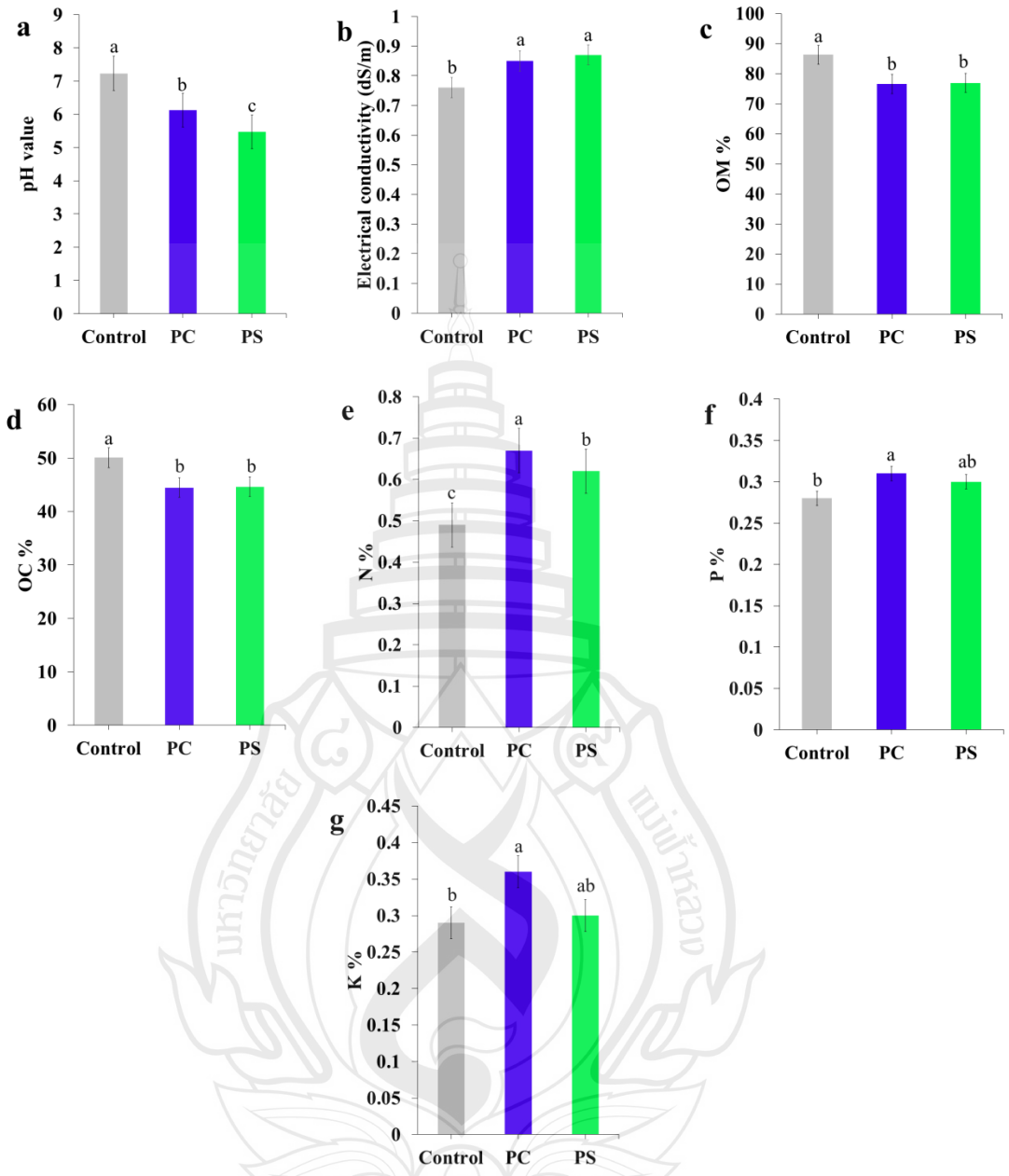
Figure 3.18 Water contact angle of MMB samples from *P. ciliatus* (MFLUCC 25-0173) and *P. subfasciatus* (MFLUCC 25-0172) at 10 s and 60 s

3.2.8 Evaluation of Chemical Properties of MMBs

The chemical properties of the MMBs, including pH, organic matter, organic carbon, nitrogen, phosphorus, and potassium contents, are presented in Figure 3.19. The pH of the initial substrate (7.23) decreased significantly in MMBs produced by *P. ciliatus* (6.12) and *P. subfasciatus* (5.47), with *P. subfasciatus* exhibiting a greater reduction. The initial EC values of the sawdust substrate before mycelium inoculation were 0.75–0.77 dS/m, which significantly increased in both *P. ciliatus* (0.82–0.88 dS/m) and *P. subfasciatus* (0.81–0.93 dS/m). Organic matter content decreased significantly in MMBs from both *P. ciliatus* (76.63%) and *P. subfasciatus* (76.97%) compared to the initial substrate (86.34%). Similarly, the organic carbon content of the initial substrate (50.08%) decreased significantly in MMBs from both *P. ciliatus* (44.45%) and *P. subfasciatus* (44.64%). While *P. subfasciatus* had a more pronounced pH reduction than *P. ciliatus*, the differences in organic matter and organic carbon

content are similar between the two species.

In contrast, nitrogen content increased significantly in MMBs colonised by *P. ciliatus* (0.67%) and *P. subfasciatus* (0.62%) compared to the initial uncolonized substrates (0.49%). Phosphorus content in the initial substrate (0.28%) also increased significantly in MMBs from both *P. ciliatus* (0.31%) and *P. subfasciatus* (0.30%). Similarly, potassium content increased in MMBs from both *P. ciliatus* (0.36%) and *P. subfasciatus* (0.30%) compared to the initial substrate (0.29%). Overall, *P. ciliatus* produced higher levels of nitrogen, phosphorus, and potassium than *P. subfasciatus*.

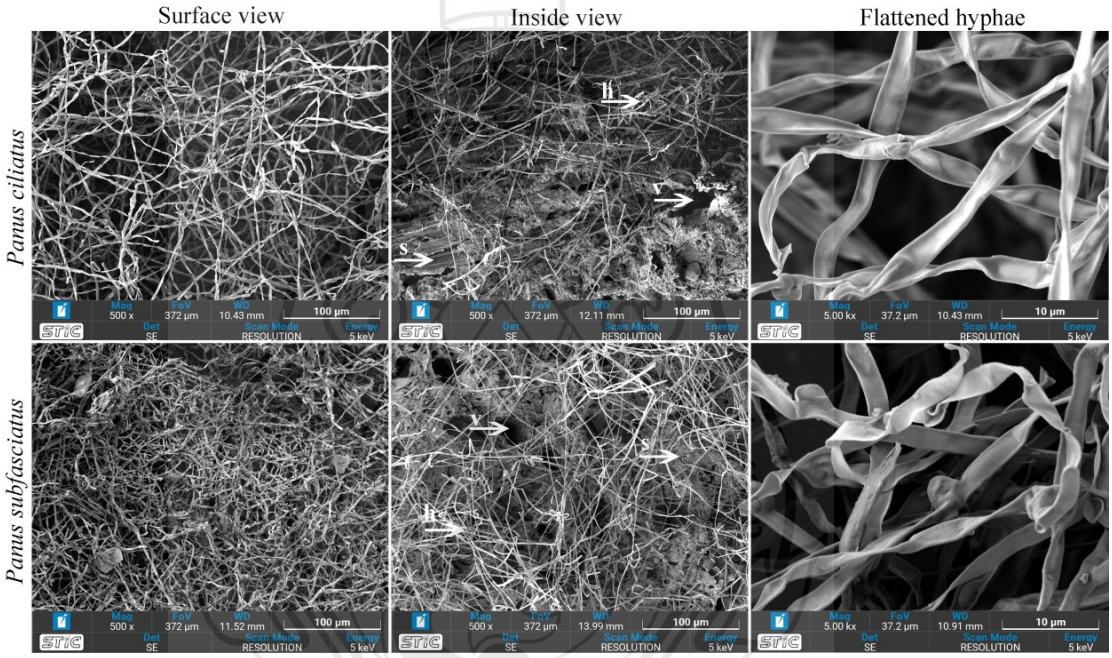


Note a pH value. b Electrical conductivity. c Organic matter content. d Organic carbon content. e Nitrogen content. f Phosphorus content. g Potassium content. Data are presented as means ± standard error. Bars with the same letter within individual tests are considered significantly different according to Duncan's multiple range tests (p <0.05). PC = *Panus ciliatus*. PS = *Panus subfasciatus.*

Figure 3.19 Chemical properties of MMBs produced from *P. ciliatus* (MFLUCC 25-0173) and *P. subfasciatus* (MFLUCC 25-0172)

3.2.9 Scanning Electron Microscopy

Hyphal structures of *P. ciliatus* and *P. subfasciatus* grown on sawdust substrates were examined using SEM. Both species exhibited similar hyphal morphology (Figure 3.20). However, visual inspection revealed a higher density of mycelium in *P. subfasciatus* compared to *P. ciliatus*. The top surfaces of the samples were generally covered with loosely interwoven, dense, hairy (fluffy) hyphae. Cross-sectional views showed a mixture of hyphae, voids, and substrate particles. Additionally, the flattened hyphae resulting from hot-air oven dehydrated MMB are also visualised.



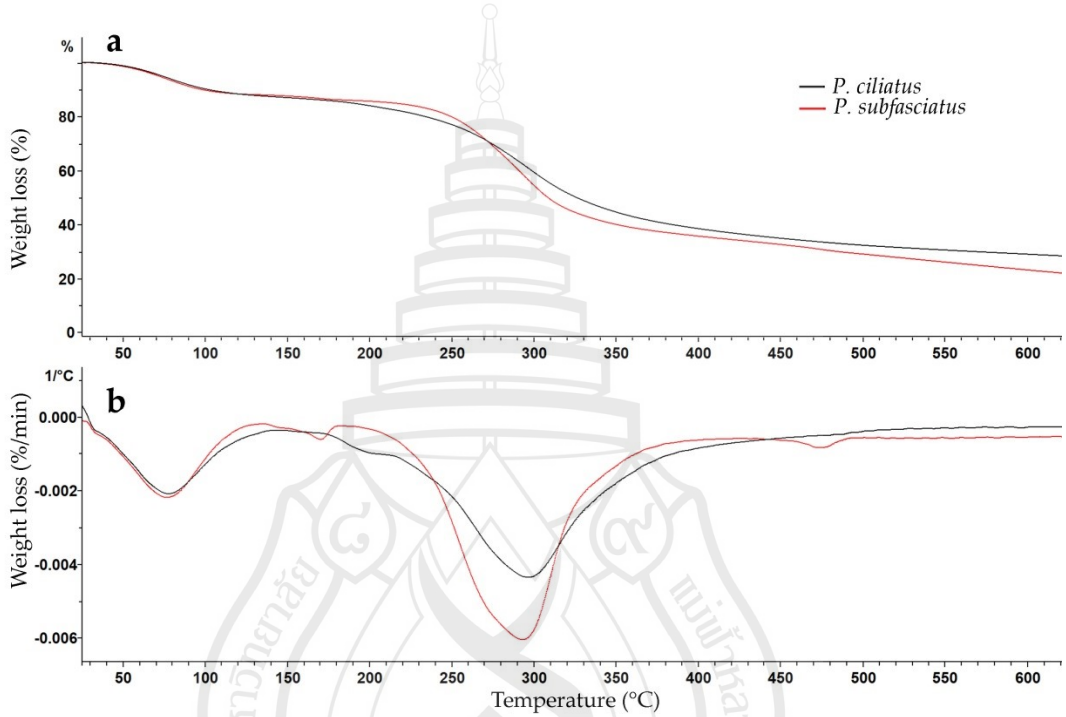
Note h = hyphae, s = substrate, v = void

Figure 3.20 Scanning Electron Microscopy images of MMBs produced by *P. ciliatus* (MFLUCC 25-0173) and *P. subfasciatus* (MFLUCC 25-0172) growth on rubber sawdust

3.2.10 Thermogravimetric Analysis

The thermal behaviour of pure mycelium from *P. ciliatus* and *P. subfasciatus* is shown in TGA and DTGA curves (Figure 3.21), exhibiting similar thermal degradation behaviour. The first weight loss occurred at approximately 76°C, corresponding to moisture evaporation, with losses of 11.65% for *P. ciliatus* and

12.69 % for *P. subfasciatus*. The second major degradation phase occurred at 293°C for *P. ciliatus* (52.89% weight loss) and 298°C for *P. subfasciatus* (59.94% weight loss). The third event, attributed to the decomposition of residual non-degraded materials and impurities, resulted in 35.47% residual mass for *P. ciliatus* and 27.36% for *P. subfasciatus*.

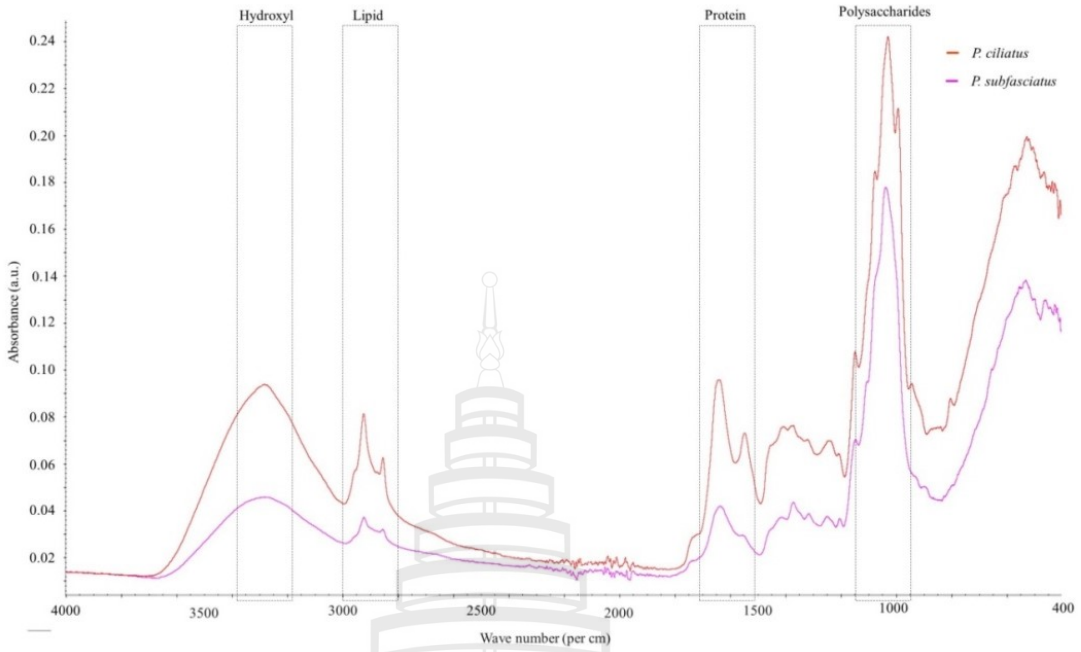


Note a TGA curves. b DTGA curves.

Figure 3.21 Thermal degradation behaviour of pure mycelium from *P. ciliatus* (MFLUCC 25-0173) and *P. subfasciatus* (MFLUCC 25-0172)

3.2.11 Fourier Transform Infrared Spectroscopy

FTIR spectra of pure mycelium of *P. ciliatus* and *P. subfasciatus* are shown in Figure 3.22. The analysis revealed characteristic absorption bands corresponding to various chemical constituents. Chemically significant regions in the spectra include the hydroxyl group (3200–3400 cm^{-1}), C-H stretching in the fatty acid region (2800–3000 cm^{-1}), protein region dominated by C=O (amide I) and N–H (amide II) (1500–1700 cm^{-1}), and the polysaccharides region (950–1150 cm^{-1}). Details of the peak in the obtained spectra are provided in Table 3.8.



Note Major absorption bands corresponding to mycelial cell wall components are labelled.

Figure 3.22 FTIR spectra of pure mycelium from *P. ciliatus* (MFLUCC 25-0173) and *P. subfasciatus* (MFLUCC 25-0172)

Table 3.8 Characteristic absorption bands observed in the FTIR spectra (4000−400cm^{-1}) of *P. ciliatus* (MFLUCC 25-0173) and *P. subfasciatus* (MFLUCC 25-0172)

Wave number range (cm^{-1})	Spectra	Peak (cm^{-1})		References
		P. ciliatus	***P. subfasciatus***	
3600–3000	O−H stretching hydrogen bonds	3281	3282	Haneef et al. (2017); Elsacker et al. (2019)
3000–2840	C–H stretching in methyl and methylene groups	2922	2921	Pandey and Pitman (2003); Schwanninger et al. (2004); Elsacker et al. (2019)
2940–2840	CH_2 asymmetric stretching	2853	−	Elsacker et al. (2019)
2900–2850	CH_3 and CH_2 stretching	2853	−	D'Souza and Kamat (2017)
1658–1625	Amide I; chitin	1640	1633	D'Souza and Kamat (2017)
1560–1520	C=C stretching of aromatic ring (syringyl) in lignin	1547	−	Elsacker et al. (2019)
1460–1400	CH_2 and CH_3 deformation in the lignin and hemicellulose; CH_2 in-plane bending vibrations in the cellulose and lignin	1405	−	Akcay et al. (2023)

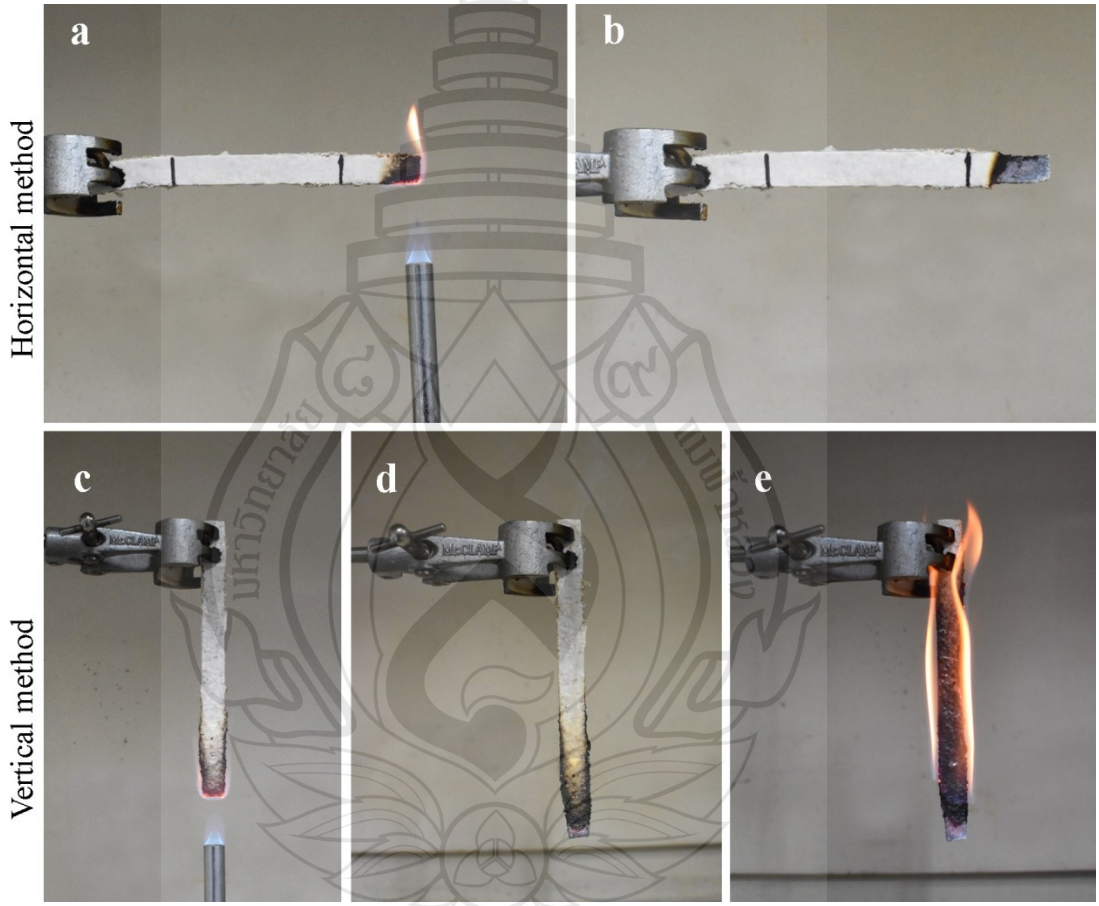
Table 3.8 (continued)

Wave number range (cm^{-1})	Spectra	Peak (cm^{-1})		References
		P. ciliatus	***P. subfasciatus***	
1370–1365	Aliphatic C–H stretch in CH_3	1370	1370	Schwanninger et al. (2004)
1375–1315	O–H bending polysaccharide; Amide III	–	1313	D'Souza and Kamat (2017)
1250–1025	C–O bond; β (1→3) glucan; cell wall polysaccharide	1241, 1075	1248	D'Souza and Kamat (2017)
1205–1200	OH plane deformation in cellulose; C−C stretching, C–O stretching, C−H deformation	–	1202	Schwanninger et al. (2004); Haneef et al. (2017)
1162–1125	C–O–C asymmetric valence vibration	1146	1145	Pandey and Pitman (2003), Schwanninger et al. (2004)
1060–1015	C–O valence vibration from C_3–O_3H	1031	1039	Schwanninger et al. (2004)
1047–1004	C_{alky}–O ether vibrations	1028	1036	Schwanninger et al. (2004)
1185–900	Polysaccharides	992	–	Naumann (2009)
950–700	Glycosidic bond β–(1 → 4) arabinogalactans, galactomannans, and cellulose	933, 943	–	Akcay et al. (2023)

Note "–" not available

3.2.12 Flammability Test

In the horizontal flammability test, following ignition, the flame burned the samples of *P. ciliatus* and *P. subfasciatus* for 21.87 ± 3.87 s and 11.12 ± 1.57 s, respectively (Figure 3.23). In both cases, the flame did not reach the starting line, and partial burning produced black and grey ash. In the vertical flammability test, after the initial 10 s ignition, the flame burned the samples of *P. ciliatus* and *P. subfasciatus* for 6.62 ± 1.72 s and 5.92 ± 2.57 s, respectively. During the second ignition, the flame extended to consume the entire samples of both species, leaving only ashes.

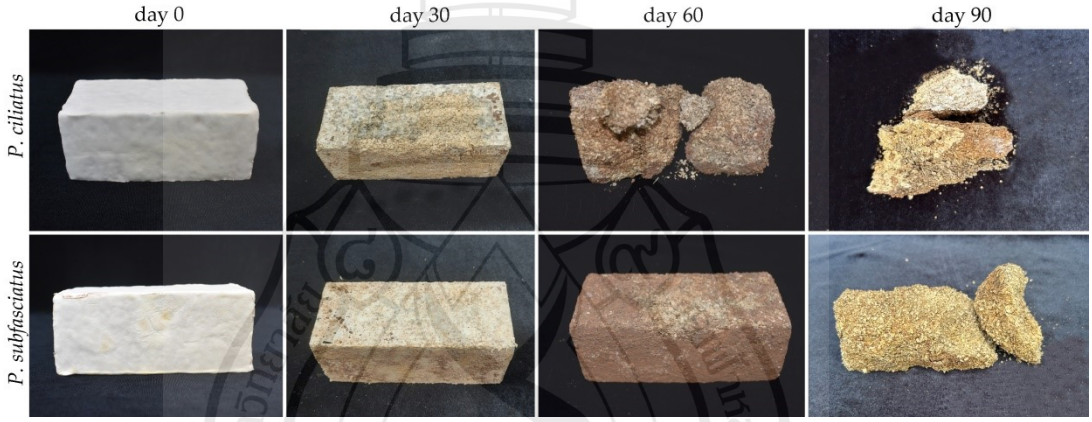


Note a Ignition at the sample tip for 30 s. b Flame self-extinguished after ignition. c Ignition at the sample tip for 10 s. d Flame self-extinguished during the first 10 s of ignition. e During the second 10 s of ignition, the flame continued to burn and reached the sample holding clamp.

Figure 3.23 Flammability testing

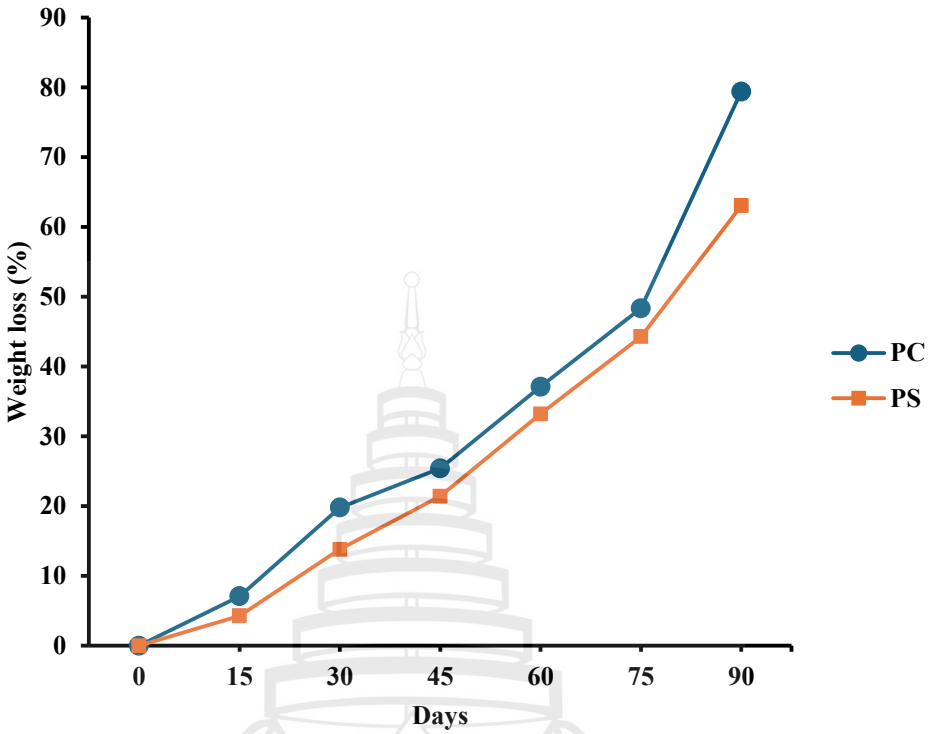
3.2.13 Soil Burial Degradability

The visual appearance of the MMB samples before and after 30, 60, and 90 days of soil burial is shown in Figure 3.24. All samples gradually disintegrate over time, with the extent of degradation increasing notably by day 90. Initially, the mycelial skin faded, followed by a progressive disintegration into the inner regions. As the burial period increased, the sample sizes decreased. The cumulative percentage weight loss over time is shown in Figure 3.25. After 90 days of burial, the samples exhibited similar degradation patterns, with an average weight loss of 79.38 ± 9.97% for *P. ciliatus* and 63.02 ± 4.42% for *P. subfasciatus*. Additionally, the colour of the test samples darkened with a prolonged burial.



Note Visual appearance of MMB samples from *P. ciliatus* (MFLUCC 25-0173) and *P. subfasciatus* (MFLUCC 25-0172) on day 0, 30, 60, and 90

Figure 3.24 Soil burial degradation test (visual appearance)



Note Cumulative percentage weight loss of MMB samples from *P. ciliatus* (MFLUCC 25-0173) and *P. subfasciatus* (MFLUCC 25-0172)

Figure 3.25 Soil burial degradability test (cumulative weight loss)

3.2.14 Viability Maintenance of Mushroom Strains

The substrate bags fully colonised by the mycelium of *Panus ciliatus* (MFLUCC 25-0173) and *P. subfasciatus* (MFLUCC 25-0172) that were incubated in the fruiting chamber produced basidiomata (Figure 3.26). Mature basidiomata were harvested, and fresh tissue was isolated to obtain pure cultures.

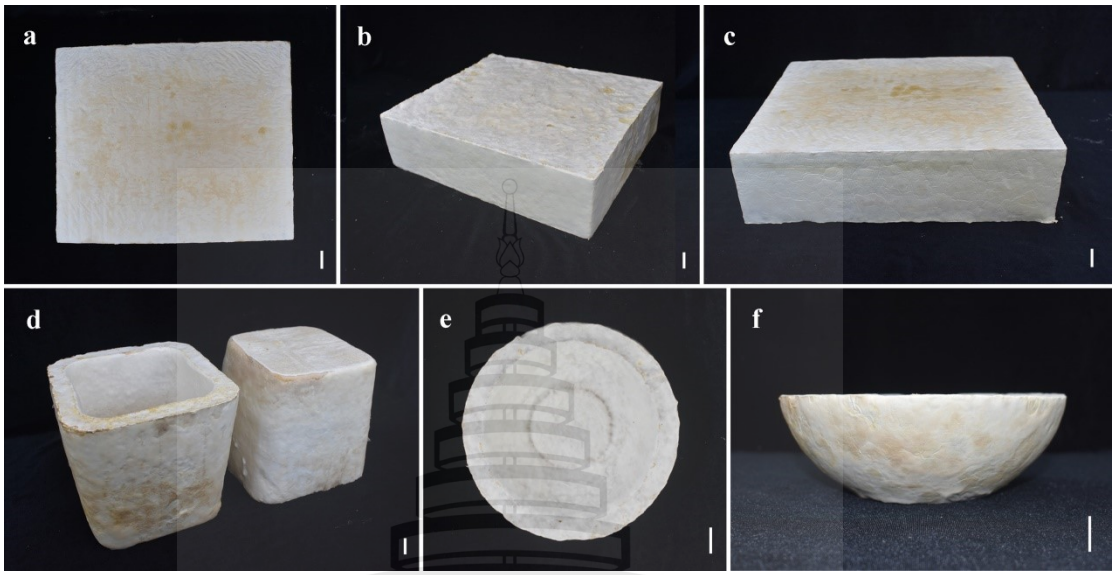
Note a, d Substrate bag fully colonised by mycelium. b, e Development of basidiomata within the bags. c, f Mature fruiting bodies. Scale bars = 2 cm.

Figure 3.26 Viability maintenance of fungal species

3.2.15 Developing Prototypes

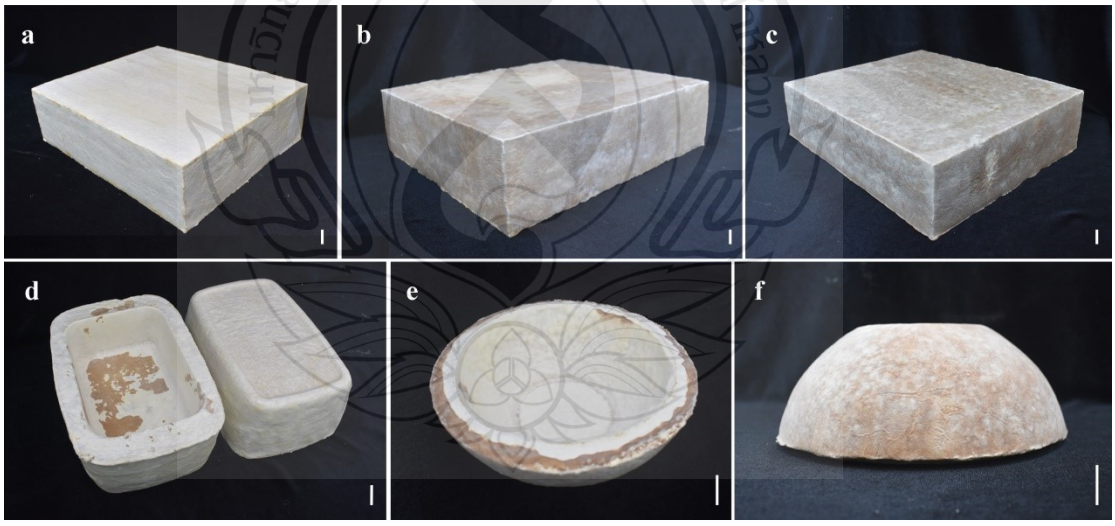
Products from both fungal species exhibited a thick, spongy, white mycelial skin with a brownish shade covering the substrate (Appendix A3). Products from *P. ciliatus* included: block (length: 29; breadth: 24.5; thickness: 8 cm), vase (top width: 16.5 cm; bottom width: 13.5 cm; height: 15 cm; thickness: 2 cm), and circular bowl (top diameter: 17.5 cm; bottom diameter: 8 cm; height: 6 cm; thickness: 1.8 cm) (Figure 3.27). *P. subfasciatus* products included: block (length: 29; breadth: 24.5; thickness: 8.5 cm), rectangular bowl (top length: 23 cm; bottom length: 20.5 cm; top breadth: 15.5 cm; bottom breadth: 13 cm; height: 8.5 cm; thickness: 2 cm), and circular bowl (top diameter: 18 cm; bottom diameter: 8 cm; height: 7 cm; thickness: 1.8 cm) (Figure 3.28). The mycelium covered all the surface and corners of the

products, with no substrate exposed. Additionally, the final products exhibited their unique mycelial skin and showed no fungal contamination.



Note a–c Block. d Vase. e, f Circular bowl. Scale bars = 2 cm.

Figure 3.27 Development of bio-composite prototypes using *P. ciliatus* (MFLUCC 25-0173) grown on rubber sawdust



Note a–c Block. d Rectangular bowls. e, f Circular bowls. Scale bars = 2 cm.

Figure 3.28 Development of bio-composite prototypes using *P. subfasciatus* (MFLUCC 25-0172) grown on rubber sawdust

3.2.16 Discussion

Two fungal species collected from forests in Chiang Rai Province, Thailand, were identified as *Panus ciliatus* and *P. subfasciatus* based on a combination of morphological characteristics and ITS phylogenetic analyses. Phylogenetic trees revealed that these two taxa form sister clades with high morphological similarity. Notably, this study reports *P. ciliatus* as a new geographical record in Thailand, thereby expanding the known distribution of the species.

Mycelium growth evaluation on five agar media demonstrated apparent differences in nutritional preferences. *Panus ciliatus* exhibited the fastest growth on MEA with abundant mycelial mat formation, while *P. subfasciatus* grew equally well on MEA and YMA. Although previous studies on *Panus* species are limited, our results support MEA as a favourable substrate, likely due to its high carbon and protein content. On rubber sawdust, both *Panus* species colonised successfully; however, *P. subfasciatus* exhibited a faster growth rate, indicating potential species-specific adaptations to lignocellulosic substrates.

Mycelium-based biomaterials (MBBs) produced from these species exhibited physical and chemical properties comparable to those reported in other fungal composites (Girometta et al., 2019). Their relatively low densities (272.99 and 273.45 kg/m^3) fall within the range of previously studied MMBs and are lighter than conventional wood products while still denser than synthetic foams.

Shrinkage values (8.54–8.55%) are also within the typical range for fungal composites and lower than many wood-based materials, suggesting good dimensional stability. However, compressive strength values were at the lower end of published ranges (0.03–4.44 MPa), likely reflecting the absence of hot or cold pressing during fabrication. Previous work has shown that pressing can significantly enhance mechanical properties, allow additional densification and improve performance in structural applications (Jones et al., 2020; Manan et al., 2021). The strength of the MMB can also be attributed to their composition, mycelium growth, density, and porosity. Nevertheless, flexural, tensile, and impact strengths of the *Panus*-based MMBs were comparable to those of polystyrene foams and natural materials, supporting their potential as sustainable alternatives for non-load-bearing uses.

Analysis of the Ashby chart reveals that the mechanical properties of MMB

reside in the intersection region between natural materials and foams, thereby implying that the MMB material investigated in this study exhibits mechanical properties appropriate for use as a foam substitute. The observed differences in the mechanical properties of MMB from *P. ciliatus* and *P. subfasciatus* are likely attributable to variations in their microstructural and biochemical composition. The superior compressive strength of MMB from *P. subfasciatus* is consistent with its higher mycelial density, as confirmed by SEM analysis. The presence of chitin fibrils in the fungal cell walls is believed to be a primary contributor to this strength by resisting crack propagation under compression (Yang et al., 2017a; Teixeira et al., 2018). Conversely, the enhanced flexural and impact strength of MMB from *P. ciliatus* may be influenced by its protein and lipid content. These components can act as plasticisers, imparting greater flexibility and toughness to the material (Haneef et al., 2017). To confirm the plasticiser effect, further study on protein and lipid content is required.

Hydrodynamic properties also suggest potential for real-world use. The water absorption capacity of *P. ciliatus* and *P. subfasciatus* is within the broad range reported for other fungal composites (24.45–560%) but was higher than that of synthetic polymers (Attias et al., 2019; Elsacker et al., 2019; de Lima et al., 2020). The lower water absorption in these samples likely reflects the use of fine sawdust particles (≤2 mm), which increases density and reduces porosity (Appels et al., 2019; Robertson, 2020). In contrast, MBBs absorb more than synthetic polymers (0.01–9%) (Jia & Kagan, 2001; Jones et al. 2020). They demonstrated acceptable hydrophobicity (water contact angles >100°) (Haneef et al., 2017). The proteins, such as mannoproteins and hydrophobins, present on the outermost layer of the fungal cell wall, are responsible for the hydrophobic nature of MMBs (Alexandre et al., 2000; Feofilova, 2010). This hydrophobic nature is an important property that benefits product development.

Chemical analyses indicated that MBBs produced from both species contained elevated nitrogen, phosphorus, and potassium relative to the initial substrates. The pH values (4.67–6.12) are consistent with prior studies (Attias et al., 2019; Aiduang et al., 2022b; Alemu et al., 2022a), with reductions attributed to the enzymatic activity of the fungal mycelium (Attias et al., 2017). On the other hand, the electrical conductivity

(EC) increased in colonised substrates, likely due to the enzymatic release of minerals (Hwang et al., 2015; Kumla et al., 2020; Aiduang et al., 2022c). Macronutrient analysis revealed elevated nitrogen, phosphorus, and potassium (NPK) contents in MMBs compared to the initial substrate, particularly in *P. ciliatus* (N:P:K = 0.67:0.31:0.36), which is higher than *P. subfasciatus* (N:P:K = 0.62:0.30:0.30). The nitrogen content obtained in this study (0.5–1.6%) is consistent with previous studies (Attias et al., 2017; de Lima et al., 2020; Zimele et al., 2020). The increased level of NPK is likely due to the enzymatic digestion and fermentation of substrates by mycelium (Alemu et al., 2022). The significant reduction in OM and OC content observed, as in earlier studies, indicates the inherent capacity of mycelium to modify lignocellulosic substrates derived from agricultural and forestry sectors (Attias et al., 2017; 2019). Following utilisation, MMBs can be easily composted and used as fertilisers in the agricultural sector, thereby reducing production costs and pollution.

Morphological observations via SEM revealed dense, interwoven hyphae binding sawdust particles, functioning as a natural adhesive. Voids within the structure explain water absorption through capillary action, while flattened hyphae indicate shrinkage during drying. Such microstructural features directly influence density, porosity, and strength.

Regarding thermal analyses, TGA and DTGA results showed thermal behaviour for both the *Panus* species. The first phase of weight loss (~12%) that occurred near 76°C was due to the removal of physically and chemically bonded moisture and volatile compounds from the samples (Joseph et al., 2003; Bruscato et al., 2019; Ahmadi et al., 2022). The major second-phase weight loss (52.89–59.94%) occurred between 293–298°C, corresponding to the decomposition of cellulose, hemicellulose, and lignin, into volatile forms (Ahmadi et al., 2022). The results in this study are similar to those in previous studies (220°C and 410°C) (Bruscato et al., 2019; Khyaju et al., 2025). The third phase is associated with non-degraded impurities, represented in the form of char (Bruscato et al., 2019; Ahmadi et al., 2022). In this study, char residues were higher in *P. ciliatus* (35.47%) than in *P. subfasciatus* (27.36%), suggesting greater thermal stability and fire resistance. Chitin and chitosan in fungal cell walls may contribute to the thermal behaviour by changing the composition of lignocellulosic substrates following colonization (Jones et al., 2018;

Girometta et al., 2019; Zhang et al., 2021a; Ahmadi et al., 2022). FTIR spectroscopy revealed the hydroxyl, lipid, protein, and polysaccharide functional groups, with *P. ciliatus* showing stronger signals for certain bonds than *P. subfasciatus*.

Fire resistance is a key requirement in transportation, building, insulation, or packaging, and MMBs show potential in these areas. Flammability tests demonstrated intrinsic fire-retardant properties, with flames self-extinguishing during both horizontal and vertical trials. This behaviour is attributed to char formation and the presence of dense mycelial mats, which limit oxygen penetration (Tanpichai & Witayakran, 2018; Tanpichai et al., 2022). During pyrolysis, phosphorus-containing compounds effectively form acids that promote dehydration and char formation (Ahmadi et al., 2022). Additionally, the hyphal surface proteins, hydrophobins, also promote char formation (Alongi et al., 2014). These findings suggest MMBs are safer alternatives to highly flammable polymer foams due to the inherent characteristics of mycelium in the former, indicating their suitability in a wide range of applications, including transportation, packaging, indoor designs, and insulation materials.

The MMBs are considered environmentally friendly and economically viable, relying on the sustainable sourcing of resources (Khyaju & Luangharn, 2024). Biodegradability test of samples produced from both *Panus* species demonstrated that the weight loss exceeded 60%, thereby confirming their biodegradable nature. The disintegration of MMBs in soil is primarily driven by the progressive breakdown of mycelium (Van Wylick et al., 2022). The observed weight loss can be attributed to multiple processes, including microbial activity, biochemical reactions, and compound leaching (Zimele et al., 2020; Van Wylick et al., 2022). MMBs undergo rapid decomposition in soil, adhering to the principles of the circular economy. Additionally, it serves as an alternative to petroleum-based materials (plastics and foams) in packaging, building, indoor uses, and insulation, which are non-biodegradable, environmentally polluting, and pose threats to people and wildlife.

Species of the genus *Panus* have not yet been reported in MMB development. This is the first successful application of mycelium from *Panus* species in combination with rubber sawdust in the design and development of construction and household items, such as blocks, vases, and bowls. Therefore, it highlights the practical utility of these fungi in the production of biomaterials. These

laboratory-scale findings indicate the potential of *Panus* species for large-scale MMB production, provided suitable manufacturing resources, financial resources, and experts are available. Additionally, the genetic modification in fungal species, such as the introduction of the glyceraldehyde-3-phosphate dehydrogenase (GPD) promoter into *Ganoderma* species, resulted in 135–165% higher β-glucan content, thereby enhancing compression strength (Madusanka et al., 2024; Salichanh et al., 2025). Similarly, for commercial production and applications, like other fungal genera (*Ganoderma*, *Pleurotus*, *Trametes*), further investigation to strengthen the mechanical properties through reinforcement and pressing could be beneficial.

Maintaining viable fungal cultures is essential for the successful mycelium-based biomaterial (MBB) production. Repeated subculturing often leads to strain degeneration (Yin et al., 2017; Chen et al., 2019; Zhao et al., 2022a); therefore, in this study, basidiomata formation was stimulated to allow re-isolation of cultures. This approach supports long-term stability and genetic fidelity of production strains and is recommended for integration into large-scale manufacturing processes.

Overall, this study provides the first integrated report on *P. ciliatus* and *P. subfasciatus* as promising fungal resources for MBB production. Their composites display several favourable properties, including low density, dimensional stability, hydrophobicity, thermal stability, fire resistance, and biodegradability. Mechanical strength remains a limitation. Targeted improvements, including pressing, substrate reinforcement, changing cultivation methods, and genetic recombination techniques, could enable these materials to become competitive, sustainable alternatives to petroleum-based foams and plastics at industrial scales.

3.3 Study on Mycelium-Based Biomaterials Developed from Twelve Fungal Strains

3.3.1 Fungal Species Identification

The fungal species used in this study were identified using phylogenetic analyses, based on the ITS gene region, and are shown in Figure 3.29 and Table 3.9.

Note a *Coriolopsis brunneoleuca* (Co). b *Earliella scabrosa* (Ea1). c *Earliella scabrosa* (Ea2). d *Ganoderma australe* (Ga1). e *Ganoderma tropicum* (Ga2). f *Hexagonia tenuis* (He1). g *Hexagonia tenuis* (He2). h *Lentinus squarrosulus* (Le). i *Microporus xanthopus* (Mi). j *Pleurotus ostreatus* (Pl). k *Trametes polyzona* (Tr1). l *Trametes sanguinea* (Tr2). Scale bar = 2 cm.

Figure 3.29 Macro-morphology of twelve fungal species used in this study

Table 3.9 Details of the twelve fungal samples used in this study

Fungal species	MFLUCC code	Family	Hyphal system	Collected area (Province)	Source
Coriolopsis brunneoleuca (Co)	24-0265	Polyporaceae	Trimitic	Chiang Mai	Mixed deciduous forest
Earliella scabrosa (Ea1)	24-0263	Polyporaceae	Trimitic	Chiang Rai	Mixed deciduous forest
Earliella scabrosa (Ea2)	24-0268	Polyporaceae	Trimitic	Chiang Rai	Mixed deciduous forest
Ganoderma australe (Ga1)	24-0262	Polyporaceae	Trimitic	Chiang Rai	Mixed deciduous forest
Ganoderma tropicum (Ga2)	24-0267	Polyporaceae	Trimitic	Chiang Rai	Mixed deciduous forest
Hexagonia tenuis (He1)	24-0266	Polyporaceae	Trimitic	Chiang Mai	Mixed deciduous forest
Hexagonia tenuis (He2)	24-0270	Polyporaceae	Trimitic	Chiang Mai	Mixed deciduous forest
Lentinus squarrosulus (Le)	24-0271	Polyporaceae	Dimitic	Chiang Rai	Local market
Microporus xanthopus (Mi)	24-0261	Polyporaceae	Trimitic	Chiang Rai	Mixed deciduous forest
Pleurotus ostreatus (Pl)	24-0260	Pleurotaceae	Monomitic	Chiang Rai	Local market
Trametes polyzona (Tr1)	24-0269	Polyporaceae	Trimitic	Chiang Rai	Mixed deciduous forest
Trametes sanguinea (Tr2)	24-0264	Polyporaceae	Trimitic	Chiang Rai	Mixed deciduous forest

3.3.2 Effect of Culture Media on Mycelial Growth

The mycelium growth rate and mycelium density of fungal species in PDA and MEA are shown in Table 3.10 and Figure 3.30. In PDA, the fastest growth rate was observed in *Lentinus squarrulosus* (13.07 mm/day) and *Trametes sanguinea* (13.58 mm/day), followed by *Microporus xanthopus* (12.77 mm/day) and *Trametes polyzona* (12.60 mm/day). In MEA, the highest growth rate was observed in *Lentinus squarrulosus* (14.08 mm/day) and *Trametes polyzona* (14.22 mm/day), followed by *Trametes sanguinea* (12.88 mm/day). However, in both media, *Ganoderma tropicum* exhibited the lowest growth rate, at 2.13 mm/day and 5.17 mm/day, respectively.

Table 3.10 Average growth rate and density of mycelium of twelve fungal strains

Fungal species	Average Growth Rate (mm/day)				Mycelial density on day 14	
	PDA		MEA		PDA	MEA
	95% confidence interval	Average	95% confidence interval	Average		
Coriolopsis brunneoleuca (Co)	10.09, 12.51	11.30 ± 0.97^{bc}	10.18, 13.56	11.87 ± 1.36^{abc}	3+	3+
Earliella scabrosa (Ea1)	10.38, 11.86	11.12 ± 0.60^{bc}	7.24, 13.59	10.42 ± 2.56^{cd}	5+	5+
Earliella scabrosa (Ea2)	8.13, 8.60	8.36 ± 0.19^{d}	8.91, 9.73	9.32 ± 0.33^{d}	5+	5+
Ganoderma australe (Ga1)	8.25, 12.95	10.60 ± 1.89^{c}	8.08, 12.88	10.48 ± 1.93^{bcd}	3+	3+
Ganoderma tropicum (Ga2)	1.44, 2.82	2.13 ± 0.56^{f}	2.64, 7.70	5.17 ± 2.04^{e}	4+	4+
Hexagonia tenuis (He1)	8.98, 12.42	10.70 ± 1.39^{c}	8.61, 14.59	11.60 ± 2.41^{bcd}	5+	5+
Hexagonia tenuis (He2)	3.35, 5.12	4.24 ± 0.72^{e}	3.59, 7.81	5.70 ± 1.70^{e}	2+	3+
Lentinus squarrosulus (Le)	11.91, 14.22	13.07 ± 0.93^{a}	12.96, 15.21	14.08 ± 0.90^{a}	2+	3+
Microporus xanthopus (Mi)	11.60, 13.94	12.77 ± 0.94^{ab}	7.01, 13.72	10.37 ± 2.70^{cd}	4+	4+
Pleurotus ostreatus (Pl)	9.17, 11.03	10.10 ± 0.75^{c}	10.87, 12.33	11.60 ± 0.59^{bcd}	5+	5+
Trametes polyzona (Tr1)	9.61, 15.59	12.60 ± 2.40^{ab}	13.30, 15.14	14.22 ± 0.74^{a}	4+	4+
Trametes sanguinea (Tr2)	12.04, 15.12	13.58 ± 1.24^{a}	11.62, 14.14	12.88 ± 1.01^{ab}	3+	3+

Note Values represent mean ± standard deviation. Within a column, values followed by the same letter are not significantly different ($p < 0.05$) by Duncan's Multiple Range Test.

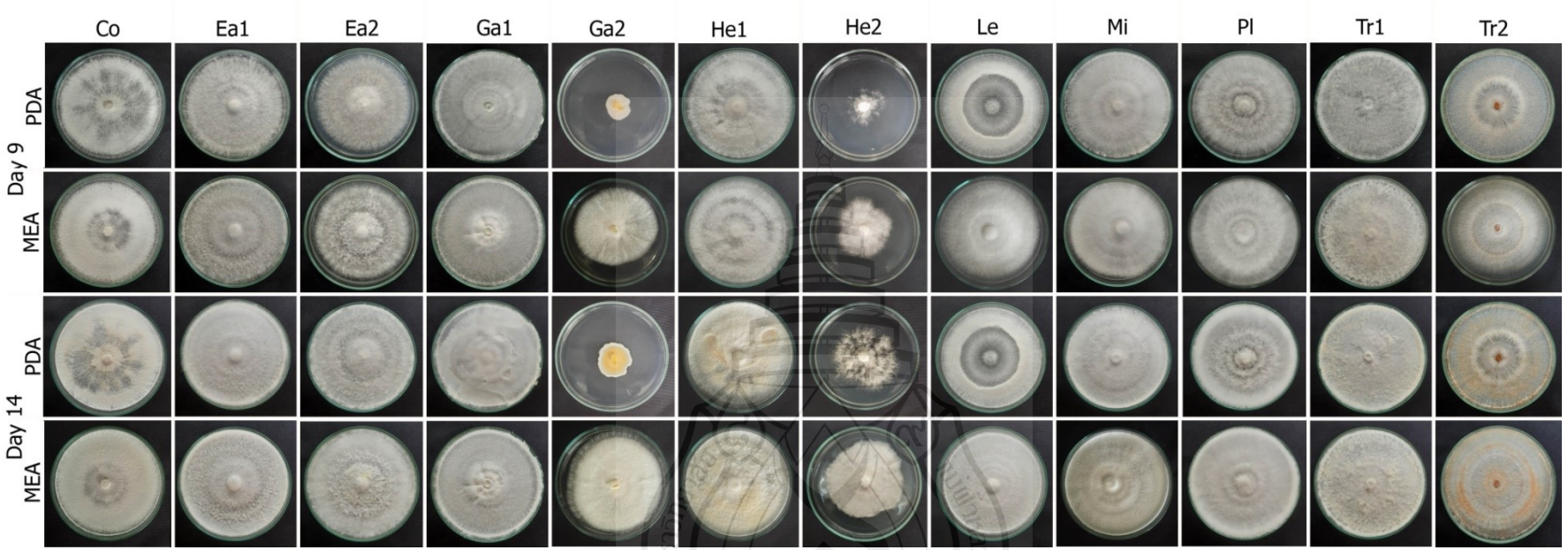
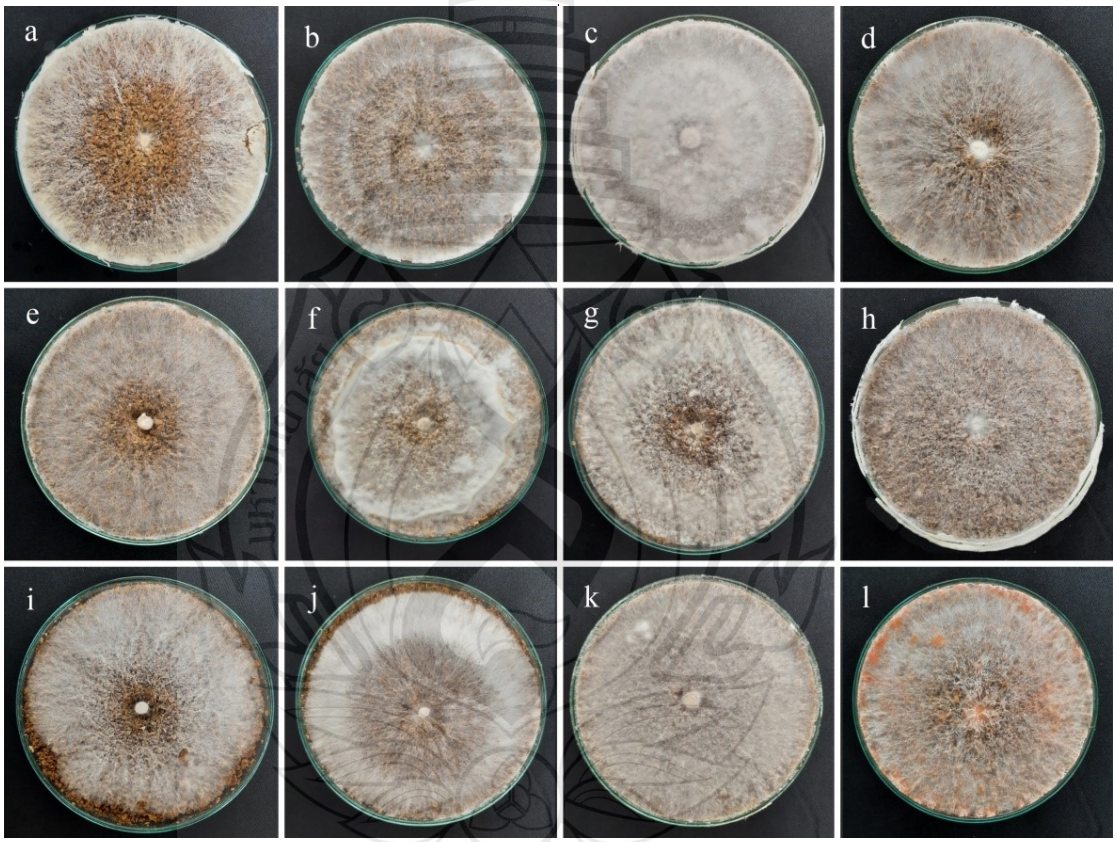


Figure 3.30 Morphology of mycelium of twelve fungal strains in PDA and MEA at days 9 and 14 after inoculation

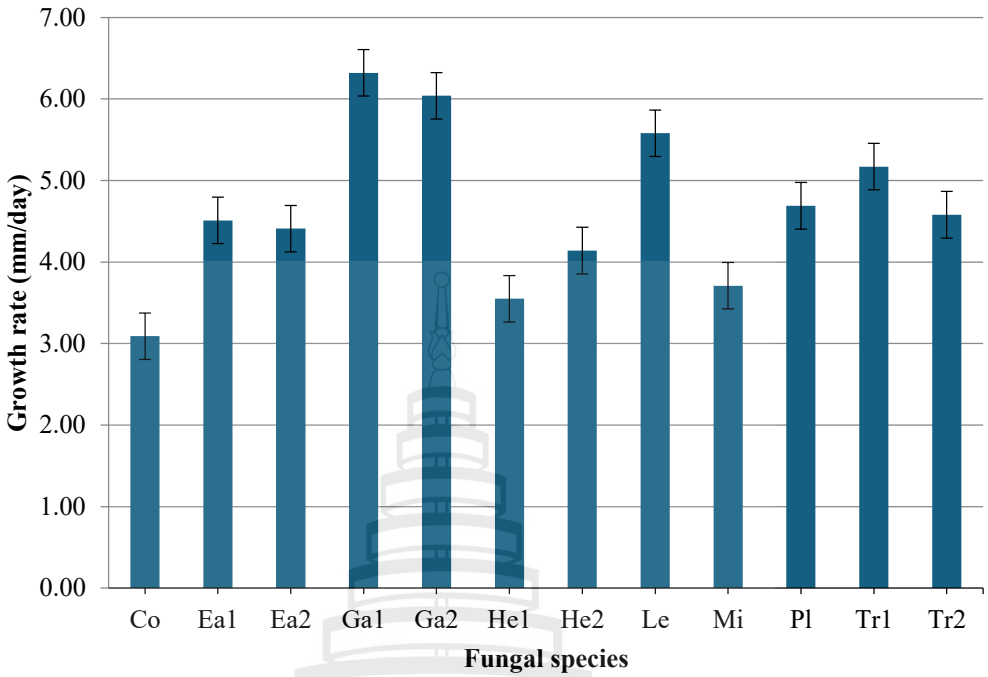
3.3.3 Mycelium Characteristics in Sawdust

The visual representation of mycelium growth of twelve fungal species in rubber sawdust on day 30 is shown in Figure 3.31. The growth rate and surface morphology of mycelium in sawdust are provided in Table 3.11 and Figure 3.32. *Ganoderma australe* and *G. tropicum* showed the fastest growth rate with 6.32 and 6.04 cm/day, respectively. *Earliella scabrosa* (Ea2), *Hexagonia tenuis* (He1), *Hexagonia tenuis* (He2), and *Pleurotus ostreatus* showed the thickest mycelial density. Orange pigmentation is visible on the mycelial surface in *Trametes sanguinea*.



Note a *Coriolopsis brunneoleuca*. b *Earliella scabrosa* (Ea1). c *Earliella scabrosa* (Ea2). d *Ganoderma australe*. e *Ganoderma tropicum*. f *Hexagonia tenuis* (He1). g *Hexagonia tenuis* (He2). h *Lentinus squarrosulus*. i *Microporus xanthopus*. j *Pleurotus ostreatus*. k *Trametes polyzona*. l *Trametes sanguinea*.

Figure 3.31 Mycelium growth of selected fungal species in sawdust on day 30



Note The error bars indicate standard deviation from means

Figure 3.32 Mycelium growth rates of the selected fungal strains in sawdust

Table 3.11 Mycelial growth characteristics of selected fungal species in sawdust

Fungal species	Growth rate (mm/day)		Mycelial characteristics
	95% confidence interval	Average	
Coriolopsis brunneoleuca (Co)	2.62, 3.08	3.09 ± 0.38^{g}	white, mycelium thick at periphery, thin at centre, 3+
Earliella scabrosa (Ea1)	3.36, 5.67	4.51 ± 0.93^{cde}	white, concentric mycelium pattern, 3+
Earliella scabrosa (Ea2)	3.42, 5.40	4.41 ± 0.80^{cde}	white, concentric mycelium pattern, 4+
Ganoderma australe (Ga1)	6.02, 6.62	6.32 ± 0.24^{a}	white, uniform mycelium in the entire plate, 3+
Ganoderma tropicum (Ga2)	5.53, 6.56	6.04 ± 0.41^{a}	white, uniform mycelium in the entire plate, 3+
Hexagonia tenuis (He1)	2.90, 4.21	3.55 ± 0.53^{fg}	white, concentric ring of mycelium, 4+
Hexagonia tenuis (He2)	3.36, 4.93	4.14 ± 0.63^{def}	white, uniform mycelium in the entire plate, 4+
Lentinus squarrosulus (Le)	4.61, 6.55	5.58 ± 0.78^{ab}	white, uniform mycelium in the entire plate, 2+
Microporus xanthopus (Mi)	3.32, 4.11	3.71 ± 0.32^{efg}	white, uniform mycelium in the entire plate, 3+
Pleurotus ostreatus (Pl)	4.28, 5.09	4.69 ± 0.32^{cd}	white, mycelium thick at periphery, thin at centre, 4+
Trametes polyzona (Tr1)	4.41, 5.93	5.17 ± 0.61^{bc}	greyish white, uniform mycelium in entire plate, 3+
Trametes sanguinea (Tr2)	3.59, 5.58	4.58 ± 0.80^{cd}	orangish white, uniform mycelium in entire plate, 3+

Note Values represent mean ± standard deviation. Within a column, values followed by the same letter are not significantly different ($p < 0.05$) by Duncan's Multiple Range Test.

3.3.4 Mycelial Characteristics in Potato Dextrose Broth

The morphology and ornamentation of every mycelium mat varied according to the strains (Figure 3.33). With the increase in the incubation period, the mycelium mats were thicker and more robust. Commercial strain *Pleurotus ostreatus* resulted in better performance than *Lentinus squarrosulus* in the thickness of the mycelium mat. Among wild strains, *Ganoderma tropicum*, *Earliella scabrosa* (Ea1), and *Trametes polyzona* exhibited desirable characteristics (thicker, stronger), while both *Hexagonia tenuis* (He1, He2) resulted as the weakest strains. Only *Ganoderma australe* had underside growth.

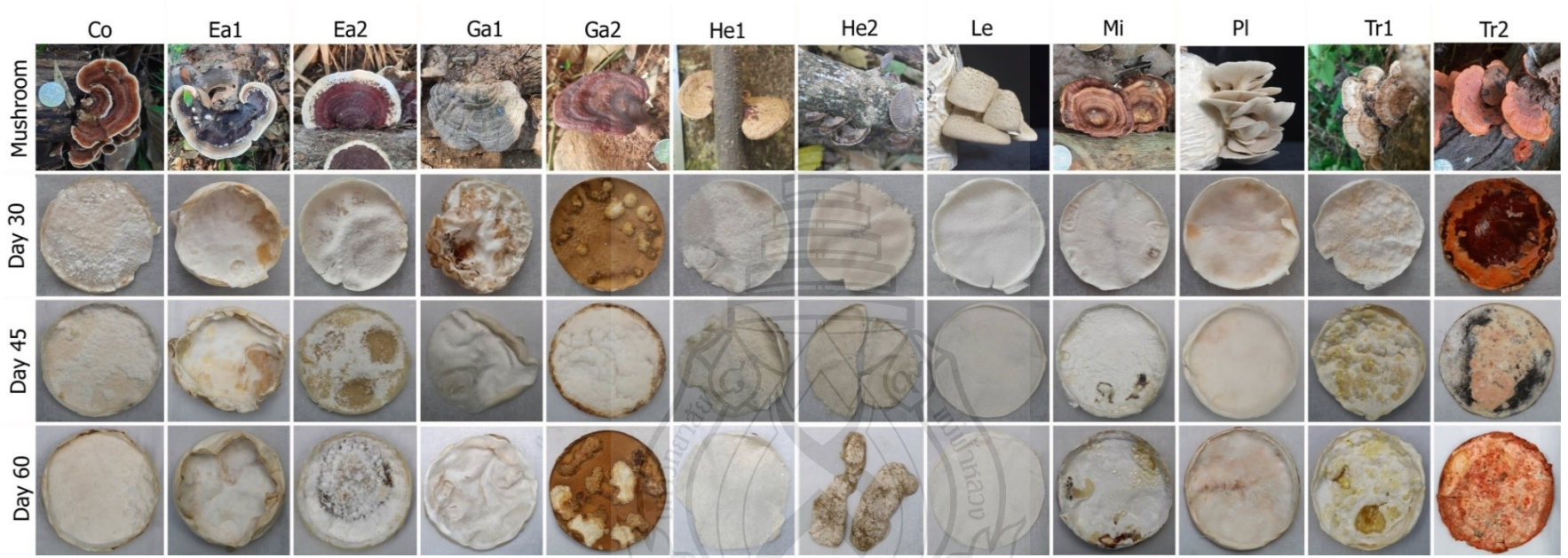


Figure 3.33 Mycelium mat produced in PDB from selected fungal species on days 30, 45, and 60

3.3.5 Mycelial Characteristics in Malt Extract Broth

The morphology and ornamentation of each mycelial mat varied according to the strain (Figure 3.34). With the longer incubation period, the mycelium mats were thicker and more robust. Both commercial strains, *Pleurotus ostreatus* and *Lentinus squarrosulus*, exhibited smooth, fluffy, denser, and rigid mycelium mats. Among wild strains, *Earliella scabrosa* (Ea1) had a thicker and more rigid mycelium mat, while *Hexagonia tenuis* (He1, He2) and *Trametes sanguinea* resulted as the weakest strains. Only *Ganoderma australe* had an underside growth.

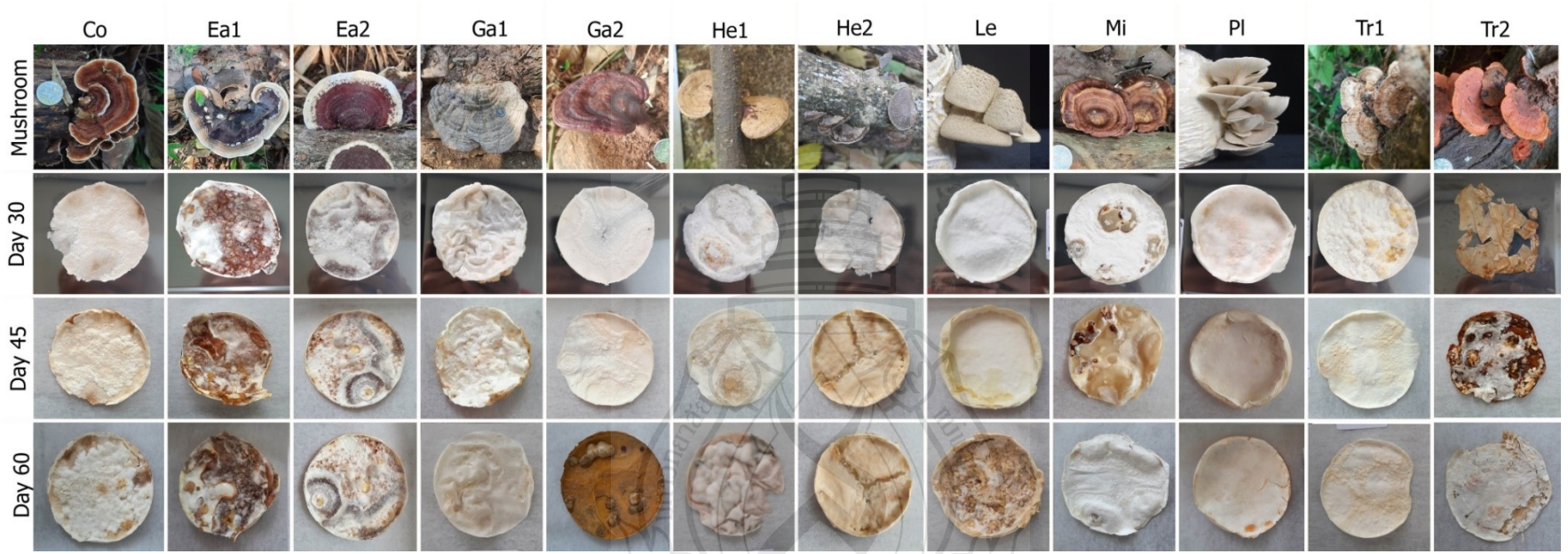


Figure 3.34 Mycelium mat produced in MEB from selected fungal species in day 30, 45 and 60

3.3.6 Evaluation of Physical Properties

3.3.6.1 Moisture content and dry density

The dry density and initial moisture content of samples are shown in Table 3.12. The initial moisture content of the test samples ranged between 54.80 to 58.76%. The dry density of samples ranged from 244.21 to 284.05 kg/m^3. The highest density was shown in *Trametes sanguinea*, with 284.05 kg/m^3, followed by *Hexagonia tenuis* (He2) with 273.87 kg/m^3.

Table 3.12 Dry density and initial moisture contents of MMB test samples

Fungal species	Weight before drying (g)	Weight after drying (g)	Initial moisture content (%)	Dry density (kg/m^3)	Average volumetric shrinkage (%)
Coriolopsis brunneoleuca (Co)	185.74 ± 12.06^{a}	76.49 ± 3.11^{c}	58.76 ± 1.17^{a}	254.97 ± 10.35^{c}	$9.52 \pm 1.09\%^{cd}$
Earliella scabrosa (Ea1)	171.78 ± 6.74^{b}	73.33 ± 0.70^{e}	57.25 ± 1.98^{abc}	244.44 ± 2.34^{e}	$7.13 \pm 1.05\%^{ef}$
Earliella scabrosa (Ea2)	174.03 ± 4.08^{b}	73.95 ± 0.35^{de}	57.49 ± 1.04^{abc}	246.49 ± 1.18^{de}	$8.30 \pm 1.04\%^{de}$
Ganoderma australe (Ga1)	n/a*	n/a*	n/a*	n/a*	n/a*
Ganoderma tropicum (Ga2)	174.30 ± 4.34^{b}	78.53 ± 2.41^{c}	54.95 ± 0.54^{d}	261.77 ± 8.05^{c}	$10.94 \pm 1.15\%^{bc}$
Hexagonia tenuis (He1)	162.86 ± 3.98^{c}	73.26 ± 2.61^{e}	55.01 ± 1.23^{d}	244.21 ± 8.71^{e}	$12.73 \pm 1.37\%^{a}$
Hexagonia tenuis (He2)	189.75 ± 6.70^{a}	82.16 ± 1.12^{b}	56.65 ± 1.99^{bcd}	273.87 ± 3.74^{b}	$7.51 \pm 1.05\%^{ef}$
Lentinus squarrosulus (Le)	173.14 ± 2.25^{b}	76.42 ± 0.88^{c}	55.86 ± 0.24^{cd}	254.74 ± 2.93^{c}	$11.16 \pm 1.75\%^{b}$
Microporus xanthopus (Mi)	n/a*	n/a*	n/a*	n/a*	n/a*
Pleurotus ostreatus (Pl)	183.46 ± 4.58^{a}	76.58 ± 0.08^{c}	58.24 ± 1.05^{ab}	255.27 ± 0.27^{c}	$7.60 \pm 1.06\%^{ef}$
Trametes polyzona (Tr1)	169.96 ± 7.73^{bc}	76.16 ± 1.89^{cd}	55.09 ± 2.76^{d}	253.87 ± 6.29^{cd}	$8.73 \pm 1.64\%^{de}$
Trametes sanguinea (Tr2)	188.58 ± 4.40^{a}	85.21 ± 1.69^{a}	54.80 ± 1.07^{d}	284.05 ± 5.62^{a}	$6.36 \pm 0.00\%^{f}$

Note Values represent mean ± standard deviation. Within a column, values followed by the same letter are not significantly different ($p < 0.05$) by Duncan's Multiple Range Test. * Specimens contaminated.

3.3.6.2 Volumetric shrinkage

The volumetric shrinkage of the samples ranged between 6.36 to 12.73% (Table 3.12, Figure 3.35). The shrinkage of samples was the highest for *Hexagonia tenuis* (He1) at 12.73%, followed by *Lentinus squarrosulus* at 6.36%.

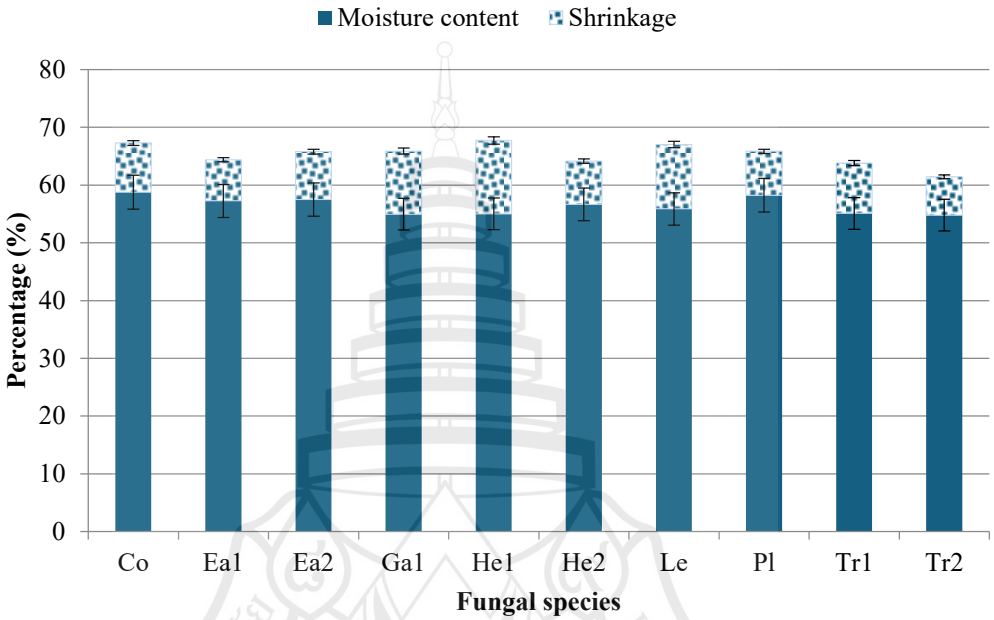
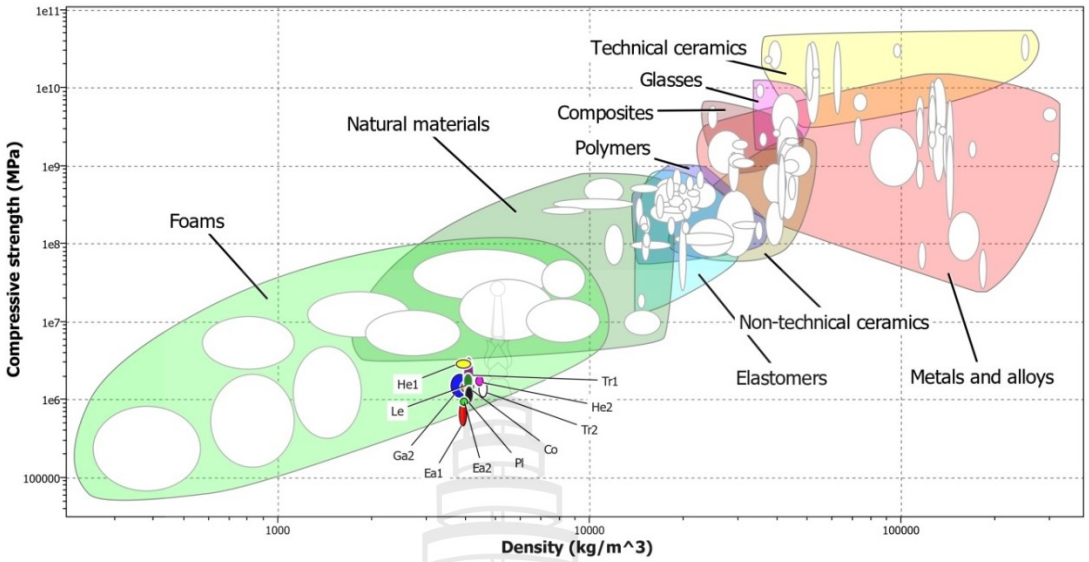


Figure 3.35 Moisture content and shrinkage percentage of test samples

3.3.7 Evaluation of Mechanical Properties

3.3.7.1 Compression strength

The compressive strength of MMB samples from the selected fungal species is provided in Table 3.13. On average, *Hexagonia* sp. and *Trametes polyzona* exhibited significantly greater compressive strength with 0.44 MPa and 0.39 MPa, respectively. The least compressive strength is shown by *Earliella scabrosa*, both with 0.12 MPa. The Ashby's chart of compressive strength against density is shown in Figure 3.36.

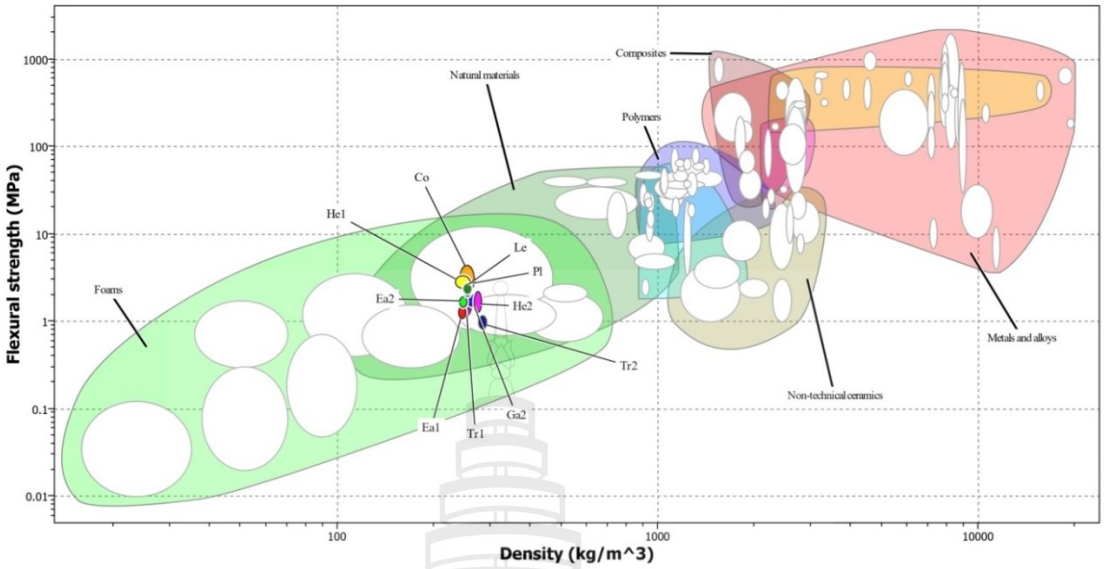


Note The members of each typical material family are enclosed in envelopes. The image was generated using CES EduPack 2014 v14.3.5.

Figure 3.36 Material property chart (Ashby) in terms of compressive strength against density

3.3.7.2 Flexural Strength

The flexural strength of MMB samples from the selected fungal species is provided in Table 3.13. On average, *Coriolopsis brunneoleuca* and *Hexagonia tenuis* (He1) showed the highest flexural strength with 3.15 MPa and 2.95 MPa, respectively. *Trametes sanguinea* showed the least value of flexural strength with 0.95 MPa. The Ashby's chart of compressive strength against density is shown in Figure 3.37.



Note The members of each typical material family are enclosed in envelopes. The image was generated using CES EduPack 2014 v14.3.5.

Figure 3.37 Material property chart (Ashby) in terms of flexural strength against density

3.3.7.3 Impact Strength

The impact strength of MMB samples from the selected fungal species is provided in Table 3.13. On average, *Ganoderma tropicum* showed the highest degree of impact strength with 0.38 kJ/m^2, followed by *Earliella scabrosa* (Ea1) with 0.30 kJ/m^2. *Pleurotus ostreatus* exhibited the lowest degree of impact strength.

Table 3.13 The compressive strength, flexural strength, and impact strength of mycelium-based biomaterial samples

Fungal species	Parameters					
	Compressive Strength (MPa)		Flexural Strength (MPa)		Impact Strength (kJ/m^2)	
	95% Confidence interval	Average	95% Confidence interval	Average	95% Confidence interval	Average
Coriolopsis brunneoleuca (Co)	0.18, 0.26	0.22 ± 0.03^{bc}	2.16, 4.14	3.15 ± 0.80^{a}	0.19, 0.35	0.27 ± 0.07^{bc}
Earliella scabrosa (Ea1)	0.07, 0.19	0.12 ± 0.04^{d}	1.03, 1.45	1.24 ± 0.17^{de}	0.19, 0.41	0.30 ± 0.09^{b}
Earliella scabrosa (Ea2)	0.10, 0.14	0.12 ± 0.02^{d}	1.37, 1.80	1.59 ± 0.18^{cd}	0.18, 0.34	0.26 ± 0.06^{bc}
Ganoderma australe (Ga1)	n/a*	n/a*	n/a*	n/a*	n/a*	n/a*
Ganoderma tropicum (Ga2)	0.13, 0.27	0.20 ± 0.06^{bc}	1.57, 2.13	1.85 ± 0.23^{c}	0.29, 0.47	0.38 ± 0.07^{a}
Hexagonia tenuis (He1)	0.39, 0.48	0.44 ± 0.04^{a}	2.52, 3.38	2.95 ± 0.34^{a}	n/a*	n/a*
Hexagonia tenuis (He2)	0.22, 0.27	0.25 ± 0.02^{b}	1.27, 2.23	1.75 ± 0.38^{c}	0.21, 0.33	0.27 ± 0.05^{bc}
Lentinus squarrosulus (Le)	0.22, 0.31	0.27 ± 0.04^{b}	2.04, 2.66	2.35 ± 0.25^{b}	0.23, 0.30	0.26 ± 0.03^{bc}
Microporus xanthopus (Mi)	n/a*	n/a*	n/a*	n/a*	n/a*	n/a*
Pleurotus ostreatus (Pl)	0.14, 0.20	0.17 ± 0.03^{cd}	2.05, 2.79	2.42 ± 0.30^{b}	0.13, 0.29	0.21 ± 0.06^{c}
Trametes polyzona (Tr1)	0.24, 0.53	0.39 ± 0.12^{a}	1.27, 2.42	1.85 ± 0.47^{c}	0.20, 0.31	0.26 ± 0.04^{bc}
Trametes sanguinea (Tr2)	0.17, 0.25	0.21 ± 0.03^{bc}	0.78, 1.12	0.95 ± 0.14^{e}	0.21, 0.24	0.23 ± 0.01^{bc}

Note Values represent mean ± standard deviation. Within a column, values with the same letter are not significantly different ($p < 0.05$) by Duncan's Multiple Range test. * Specimen failed to grow.

3.3.8 Evaluation of Hydrodynamic Properties

3.4.8.1 Water absorption

The water absorption ability of test samples of different fungal species is shown in Figure 3.38. In the first 24 h period, the highest water absorption was by *Trametes polyzona* at 177%, and the lowest absorption was by *Ganoderma tropicum* with 41.52%. After 92 h, the water absorption range was 107.18−240.17% when left submerged in water for 24−192 h.

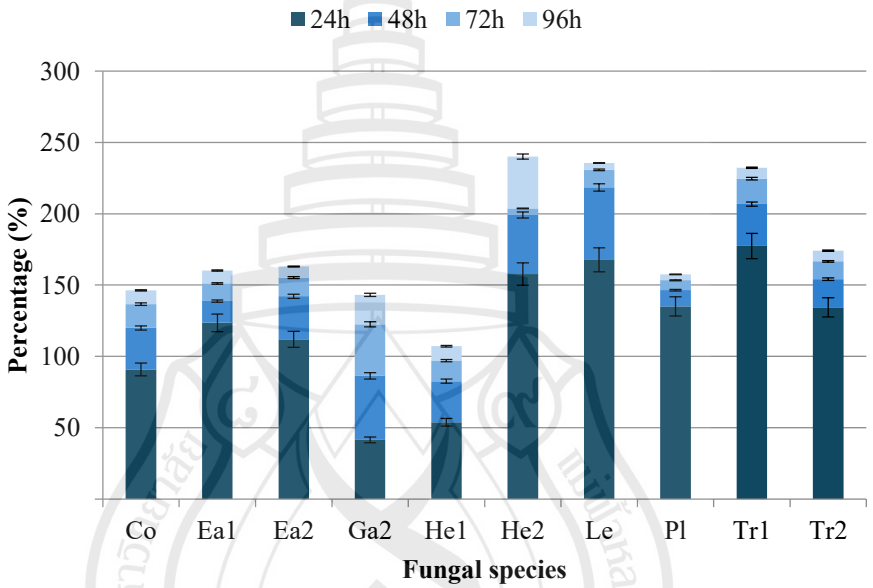


Figure 3.38 Water absorbsion by the test samples of selected fungal species

3.4.8.2 Water Contact Angle Analysis

The water contact angle (WCA) of the pure mycelium mats of twelve fungal species was compared (Figure 3.39, Table 3.14). The WCA values of all the mushroom species in 10 and 60 s were above 90°, indicating their hydrophobic nature. At 10 s, *Lentinus squarrosulus* and *Pleurotus ostreatus* resulted in the greatest WCA value with 125.13° and 125.62°, respectively. The least value was observed in *Trametes polyzona* with 106.82°. At 60 s, *Pleurotus ostreatus* resulted in the largest WCA value (124.11°), followed by *Lentinus squarrosulus* (122.88°). Mycelium mats of *Ganoderma tropicum*, *G. australe*, and *Trametes polyzona* result in the least WCA values at 60 s among all the fungal species. Water absorption by the mycelium mats, up to 60 s, was negligible for all the fungal species.

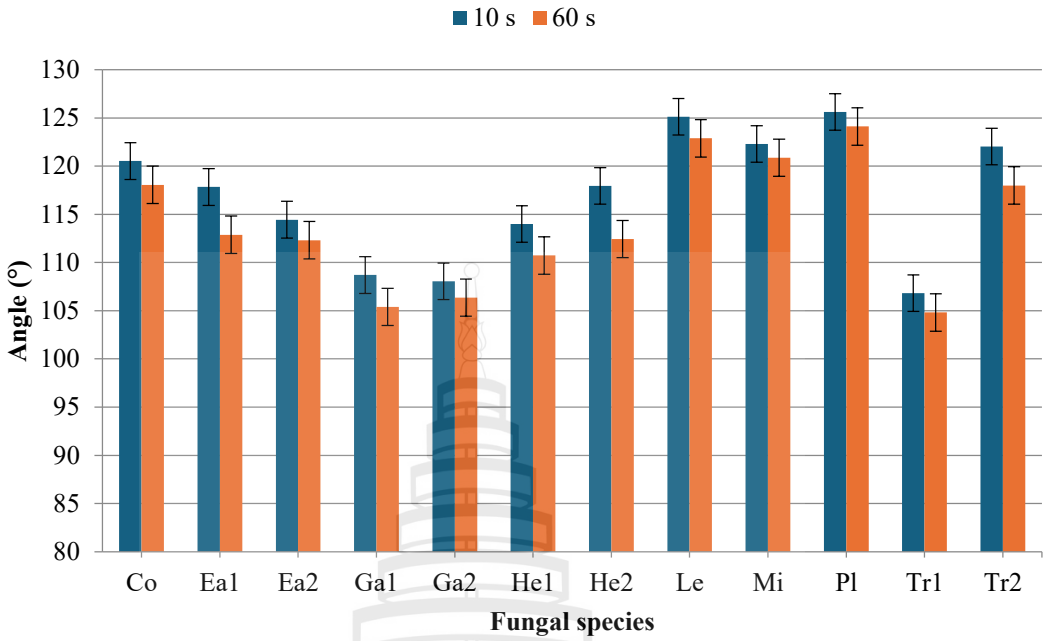


Figure 3.39 Water contact angle values of pure mycelium mats of selected fungal species measured at 10s and 60s

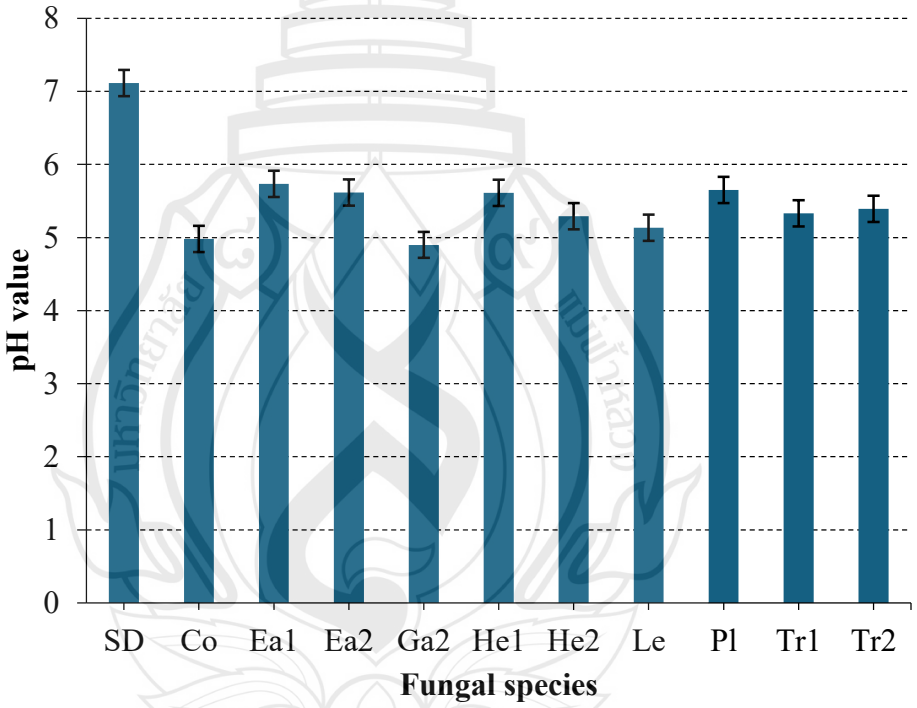
Table 3.14 The water contact angle values of pure mycelium mat samples measured at 10 and 60 s

Fungal species	Contact angle value (°)			
	at 10 seconds		at 60 seconds	
	95% Confidence interval	Average	95% Confidence interval	Average
Coriolopsis brunneoleuca (Co)	108.43, 132.61	120.52 ± 9.74^{ab}	105.00, 131.12	118.06 ± 10.52^{abc}
Earliella scabrosa (Ea1)	106.73, 128.93	117.83 ± 8.94^{abc}	102.22, 123.53	112.88 ± 8.58^{bcd}
Earliella scabrosa (Ea2)	108.11, 120.76	114.44 ± 5.10^{bcd}	107.24, 117.38	112.31 ± 4.08^{bcd}
Ganoderma australe (Ga1)	98.94, 118.46	108.7 ± 7.86^{cd}	96.40, 114.40	105.4 ± 7.25^{d}
Ganoderma tropicum (Ga2)	101.18, 114.94	108.06 ± 5.54^{cd}	98.45, 114.27	106.36 ± 6.37^{d}
Hexagonia tenuis (He1)	110.14, 117.86	114 ± 3.11^{bcd}	105.73, 115.73	110.73 ± 4.03^{cd}
Hexagonia tenuis (He2)	106.37, 129.82	117.94 ± 9.32^{abc}	101.44, 123.42	112.43 ± 8.85^{bcd}
Lentinus squarrosulus (Le)	112.00, 138.27	125.13 ± 10.58^{a}	109.91, 135.86	122.88 ± 10.45^{ab}
Microporus xanthopus (Mi)	114.30, 130.30	122.3 ± 6.44^{ab}	113.45, 128.30	120.87 ± 5.98^{abc}
Pleurotus ostreatus (Pl)	119.25, 131.99	125.62 ± 5.13^{a}	116.20, 132.03	124.11 ± 6.37^{a}
Trametes polyzona (Tr1)	100.93, 112.71	106.82 ± 4.74^{d}	102.01, 107.62	104.82 ± 2.26^{d}
Trametes sanguinea (Tr2)	116.59, 127.47	122.03 ± 4.38^{ab}	106.98, 129.01	117.99 ± 8.87^{abc}

Note Values represent mean ± standard deviation. Within a column, values with the same letter are not significantly different ($p < 0.05$) by Duncan's Multiple Range test.

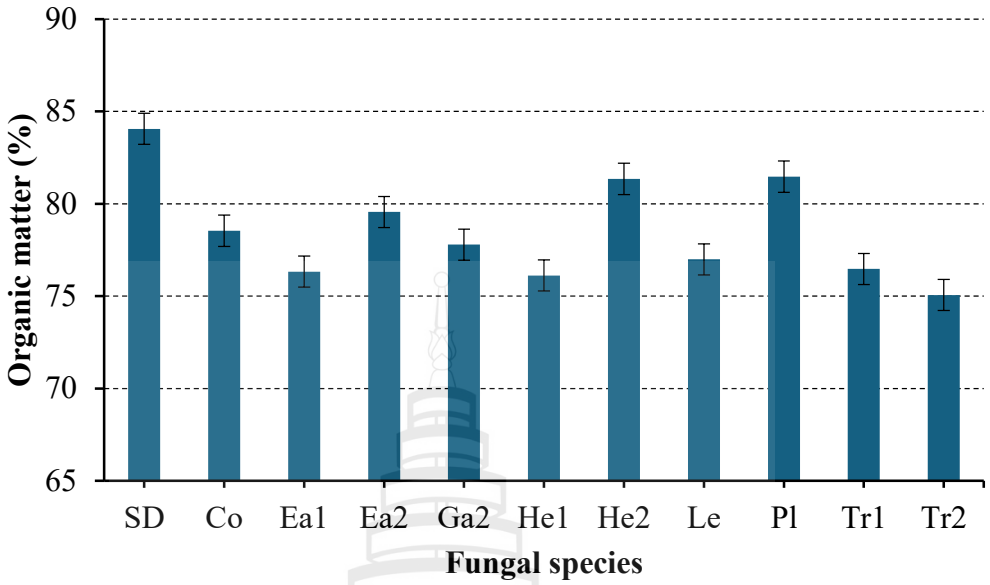
3.3.9 Evaluation of Chemical Properties

The pH value, organic matter cotent and Nitrogen content of test samples and sawdust (control) are shown in Table 3.15. The initial pH value of the growing substrate was 7.11. The final pH values of the final test samples were within the range 4.90−5.74 (Figure 3.40). The final pH value significantly decreased from the initial pH value of the sawdust substrates. The organic matter content decreased in MMBs from all fungal strains (Figure 3.41). Notably, Nitrogen content increased in all the MMBs showed increased levels in *Coriolopsis brunneoleuca*, *Earliella scabrosa* (Ea2), *Hexagonia* sp. (He1), *Hexagonia* sp. (He2), and *Lentinus squarrosulus* (Figure 3.42).



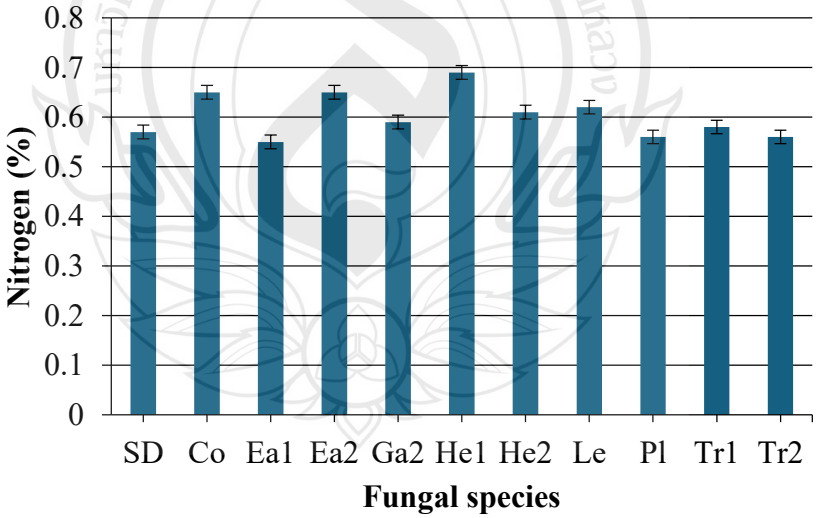
Note Data are presented in means, and the error bar at each point indicates the ± standard deviation.

Figure 3.40 The pH values of the initial sawdust substrate and final test samples



Note Data are presented in means, and the error bar at each point indicates the ± standard deviation.

Figure 3.41 The organic matter content of the initial sawdust substrate and final test samples



Note Data are presented in means, and the error bar at each point indicates the ± standard deviation.

Figure 3.42 The nitrogen content of the initial sawdust substrate and final test samples

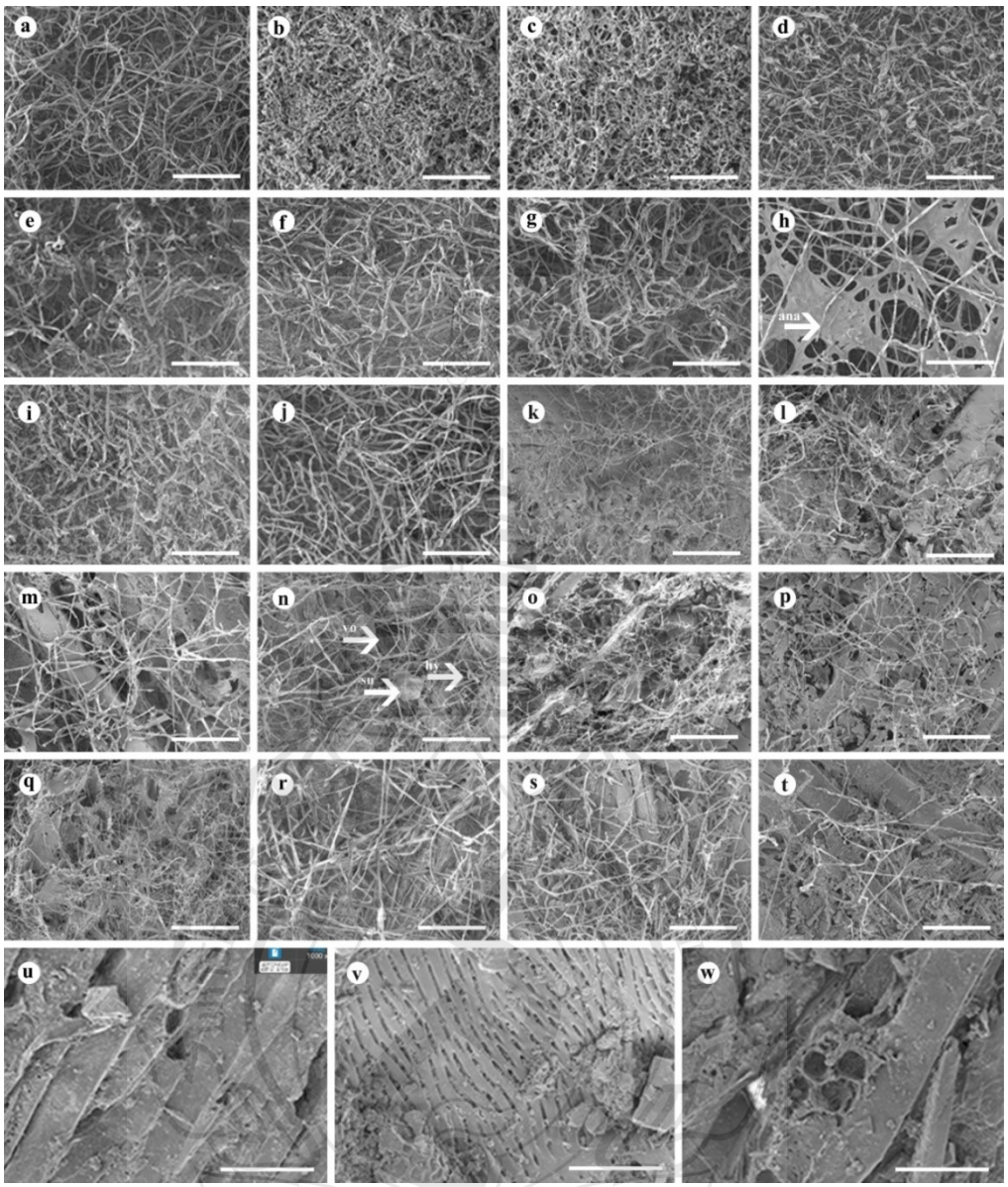
Table 3.15 The pH, organic matter, and Nitrogen content of composites prepared from selected fungal species

Parameters	Fungal species												
	Control (SD)	**Co**	**Ea1**	**Ea2**	**Ga1**	**Ga2**	**He1**	**He2**	**Le**	**Mi**	**Pl**	**Tr1**	**Tr2**
pH	7.11 ± 0.01^{a}	4.98 ± 0.00^{i}	5.74 ± 0.01^{b}	5.62 ± 0.01^{d}	n/a*	4.90 ± 0.00^{j}	5.61 ± 0.01^{d}	5.61 ± 0.02^{g}	5.61 ± 0.03^{h}	n/a*	5.61 ± 0.04^{c}	5.61 ± 0.05^{f}	5.61 ± 0.06^{e}
Organic matter (%)	84.06 ± 0.25^{a}	78.54 ± 0.91^{cd}	76.33 ± 1.20^{ef}	79.56 ± 0.85^{c}	n/a*	77.79 ± 1.28^{cde}	76.12 ± 0.63^{ef}	81.35 ± 1.36^{b}	76.99 ± 1.87^{def}	n/a*	81.47 ± 0.79^{b}	76.47 ± 1.01^{ef}	75.06 ± 0.05^{f}
Nitrogen (%)	0.57 ± 0.01^{def}	0.65 ± 0.03^{b}	0.55 ± 0.01^{f}	0.65 ± 0.01^{b}	n/a*	0.59 ± 0.01^{d}	0.69 ± 0.01^{a}	0.61 ± 0.01^{c}	0.62 ± 0.01^{c}	n/a*	0.56 ± 0.01^{ef}	0.58 ± 0.00^{de}	0.56 ± 0.01^{ef}

Note Values represent mean ± standard deviation. Within a column, values with the same letter are not significantly different ($p < 0.05$) by Duncan's Multiple Range test. * Specimen failed to grow.

3.3.10 Scanning Electron Microscopy

Hyphal structures of the selected fungal species grown on sawdust that were examined using SEM are shown in Figure 3.43. The surface view shows a dense hyphal network, either as a strand or anastomosis hypha, and the latter is more prominent in *Pleurotus ostreatus*. Visual inspection of surface mycelium in *Earliella scabrosa* (b, c) is comparatively much denser, while it is loosely interwoven and fluffy in other fungal species. Cross-sectional view showed the arrangement of hyphae, substrates, and voids, where multi-dimensional networks of hyphae bind discrete substrate particles, providing a rigid shape. Microstructure visualisation of the sawdust substrate (control) showed the surface roughness differing sized discrete particles.

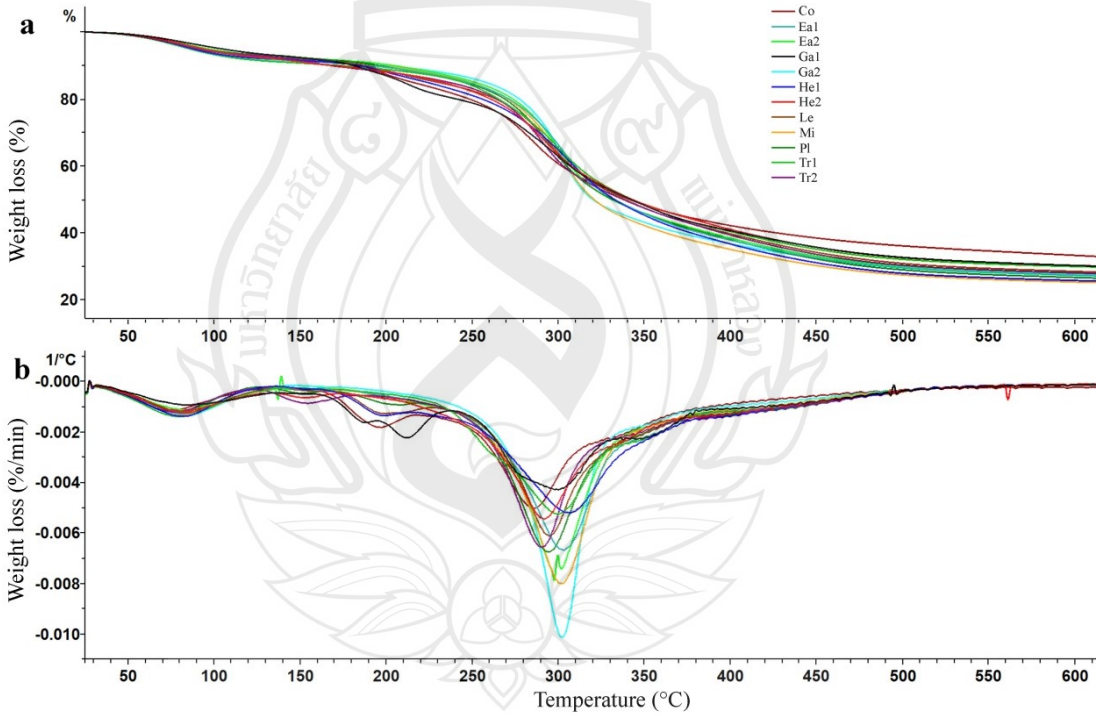


Note Surface view: a *Coriolopsis brunneoleuca*. b *Earliella scabrosa*. c *Earliella scabrosa*. d *Ganoderma tropicum*. e *Hexagonia tenuis*. f *Hexagonia tenuis*. g *Lentinus squarrosulus*. h *Pleurotus ostreatus*. i *Trametes polyzona*. j *Trametes sanguinea*. Cross-section view of test samples: k *Coriolopsis brunneoleuca*. l *Earliella scabrosa*. m *Earliella scabrosa*. n *Ganoderma tropicum*. o *Hexagonia tenuis*. p *Hexagonia tenuis*. q *Lentinus squarrosulus*. r *Pleurotus ostreatus*. s *Trametes polyzona*. t *Trametes sanguinea*. u–w uncolonized sawdust. ana = anastomosis hypha. hy = hypha. su = substrate. vo = voids. Scale bars: a–w = 50 μm.

Figure 3.43 Scanning electron microscopy images of test samples

3.3.11 Thermogravimetric Analysis on Pure Mycelium Mats

The Thermal behaviour of pure mycelium mats from selected fungal species is shown by TGA and the DTGA curves (Figure 3.44), exhibiting similar thermal degradation behaviour in all three stages of the test. The first event was observed at below 100°C, resulting in about 8 % mass loss. In the second event, the initial degradation peak temperature ranged from around 285°C for *Coriolopsis brunneoleuca* to around 306°C for *Hexagonia tenuis* (He1), resulting in about 63 % mass losses. The third event (decomposition) associated with non-degraded wastes and impurities accounts for around 20% at approximately 810°C. The water content of the mats was lowest for *Ganoderma australe* (6.78%) and highest for *Ganoderma tropicum* (8.86%), and the initial degradation temperature was lowest at ±285°C for *Coiolopsis brunneoleuca* and highest at ±306°C for *Hexagonia tenuis* (He1).



Note a TGA. b DTGA. The different colour lines represent mycelium mats of selected fungal species.

Figure 3.44 Thermal analysis of pure mycelium mats of selected fungal species

3.3.12 Fourier Transform Infrared Spectroscopy

FTIR spectra of selected fungal species, along with their absorption bands, are shown in Figure 3.45. The hydroxyl group (3200–3400 cm^{-1}), C-H stretching in the fatty acid region (2800–3000 cm^{-1}), protein region dominated by C=O (amide I) and N–H (amide II) (1500–1700 cm^{-1}), and polysaccharide region (900–1200 cm^{-1}) are the significant regions observed in the spectra. Details of the peak in the obtained spectra are provided in Table 3.16.

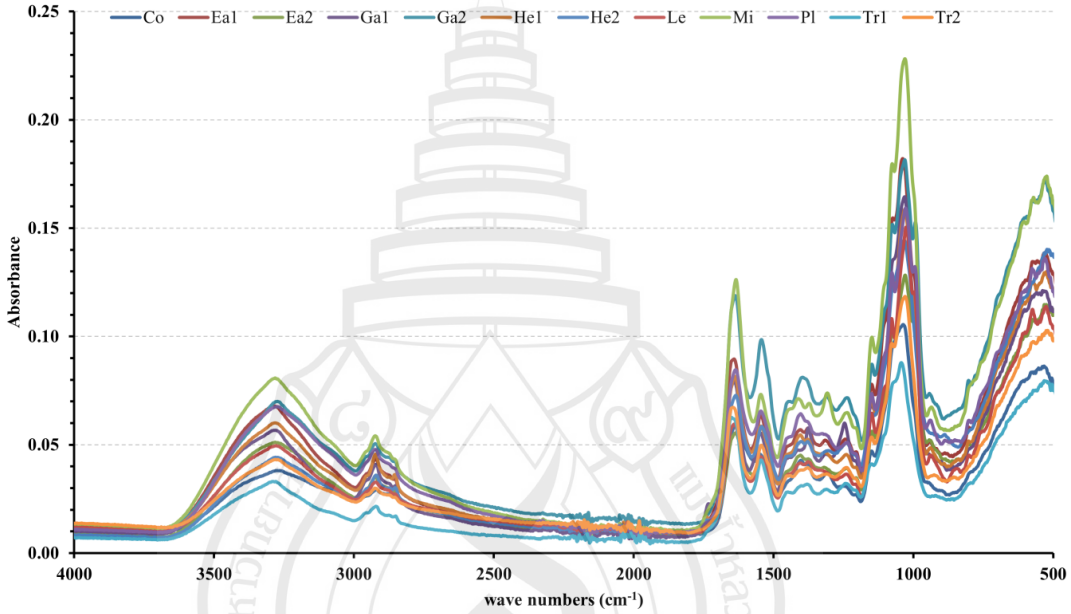


Figure 3.45 FTIR spectra of pure mycelium from the selected fungal species

Table 3.16 Characteristics absorption bands observed in the FTIR spectra (4000−400cm^{-1}) of the mycelium samples of selected fungal species

Wave number (cm^{-1})	Band origin/Spectra	Wavenumbers (cm^{-1})												References
		Co	Ea1	Ea2	Ga1	Ga2	He1	He2	Le	Mi	Pl	Tr1	Tr2	
3600–3000	O−H stretching hydrogen bonds	3266.54	3281.93	3281.59	3279.35	3273.32	3280.15	3280.11	3278.31	3281.55	–	3279.31	3279.88	Mohebby (2005), Haneef et al. (2017)
3000–2840	C-H stretching in methyl and methylene groups	2920.52	2922.24	2923.03	2920.57	2924.01	2922.46, 2853.13	2921.14	2921.98	2923.89	3276.75, 2924.47	2921.52	2925.22	Pandey and Pitman (2003), Schwanninger et al. (2004)
2940–2840	CH_2 asymmetric stretching	2920.52	2922.24	2923.03	2920.57	2924.01	2922.46, 2853.13	2921.14	2921.98	2923.89	2924.47	2921.52	2925.22	Elsacker et al. (2019)
1658–1625	Amide I, chitin	1632.86	1640.93	1636.02	1640.75	1636.77	1638.55	1634.95	1639.35	1633.90	1635.59	1650.58	1644.51	D'Souza and Kamat (2017)
1560–1520	C=C stretching of aromatic ring (syringyl) in lignin	1547.58	1545.29	1544.60	1546.46	1543.07	1545.66	1542.19	1544.90	1545.40	1545.09	1544.34	1543.56	Pandey and Pitman (2003), Schwanninger et al. (2004)

Table 3.16 (continued)

Wave number (cm^{-1})	Band origin/Spectra	wavenumbers (cm^{-1})												References
		Co	Ea1	Ea2	Ga1	Ga2	He1	He2	Le	Mi	Pl	Tr1	Tr2	
1460–1400	CH2 and CH_3 deformation in the lignin and hemicellulose, CH_2 in-plane bending vibrations in the cellulose and lignin	1402.44	–	1403.89	–	–	1404.28	1401.55	–	1412.42	1403.05	–	–	Raspolli et al. (2015), Akcay et al. (2023)
1390–1370	C–H symmetric deformation vibration, R–CH_3	–	1376.28	–	1375.37	–	–	–	1376.10	–	–	1380.44	1377.60	Baudot et al. (2010)
1375–1315	O-H bending polysaccharide, Amide III	–	1315.40	–	–	–	–	–	–	–	–	–	–	D'Souza and Kamat (2017)
1250–1025	C-O bond, β (1→3) glucan, cell wall polysaccharide	1149.26, 1036.37	1243.59, 1149.26, 1038.36	1238.61, 1147.98, 1074.63, 1029.34	1245.96, 1149.67, 1031.25	1238.33, 1148.21, 1074.96, 1030.61	1239.51, 1149.66, 1076.23, 1030.47	1239.45, 1032.44	1238.92, 1149.44, 1077.42, 1025.98	1236.04, 1148.12, 1075.71, 1030.30	1236.70, 1149.24, 1076.79, 1027.71	1243.23, 1043.14	1239.05, 1149.47, 1076.66, 1029.59	D'Souza and Kamat (2017)
1162–1125	C-O-C vibration in cellulose and hemicellulose	1149.26	1149.26	1147.98	1149.67	1148.21	1149.66	–	1149.44	1148.12	1149.24	–	1149.47	Pandey and Pitman (2003), Schwanninger et al. (2004), Mohebby (2005)

Table 3.16 (continued)

Wave number (cm^{-1})	Band origin/Spectra	wavenumbers (cm^{-1})												References
		Co	Ea1	Ea2	Ga1	Ga2	He1	He2	Le	Mi	Pl	Tr1	Tr2	
1060–1015	C-O valence vibration from C3-O3H	1036.37	1038.36	1029.34	1031.25	1030.61	1030.47	1032.44	1025.98	1030.30	1027.71	1043.14	1029.59	Schwanninger et al. (2004)
1047–1004	C-O stretching in cellulose	1036.37	1038.36	1029.34	1031.25	1030.61	1030.47	1032.44	1025.98	1030.30	1027.71	1043.14	1029.59	Pandey and Pitman (2003), Schwanninger et al. (2004), Mohebby (2005)
1185–900	Polysaccharides	1149.26, 1036.37	1149.26, 1038.36	1147.98, 1074.63, 1029.34, 992.85	1149.67, 1031.25	1148.21, 1074.96, 1030.61, 992.62	1149.66, 1076.23, 1030.47, 939.08	1032.44	1149.44, 1077.42, 1025.98, 938.13	1148.12, 1075.71, 1030.30, 935.52	1149.24, 1076.79, 1027.71, 994.77, 939.66	1043.14	1149.47, 1076.66, 925.47	Naumann (2009)
950–700	glycosidic bond β-(1 → 4) arabinogalactans, galactomannans, and cellulose	–	–	803.00	–	–	939.08	–	938.13	935.52	939.66	–	925.47	Reis et al. (2017)

3.3.13 Soil Burial Biodegradability

All the test samples gradually disintegrate over time, except for *Ganoderma tropicum*. The cumulative weight loss of all samples exceeded 60% by day 90, except for the samples from *Ganoderma tropicum* with only 32.05% weight loss (Table 3.17, Figure 3.46). The samples from *Pleurotus ostreatus* showed the greatest cumulative weight loss with 87.11%, followed by *Hexagonia tenuis* (He2) with 79.70%. The visual appearance of the samples before and after 30, 60, and 90 days of soil burial is shown in Figure 3.47. In the first 30 days, the samples' surface mycelium mats got eroded, without changing their shape and size. Till day 60, the samples were either broken down into pieces or deeply eroded. By day 90, every sample broke down into smaller pieces. However, the sample from *Ganoderma tropicum* showed no change in shape and no disintegration compared to other samples. Additionally, the samples turned blackish with increased soil burial.

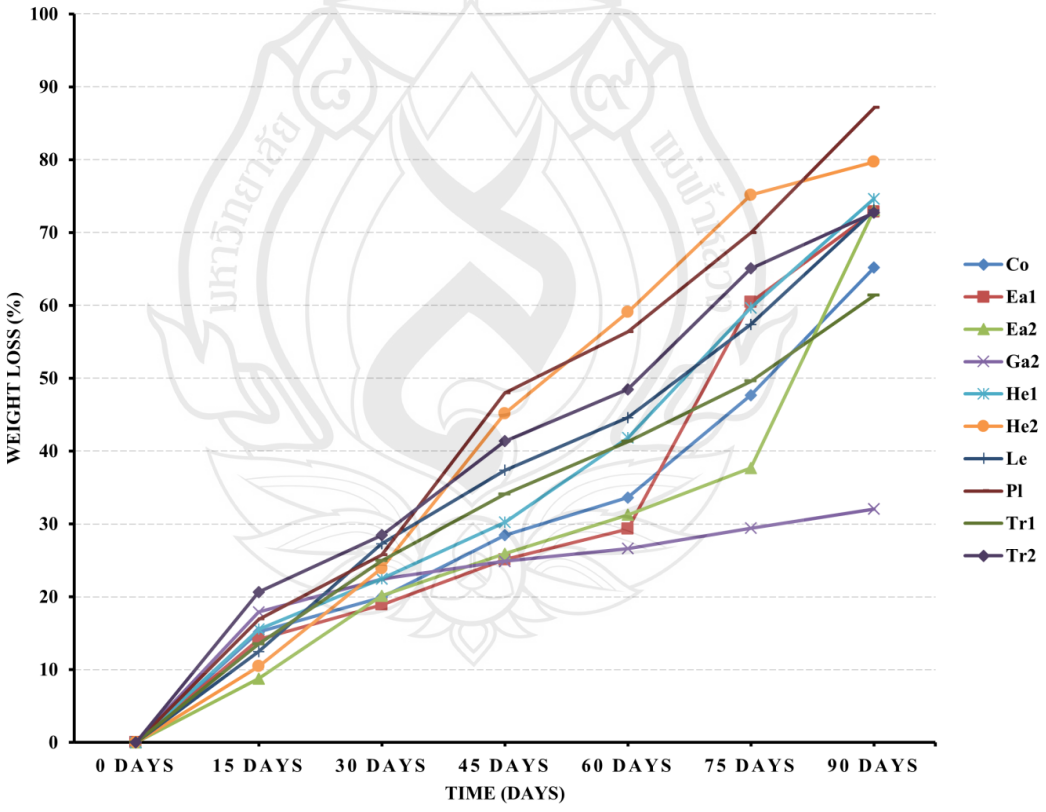


Figure 3.46 Cumulative percentage weight loss of MMB samples during the soil burial degradability test

Figure 3.47 Visual appearance of MMB samples of selected fungal species on day 0, 30, 60, and 90 during the soil burial degradability test

Table 3.17 Cumulative percentage weight loss of MMB samples during the soil burial degradability test

Fungal Species	Time (days)					
	15	**30**	**45**	**60**	**75**	**90**
Coriolopsis brunneoleuca (Co)	15.18 ± 0.44^{bcd}	19.94 ± 0.45^{de}	28.45 ± 2.08^{de}	33.60 ± 2.39^{d}	47.66 ± 7.12^{cd}	65.17 ± 4.19^{d}
Earliella scabrosa (Ea1)	14.15 ± 0.04^{cd}	18.91 ± 0.17^{e}	25.12 ± 2.32^{e}	29.31 ± 1.43^{de}	60.43 ± 4.49^{bc}	72.87 ± 3.40^{c}
Earliella scabrosa (Ea2)	8.78 ± 1.11^{f}	20.13 ± 0.49^{cde}	25.90 ± 1.47^{e}	31.24 ± 2.86^{de}	37.68 ± 18.94^{de}	73.11 ± 3.30^{c}
Ganoderma australe (Ga1)	n/a*	n/a*	n/a*	n/a*	n/a*	n/a*
Ganoderma tropicum (Ga2)	17.90 ± 0.86^{ab}	22.44 ± 0.82^{bcde}	24.89 ± 1.14^{e}	26.62 ± 1.40^{e}	29.41 ± 1.43^{e}	32.05 ± 1.36^{e}
Hexagonia tenuis (He1)	15.54 ± 2.30^{bcd}	22.47 ± 3.55^{bcde}	30.21 ± 4.75^{de}	41.81 ± 5.07^{bc}	59.68 ± 5.82^{bc}	74.63 ± 4.65^{bc}
Hexagonia tenuis (He2)	10.45 ± 1.53ed	23.91 ± 3.08^{abcd}	45.17 ± 4.73^{a}	59.08 ± 5.21^{a}	75.16 ± 2.10^{a}	79.70 ± 1.83^{b}
Lentinus squarrosulus (Le)	12.49 ± 3.01^{de}	27.28 ± 3.53^{ab}	37.37 ± 3.81^{bc}	44.57 ± 2.98^{bc}	57.39 ± 2.94^{bc}	73.08 ± 2.06^{c}
Microporus xanthopus (Mi)	n/a*	n/a*	n/a*	n/a*	n/a*	n/a*
Pleurotus ostreatus (Pl)	16.90 ± 2.21^{bc}	25.74 ± 5.43^{ab}	47.94 ± 7.00^{a}	56.36 ± 6.54^{a}	69.96 ± 6.47^{ab}	87.11 ± 2.58^{a}
Trametes polyzona (Tr1)	13.49 ± 2.94^{cde}	24.92 ± 1.16^{abc}	34.09 ± 2.33^{cd}	41.31 ± 3.15^{c}	49.59 ± 2.98^{cd}	61.36 ± 2.55^{d}
Trametes sanguinea (Tr2)	20.65 ± 1.49^{a}	28.45 ± 0.74^{a}	41.35 ± 3.08^{ab}	48.47 ± 2.84^{b}	65.07 ± 3.22^{ab}	72.73 ± 4.19^{c}

Note Values represent mean ± standard deviation. Within a column, values followed by the same letter are not significantly different ($p < 0.05$) by Duncan's Multiple Range Test. * Specimen failed to grow.

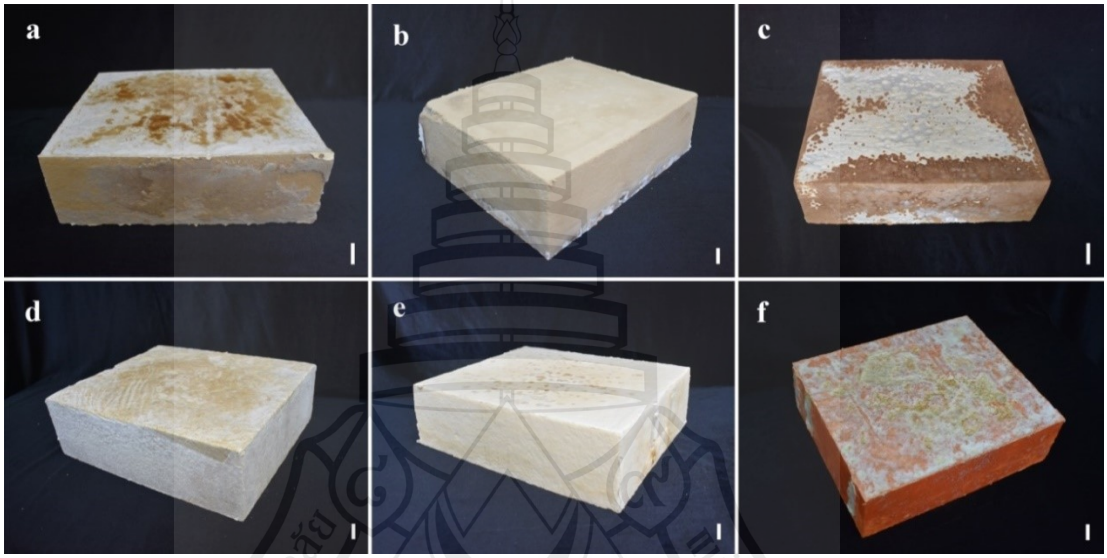
3.3.14 Viability Maintenance of Fungal Species

The substrate bags fully colonised by the mycelium of fungal species that were incubated in the fruiting chamber produced basidiomata (Figure 3.48). Mature basidiomata were harvested, and fresh tissue was re-isolated to obtain pure cultures for further studies.

Figure 3.48 Viability maintenance of fungal strains showing substrate bag fully colonised by mycelium, developing basidiomata in bags, and mature basidiomata produced

3.3.15 Developing Prototypes

Individual cuboid blocks of dimension 30×25×10 cm were developed and deactivated (Appendix A3, Figure 3.49). The individual blocks showed diverse surface colour and texture that correspond to fungal species. The final blocks showed acceptable geometric dimension, shape stability, rigidity, and were devoid of alien fungal contamination.



Note a Product from *Earliella scabrosa* (Ea1). b Product from *Earliella scabrosa* (Ea2). c Product from *Hexagonia tenuis* (He1). d Product from *Pleurotus ostreatus*. e Product from *Trametes polyzona*. f Product from *Trametes sanguinea*. Scale bars = 2 cm.

Figure 3.49 Cuboid blocks (representative) of prototypic wall

3.3.16 Discussions

Proper identification of the fungal specimens, based on a combined approach of morphology and phylogeny (ITS), provided the scientific basis for significance in applications. Analysis of the Ashby chart reveals that the mechanical properties (compressive strength vs density and flexural strength vs density) of MMBs of selected fungal species reside in the natural materials region, thereby implying that the MMB material exhibits mechanical properties appropriate for use as a foam substitute. The observed differences in the compressive strength among the selected fungal species might be due to variations in the mycelial network and density. The highest and the lowest

impact strength in *Ganoderma tropicum* and *Pleurotus ostreatus* might be attributed to their trimitic and monomitic hyphal system, respectively.

The WCA values demonstrated the hydrophobic behaviour of pure mycelium mats. These WCA values align with the results of previous studies (Haneef et al., 2017; Khyaju et al., 2025). This behaviour indicates the potential application of mushroom mycelium in several sectors, including packaging and medical scaffolds (Antinori et al., 2021; Sun et al., 2020). The proteins such as mannoproteins and hydrophobins, present on the outermost layer of the fungal cell wall, might be responsible for the hydrophobic nature of MMBs (Alexandre et al., 2000; Feofilova, 2010).

Regarding, the chemical analyses, the results are in accordance with prior studies (Attias et al., 2019; Aiduang et al., 2022b; Alemu et al., 2022a). The decrease in pH values was the result of enzymatic digestion of growing substrates by fungal mycelium (Attias et al., 2017; Aiduang et al., 2022b).

SEM analysis revealed the presence of dense and interwoven hyphal networks providing shape stability and strengthening to MMB. The multi-dimensional mycelium network acted as a natural adhesive or binding agent, providing enhanced mechanical strength to the final materials. The thicker surface mycelium layer aids in the hydrophobicity behaviour of the material. The voids among the hyphae and substrates reflect the porosity, thereby affecting the hydrodynamic behaviour and density of the materials. The voids and spongy mycelial network aid in absorbing external pressure shock, thereby featuring suitability for packaging purposes. The surface roughness of sawdust substrate provided increased surface area and microcracks or voids, which ultimately eased hyphae to penetrate, ferment, and absorb nutrients.

In thermal analysis, the lower temperature value is attributed to the removal of free and chemically linked water (Joseph et al., 2003; Bruscato et al., 2019; Gomez et al., 2021). The second stage relates to the thermal degradation of lignocellulosic components (i.e. cellulose, hemicellulose and lignin) occurring between 220 and 410°C (Kim et al., 2006; De Rosa et al., 2010; Borsoi et al., 2013; Bruscato et al., 2019).

FTIR spectroscopy revealed chemically bonded key functional groups: hydroxyl, lipid, protein, and polysaccharides, with mostly similar signals for all fungal species. Samples from *Microporus xanthopus* (Mi) showed stronger signals in some of the abovementioned functional groups.

The soil burial degradability test has provided strong evidence that mycelium-based biomaterials (MMBs) are completely biodegradable within a short period. Microbial enzymes might have helped decompose and disintegrate MMB over time, thereby leaving no end product waste in the environment. Heavy decomposition of the samples from *Pleurotus ostreatus* might be attributed to a monomitic hyphal system, while *Ganoderma tropicum* could take somewhat longer to decompose due to having a trimitic hyphal system.

MMB production faces the culture degeneration issue due to repeated subculturing. The cultivation technique provides mature basidiomata for re-isolation for further continuation of MMB production.

Successfully developed prototypic insulation wall, using the above-mentioned fungal species and rubber sawdust, provides insights for commercial production. This practical output is also attributed with multidisciplinary characteristics as described above.

CHAPTER 4

GLOBAL CHECKLIST OF MUSHROOMS (BASIDIOMYCOTA) USED IN MYCELIUM-BASED BIOMATERIALS AND THE CHALLENGES AND OPPORTUNITIES

4.1 Introduction

Mushrooms or macrofungi are the fruiting bodies of fungi that grow above ground or on a substrate. These mushrooms primarily belong to the phylum Basidiomycota, which includes gilled fungi, puffballs, bracket fungi, coral fungi, jelly fungi, and crust fungi (Rathore et al., 2019). Mushrooms have been widely used in food, medicine, and the extraction of secondary compounds (Rathore et al., 2019). They are an important source of bioactive and medicinal compounds, such as terpenes, polysaccharides, proteins, and vitamins, and are known for their antioxidant, antimicrobial, anticancer, antitumor, and immunomodulatory properties.

Mycelium, the vegetative structure of filamentous fungi, acts as a unit-binding agent, connecting hyphae and substrates (Jiang et al., 2016; Abhijith et al., 2018). It grows on lignocellulosic substrates, forming two- or three-dimensional networks (Crowther et al., 2014). Among several applications of mushrooms, mushroom mycelium-based biomaterials (MMBs) are a novel class of sustainable, eco-friendly, and biodegradable materials. As a result, research and development on MMBs is growing worldwide, with major efforts in Asia, Europe, and North America (Figure 4.1).

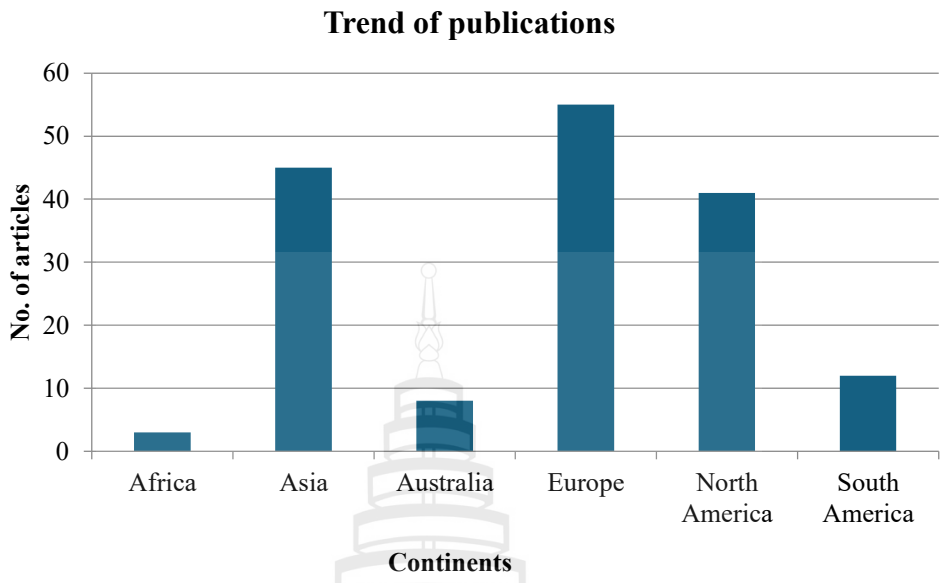


Figure 4.1 Mushroom mycelium-based biomaterials-related articles published up to 2024 from different continents

One of the key factors in selecting mushroom species for MMBs development is their hyphal properties (Porter et al., 2023). Mushrooms are categorised into monomitic, dimitic, or trimitic hyphal systems based on the presence and composition of generative, skeletal, and ligative (binding hyphae), and differ in cell wall thickness, internal structure, and branching patterns (Jones et al., 2020). For enhanced mechanical strength, mushrooms with dimitic or trimitic hyphal systems are preferred over monomitic systems (Porter et al., 2023).

The MMBs have several applications, including packaging, construction, thermal and acoustic insulation, architectural designs, and textiles (Joshi et al., 2020; Khyaju & Luangharn, 2024). These sustainable innovations have attracted people and companies and hold the potential to be incorporated into human daily life (Elsacker et al., 2020). The use of mushroom mycelium has expanded from an experimental laboratory to large-scale commercial applications, including companies such as Ecovative Design, Mycoworks, and Mogu, which are producing MMBs (Attias et al., 2019; Dessi-Olive, 2022a).

Basidiomycota constitutes four subphyla, 20 classes, 77 orders, 297 families, 2,134 genera, and approximately 41,270 recognised species (He et al., 2019, 2024; Hyde et al., 2024b). However, only a countable number of mushroom species, such as *Ganoderma*, *Lentinus*, *Pleurotus*, and *Trametes*, have been studied for MMB production, leaving many species unexplored (Figure 4.2). Research on mushroom species to develop MMBs with superior material properties is increasing worldwide. Recently, genetically modified mushroom species (GMOs) have broadened the technological capabilities in biomaterial development (Madusanka et al., 2024). The genome editing technique CRISPR/Cas9 has been applied to several mushroom species, including *Agaricus bisporus*, *Ganoderma lucidum*, *Lentinula edodes*, and *Schizophyllum commune* (Jan Vonk et al., 2019; Song et al., 2019; Liu et al., 2020; Choi et al., 2023a; Kamiya et al., 2023). Genetic modification by the incorporation of a *Saccharomyces cerevisiae* CDA1 chitin deacetylase-encoding gene controlled by glyceraldehyde-3-phosphate dehydrogenase promoter in a *Ganoderma* sp. showed higher β-glucan content (Madusanka et al., 2024). In *Schizophyllum commune*, deletion of the hydrophobin gene sc3 increased the density of pure mycelium, resulting in enhanced mechanical properties compared to its wild-type strain (Appels et al., 2018). However, the knowledge required to utilise the remaining taxa for MMBs remains underexplored.

Note a *Ganoderma williamsianum*. b *Lentinus squarrosulus*. c *Pleurotus ostreatus*. d *Trametes hirsuta*.

Figure 4.2 Mushroom genera (representative) commonly used in mushroom mycelium-based biomaterial development

The fragmented information on the research and findings on mushroom species used in MMBs needs to be compiled. The polyphasic approach to identifying mushroom species, combining morphology and phylogeny, is crucial before application in MMBs. The undisclosed name of the mushroom species used in MMBs cannot be overlooked and needs to be categorised for consistency and reliability. In addition, pointing out the key limitations and a way out for MMBs research was lacking. These identified knowledge gaps can provide a basis for comprehensive research. In this study, information on mushroom species utilised in MMBs from all available published works up to 2024 has been documented, providing a centralised reference for the field. The details on the hyphal system type, substrates used, and the end products have provided insights into the current scenario and future scope. Besides the critical investigation of the reported limitations or

challenges in this sector, this study has provided rational ways to strengthen the research, its development, and commercial production.

4.2 Materials and Methods

The data were collected, tabulated, and analysed based on findings from online platforms including Google Scholar (https://scholar.google.com/), PubMed (https://pubmed.ncbi.nlm.nih.gov/), Science Direct (https://www.sciencedirect.com/), Elsevier (https://www.elsevier.com/), Semantic Scholar (https://www.semantic scholar.org/) using keywords such as mycelium-based biomaterial, mycelium-based composite, mycelium-based leather, and pure mycelium materials. Microsoft Office Professional Plus 2010 was used to analyse the results and to generate bar diagrams and pie charts.

4.3 Results and Discussion

4.3.1 Mushroom Species in Mycelium-Based Biomaterials

Mushroom mycelium expands through the growth of hyphal apical tips, eventually forming dense mycelial colonies (Islam et al., 2018). These colonies are composed of hyphae, which are fibrous, thread-like structures made of natural polymers such as chitin, beta-glucans, and proteins that provide structural integrity, durability, and functionality (Ruiz-Herrera, 1991; Islam et al., 2017). The outer surface of hyphae is rich in beta-glucans, which act as mucilage, along with chitin microfibrils that provide mechanical rigidity and strength (Ruiz-Herrera, 1991). Mycelium colonies interconnect randomly through anastomosis, creating a network of hyphae. Saprobic mushrooms use their mycelium networks to degrade lignocellulosic residues into simpler forms of nutrients and bind the substrates together through complex biochemical processes. The mycelium penetrates the

substrates via physical pressure and enzymatic secretion, allowing it to access essential nutrients (Rathore et al., 2019).

The development of MMBs has been explored using a limited number of mushroom species, primarily from the orders *Polyporales* (67 species) and *Agaricales* (20 species), and a few from the orders *Hymenochaetales* (6 species), *Auriculariales* (2 species), *Russulales* (2 species), and *Gleophyllales* (1 species) (Figure 4.3, Table 4.1, 4.3). The differences between the fungal species described and those used in MMBs underscore the need for a more systematic study to explore their immense potential. All the described fungal species might not be suitable for superior-quality MMB development. To provide a systematic direction for MMBs research, selection criteria for fungal species are crucial. Research on MMBs includes preliminary characterisation studies and applications in packaging, construction, architectural design, and textiles. Based on extensive studies, some scholars have proposed a set of key criteria for selecting fungal species suitable for MMBs production (Sydor et al., 2022; Aiduang et al., 2024). The criteria for selecting suitable fungal candidates can be summarised as follows: vigorous hyphal growth, trimitic or dimitic hyphal systems, classification as white-rot fungi, adaptability to a wide range of substrates and growth conditions, non-sporulating behaviour, saprobic lifestyle, antimicrobial properties, and being non-toxic and non-allergenic.

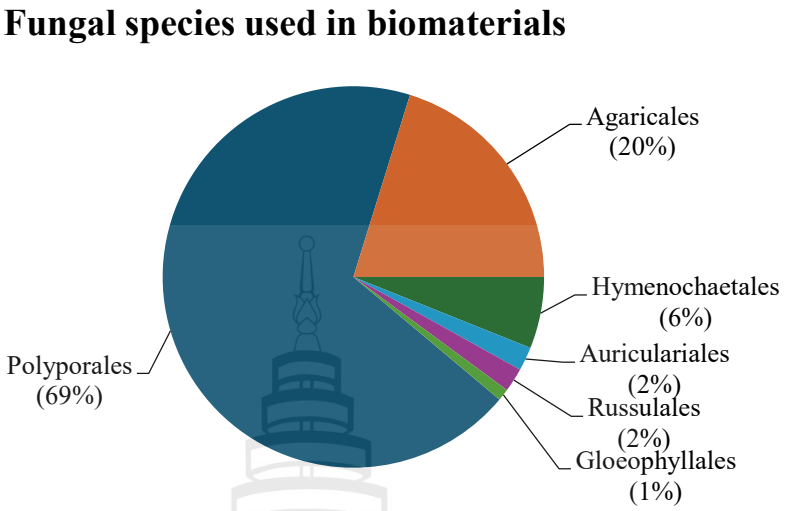


Figure 4.3 Fungal species belonging to different orders commonly used in the mycelium-based biomaterials applications

Table 4.1 Classification of fungal species used in experimental studies for mycelium-based biomaterials

Order	Family	Genus	Species
Agaricales	Agaricaceae	*Agaricus*	*A. bisporus, A. bitorquis*
	Lyophyllaceae	*Hypsizygus*	*H. ulmarius*
	Omphalotaceae	*Lentinula*	*L. edodes*
	Physalacriaceae	*Flammulina*	*F. velutipes*
		Oudemansiella	*O. radicata*
	Pleurotaceae	*Pleurotus*	*P. albidus, P. citrinopileatus, P. cornucopiae, P. djamor, P. eryngii, P. ostreatus, P. pulmonarius, P. salmoneostramineus*
	Pluteaceae	*Volvariella*	*V. volvacea*
	Psathyrellaceae	*Coprinopsis*	*C. cinerea*
	Schizophyllaceae	*Schizophyllum*	*S. commune*
	Strophariaceae	*Kuehneromyces*	*K. mutabilis*
		Stropharia	*S. rugosoannulata*
	Tubariaceae	*Cyclocybe*	*C. aegerita*
Auriculariales	Auriculariaceae	*Auricularia*	*A. auricula-judae, A. polytricha*
Gloeophyllales	Gloeophyllaceae	*Gloeophyllum*	*G. sepiarium*

Table 4.1 (continued)

Order	Family	Genus	Species
Hymenochaetales	Hymenochaetaceae	*Fomitiporia*	*F. mediterranea*
		Inonotus	*I. obliquus*
		Nothophellinus	*N. andinopatagonicus*
		Phellinus	*P. igniarius*
	Incertae sedis	*Trichaptum*	*T. abietinum*
	Oxyporaceae	*Oxysporus*	*O. latermarginatus*
Polyporales	Cerrenaceae	*Cerrena*	*C. zonata*
	Dacryobolaceae	*Postia*	*P. balsamea*
	Fomitopsidaceae	*Fomitopsis*	*F. iberica, F. pinicola, F.rossea*
		Piptoporus	*P. betulinus*
		Wolfiporia	*W. extensa*
	Grifolaceae	*Grifola*	*G. frondosa*
	Incertae sedis	*Aegerita*	*A. agrocibe*
		Ryvardenia	*R. cretacea*

Table 4.1 (continued)

Order	Family	Genus	Species
	Irpicaceae	*Ceriporia*	*C. lacerata*
		Irpex	*I. lacteus*
	Laetiporaceae	*Laetiporus*	*L. sulpureus*
		Phaeolus	*P. schweinitzii*
	Meruliaceae	*Aurantiporus*	*Aurantiporus* sp.
		Irpiciporus	*I. pachyodon*
	Panaceae	*Panus*	*P. conchatus*
	Phanerochaetaceae	*Bjerkandera*	*B. adusta*
		Phanerochaete	*P. chrysosporium*
		Terana	*T. caerulea*
	Podoscyphaceae	*Abortiporus*	*A. biennis*
	Polyporaceae	*Cerioporus*	*C. lacerata*
		Coriolopsis	*C. gallica, C. rigida, C. trogii*
		Daedaleopsis	*D. confragrosa, D. tricolor*
		Earliella	*E. scabrosa*

Table 4.1 (continued)

Order	Family	Genus	Species
		Fomes	*F. formentarius*
		Fomitella	*F. fraxinea*
		Funalia	*F. trogii*
		Ganoderma	*G. applantum, G. australe, G. carnosum, G. curtisii, G. fornicatum, G. lingzhi, G. lucidum, G. mexicanum, G. resinaceum, G. sessile, G. steyaertanum, G. williamsianum*
		Hexagonia	*Hexagonia* sp.
		Lentinus	*L. arcularius, L. crinitus, L. polychrous, L. sajor-caju, L. squarrosulus, L. velutinus*
		Lenzites	*L. betulinus*
		Megasporoporia	*M. minor*
		Microporus	*M. affinis*
		Neofavolus	*N. alveolaris*
		Polyporus	*P. arcularius, P. brumalis, P. squamosus*

Table 4.1 (continued)

Order	Family	Genus	Species
		Trametes	*T. coccinea, T. gibbosa, T. hirsuta, T. multicolor, T. ochracea, T. orientalis, T. pubescens, T. suaveolens, T. versicolor, T. villosa*
Russulales	Hericiaceae	*Hericium*	*H. erinaceus*
	Stereaceae	*Stereum*	*S. hirsutum*

Note The taxon name is provided in the same format as the published papers.

4.3.2 Mushroom Hyphal Systems

Hyphae serve as the fundamental structural units that collectively form mycelium and basidiomata. Mycelium functions as a natural adhesive, binding substrates together and contributing to the structural integrity of mycelium-based biomaterials (MMBs). Mushrooms are classified into three hyphal systems based on their composition: monomitic, dimitic, and trimitic (Figure 4.4) (Shin et al., 2025). Monomitic hyphal system consists only of generative hyphae, whereas dimitic hyphal system incorporates generative hyphae with either skeletal or ligative hyphae. In contrast, the trimitic hyphal system contains all three hyphal types, which enhance structural properties. The hyphal system type of mushrooms affects the mechanical and material properties of MMBs (Porter & Naleway, 2022). Therefore, selecting suitable mushroom species is a critical factor for producing high-quality biomaterials (Aiduang et al., 2024). The classification of mushroom species used in biomaterial applications is based on their hyphal system (Table 4.2).

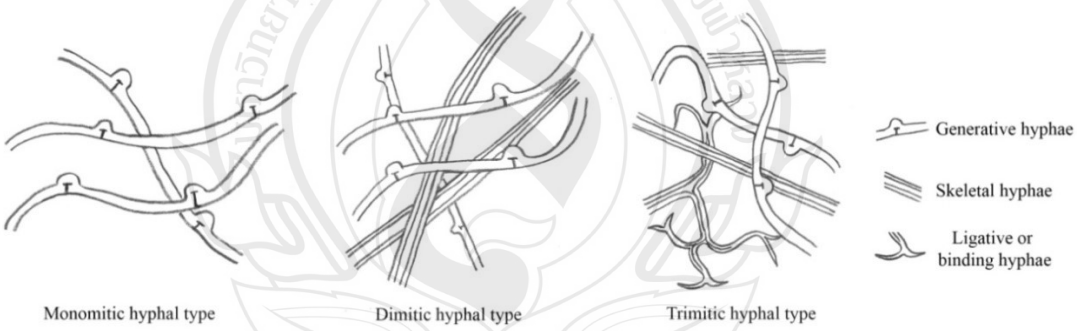


Figure 4.4 A schematic representation of hyphal system types

Table 4.2 Classification of mushroom species based on hyphal system for the development of mycelium-based biomaterials

Mushroom Hyphal Systems		
Monomitic	**Dimitic**	**Trimitic**
Agaricus bisporus	*Cerioporus laceratus* (*Polyporus megasporoporus*)	*Coriolopsis gallica*
Agaricus bitorquis	*Cerrena zonata*	*C. rigida* (*Funalia rigida*)
Abortiporus biennis	*Fomitella fraxinea* (*Vanderbylia fraxinea*)	*C. trogii* (*Trametes trogii*)
Aurantiporus sp.	*Fomitiporia mediterranea*	*Daedaleopsis confragosa*
Auricularia auricula-judae	*Fomitopsis iberica* (*F. marianiae*)	*D. tricolor*
A. polytricha (*A. nigricans*)	*F. pinicola*	*Earliella scabrosa*
Bjerkandera adusta	*F. rosea* (*Rhodofomes roseus*)	*Fomes fomentarius*
Ceriporia lacerata (*Irpex laceratus*)	*Ganoderma mexicanum* (*Phellinus nilgheriensis*)	*Funalia trogii* (*Trametes trogii*)
Coprinopsis cinerea	*Grifola frondosa*	*Ganoderma applanatum*
Cyclocybe aegerita	*Irpex lacteus*	*G. australe*
Flammulina velutipes	*Irpiciporus pachyodon*	*G. carnosum*
Hericium erinaceus	*Laetiporus sulphureus*	*G. curtisii*

Table 4.2 (continued)

Mushroom Hyphal Systems		
Monomitic	**Dimitic**	**Trimitic**
Hypsizygus ulmarius	*Lentinus arcularius*	*G. fornicatum*
Inonotus obliquus	*L. crinitus*	*G. lingzhi* (*G. sichuanense*)
Kuehneromyces mutabilis	*L. polychrous*	*G. lucidum*
Lentinula edodes	*L. sajor-caju*	*G. resinaceum*
Oudemansiella radicata	*L. squarrosulus*	*G. sessile* (*G. resinaceum*)
(*Hymenopellis colensoi*)		
Phanerochaete chrysosporium	*L. velutinus*	*G. steyaertanum*
Phaeolus schweinitzii	*Neofavolus alveolaris*	*G. williamsianum*
Pleurotus albidus	*Oxyporus latemarginatus*	*Hexagonia* sp.
	(*Irpex latemarginatus*)	
P. citrinopileatus	*Panus conchatus*	*Lenzites betulinus*
P. cornucopiae	*Phellinus igniarius*	*Microporus affinis*
P. djamor	*Piptoporus betulinus* (*Fomitopsis betulina*)	*Stropharia rugosoannulata*
P. eryngii	*Polyporus arcularius* (*Lentinus arcularius*)	*Trametes coccinea*

Table 4.2 (continued)

Mushroom Hyphal Systems		
Monomitic	**Dimitic**	**Trimitic**
P. ostreatus	*P. brumalis* (*L. brumalis*)	*T. gibbosa*
P. pulmonarius	*P. squamosus* (*Cerioporus squamosus*)	*T. hirsuta*
P. salmoneostramineus (*P. djamor*)		*T. multicolor* (*T. ochracea*)
Postia balsamea	Di-trimitic	*T. ochracea*
Ryvardenia cretacea	*Gloeophyllum sepiarium*	*T. orientalis*
Schizophyllum commune	*Megasporoporia minor*	*T. pubescens*
Terana caerulea	*Nothophellinus andinopatagonicus*	*T. suaveolens*
Volvariella volvacea	*Trichaptum abietinum*	*T. versicolor*
Wolfiporia extensa		*T. villosa*
	Psuedodimitic	
	Stereum hirsutum	

Note The taxon name in parentheses indicates the current name according to Index Fungorum (accessed on 29.03.2025).

Table 4.3 Fungal species (Basidiomycota), main substrates, and intended applications of mycelium-based biomaterials

Fungal Species	Main Substrates	Intended Application	Country	References
Abortiporus biennis, Bjerkandera adusta, Coriolopsis gallica, C. trogii, Daedaleopsis confragosa, D. tricolor, Fomes fomentarius, Fomitiporia mediterranea, Fomitopsis iberica, F. pinicola, Ganoderma carnosum, G. lucidum, Irpex lacteus, Irpiciporus pachyodon, Lenzites betulinus, Neofavolus alveolaris, Stereum hirsutum, Terana caerulea, Trametes hirsuta, T. suaveolens	MEA, Millet slurry	Leather	Italy	Cartabia et al. (2021)
Abortiporus biennis, Bjerkandera adusta, Daedaleopis tricolor, Fomes fomentarius, Irpex lacteus, Lentinus arcularius, Pleurotus ostreatus, Trametes versicolor	Wheat bran, minced wheat straws, coconut husk fibres, broadleaf sawdust	Packaging	Romania	Balaes et al. (2023)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
Agaricus bisporus, Flammulina velutipes, Ganoderma lucidum, Kuehneromyces mutabilis, Lentinula edodes, Pleurotus ostreatus, P. ostreatus sajorcaju, P. ostreatus florida	Oak husk, rapeseed cake	Biocomposites	Finland	Tacer-Caba et al. (2020)
Agaricus bisporus, A. bitorquis	Wheat straw	Building insulation materials	Chile	Velasco et al. (2014)
Agaricus bisporus, Fomes fomentarius, Ganoderma applanatum, Trametes versicolor	Bleached softwood kraft fibres, hemp fibres	Mycocel biopolymers	Latvia	Irbe et al. (2021)
Agaricus bisporus, Hericium erinaceus (spent mushroom)	Birch sawdust	Packaging materials	Austria	Zhao et al. (2024)
Agaricus bisporus, Trametes versicolor	Sugarcane molasses	Industrial applications (paper, coatings)	Australia	Jones et al. (2019a)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
Aurantiporus sp., *Ganoderma curtisii, G. mexicanum, Lentinus crinitus, Panus conchatus, Pleurotus ostreatus*	PDA	Mycelium films	Mexico	César et al. (2021a)
Auricularia auricula-judae, Lentinus polychrous, L. squarrosulus, Pleurotus ostreatus	Rice husks, coconut husks, rice straw	Biocomposites	Thailand	Ly and Jitjak (2022)
Auricularia auricula-judae, Pleurotus ostreatus, P. sajor-caju, Schizophyllum commune	Water hyacinth, rice bran	Biocomposites	Thailand	Sakunwongwiriya et al. (2024)
Auricularia polytricha, Ganoderma lucidum, Pleurotus ostreatus	Rubber tree sawdust, diaper core, food waste (coffee, banana skin, eggshell, sugarcane)	Bio-boards	China	Khoo et al. (2020)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
Auricularia polytricha, Ganoderma lucidum, Pleurotus ostreatus	PDB	Mycelium mats	China	Shao et al. (2024)
Bjerkandera adusta, Elfvingia applanata, Fomitella fraxinea, Fomitopsis pinicola, F. rosea, Ganoderma applanatum, G. lucidum, Microporus affinis, Postia balsamea, Trametes versicolor, T. suaveolens, Wolfiporia extensa	Oak sawdust, rice bran	Leather	South Korea	Raman et al. (2022)
Ceriporia lacerata	Soyabean straw	Insulation materials	China	Shao et al. (2016)
Cerrena sp., *Ganoderma* sp., *Pycnoporus* sp.	White wood sawdust, coffee waste, coffee grounds, wheat bran	Biocomposites	Brazil	de Oliveira et al. (2022)
Coprinospsis cinerea, Pleurotus djamor	PDA	Biocomposites	China	Chang et al. (2019)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
Coriolopsis rigida, Pycnoporus sanguineus, Trametes villosa	Sawdust of eucalyptus, pine	Biocomposites	Brazil	Catto et al. (2014)
Coriolus brevis, C. hirsuta, C. versicolor, Fomitella fraxinea, Ganoderma lucidum, Polyporus arcularius, P. squamosus, Pycnoporus coccineus, T. fuciformis, Trametes gibbosa, T. orientalis	Sawdust, PDB	Mycelium mats	South Korea	Bae et al. 2021
Coriolus versicolor, Pleurotus ostreatus	Wood chips, hemp hurd, loose hemp fibre, non-woven hemp mats	Biofoams	Netherlands	Lelivelt et al. (2015)
Coriolus versicolor, P. ostreatus	Hemp herds, woodchips	Insulation materials	Germany	Reibert et al. (2022)
Cyclocybe aegerita, Pleurotus ostreatus, P. pulmonarius, P. salmoneo-stramineus	Woodchips substrates of Eucalyptus, Oak, Pine, Apple, Vine	Design and architecture	Israel	Attias et al. (2017)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
Daedaleopsis confragosa, Ganoderma resinaceum, Trametes versicolor	Corn stover, kenaf pith, hemp pith	Biocomposites	USA	Bajwa et al. (2017)
Daedaleopsis tricolor, Fomes fomentarius, Stereum hirsutum, Trametes versicolor	Hemp shives	Biocomposites	Belgium	Verhelst et al. (2024)
Earliella sp., *Hexagonia sp., Lentinus sp., Pleurotus* sp., *Pycnoporus* sp.	Rubber sawdust, rice straw	Biocomposites	Thailand	Aiduang et al. (2022a)
Flammulina velutipes, Ganoderma applanatum, G. lucidum, Hericium erinaceus, Lentinula edodes, Pleurotus eryngii, Trametes hirsuta	Malt agar, cellulose microcrystals, cellulose microfibrils	Mycelium mats	Russia	Rakitina et al. (2022)
Flammulina velutipes, Lentinula edodes, Lentinus polychrous, Pleurotus ostreatus	Coconut husk, rice husk	Biocomposites	Thailand	Ly and Jitjak (2020)
Fomes fomentarius	Hemp shives, rapeseed straw	Biocomposites	Germany	Pohl et al. (2022)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
F. fomentarius	Hemp shives	Insulation materials	Germany	Schmidt et al. (2023)
F. fomentarius	Hemp shives, rapeseed straw, poplar wood chips	Construction materials	Germany	Stelzer et al. (2021)
Fomes fomentarius, Fomitopsis pinicola, Ganoderma lucidum, Irpex lacteus, Pleurotus ostreatus, Schizophyllum commune, Trametes versicolor	Cellulose from softwood kraft pulp	Cellulose fibre foams	USA	Amstislavski et al. (2024)
Fomes fomentarius, Fomitopsis pinicola, Pleurotus eryngii, Trametes versicolor	MEB, woven fabric	Mycelium mats	Germany	Kniep et al. (2024)
Fomes fomentarius, Ganoderma lucidum, Pycnoporus sanguineus, Trametes hirsuta	Beech sawdust, spruce sawdust	Construction materials	Germany	Saez et al. (2021)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
Fomes fomentarius, Pleurotus ostreatus	Wood chips of beech, European oak, pear	Construction materials	Germany	Moser et al. (2017)
Fomitopsis pinicola, Ganoderma carnosum, Pleurotus eryngii, P. ostreatus, Trametes versicolor	Wheat straw, pine sawdust, oak shavings, tree of heaven wood chips, shredded beech wood	Insulation	Italy	Charpentier-Alfaro et al. (2023)
Fomitopsis pinicola, Gloeophyllum sepiarium, Laetiporus sulphureus, Phaeolus schweinitzii, Piptoporus betulinus, Pleurotus ostreatus, Polyporus arcularius, Trametes pubescens, T. suaveolens, Trichaptum abietinum	Sawdust and shavings of Birch, Aspen, Spruce, Pine, Fir	Insulation materials	Canada	Wimmers et al. (2019)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
Funalia trogii, Ganoderma australe, Nothophellinus andinopatagonicus, Pleurotus ostreatus, Ryvardenia cretacea	Poplar sawdust	Biocomposites	Argentina	Aquino et al. (2022)
Ganoderma australe, Pleurotus ostreatus, Trametes versicolor	Molasses	Mycelium mats	Australia	Chulikavit et al. (2022)
Ganoderma curtisii	Guayule bagasse	Insulation	Mexico	César et al. (2023)
Ganoderma fornicatum, G. williamsianum, Lentinus sajor-caju, Schizophyllum commune	Rubber tree sawdust, corn husk, rice straw	Biocomposites	Thailand	Aiduang et al. (2022c)
Ganoderma fornicatum, G. williamsianum, Lentinus sajor-caju, Schizophyllum commune, Trametes coccinea	Bamboo sawdust, corn pericarp	Interior designs	Thailand	Aiduang et al. (2024)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
Ganoderma lucidum	Palm sugar fibre, cassava bagasse	Composite board	Indonesia	Agustina et al. (2019)
G. lucidum	Potato Dextrose Broth	Mycelium mats	Italy	Antinori et al. (2020)
G. lucidum	Sawdust	Pure mycelium mats	Indonesia	Bahua et al. (2024)
G. lucidum	Sawdust (*Albizia chinensis*), empty fruit bunch fibres	Biocomposites	Singapore	Chan et al. (2021)
G. lucidum	Beech wood shavings, spelt flour, plaster dust	Electronic parts	Austria	Danninger et al. (2022)
G. lucidum	Cellulose fibre, rapeseed bagasse	Insulation materials	Netherlands	Gauvin et al. (2021)
G. lucidum	Wood chips, sawdust, sugarcane, and cassava fibrous waste products	Architecture design	Germany	Heisel et al. (2017)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
G. lucidum	Cotton stalk	Biocomposites	China	Liu et al. (2019)
G. lucidum	MEB	Mycelium mats	France	Mazian et al. (2023)
G. lucidum	Hemp fibres, hemp hurds, pine wood sawdust, Silvergrass shavings	Building materials	Germany	Özdemir et al. (2022)
G. lucidum	Wheat straw, polypropylene with bacterial spores	Thermal Insulation	Romania	Răut et al. (2021)
G. lucidum	Bamboo fiber	Biocomposites	Indonesia	Ridzqo et al. (2020)
G. lucidum	Bamboo fibre, chitosan	Biocomposites	Singapore	Soh et al. (2020)
G. lucidum	Sawdust	Biocomposites	USA	Travaglini (2019)
G. lucidum	Rapeseed straw, cellulose fibre	Insulation materials	Netherlands	Tsao (2020)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
G. lucidum	Sawdust	Biocomposites	China	Wang et al. (2024)
Ganoderma lucidum, Hypsizygus ulmarius, Pleurotus citrinopileatus, P. cornucopiae, P. djmor, P. eryngii. P. ostreatus, P. pulmonarius, Polyporus brumalis, Stropharia rugosoannulata, Trametes versicolor	MEA, MEB	Biocomposites	Australia	Jones et al. (2018c)
Ganoderma lucidum, Pleurotus citrinopileatus, P. eryngii, P. ostreatus	Jute, cotton	Footwear products	USA	Silverman et al. (2020)
G. lucidum, P. djamor	Paste mixture of whole wheat flour, malt extract, xanthan gum, tartar, citric acid	Mycelium mats	USA	Crawford et al. (2024)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
G. lucidum, P. ostreatus	Cellulose, PDB	Biofilms	Italy	Haneef et al. (2017)
G. lucidum, P. ostreatus	Beech sawdust, oak sawdust, bleached cellulose pulp, shredded cardboard, shredded newspaper, cotton fibres, soy silk fibres, wheat bran, wheat straw, burlap, clay, sand	Biocomposites	Austria	Vašatko et al. (2022)
G. lucidum, P. ostreatus	Potato Dextrose Broth (PDB)	Bio-scaffolds	Italy	Antinori et al. (2021)
Ganoderma lucidum, Pleurotus ostreatus, Polyporus squamosus	Canola straw, Cattail, hemp	Packaging materials	Canada	Rahman (2024)
Ganoderma lucidum, Trametes versicolor	Spent coffee grounds, coffee chaff, hay straw, hemp dust	Biocomposites	Romania	Barta et al. (2024)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
G. lucidum, T. versicolor	Beech sawdust, spent mushroom substrate	Insulation materials	Germany	Schritt et al. (2021)
Ganoderma resinaceum	Waste rose flower, lavender straw	Biocomposites	Bulgaria	Angelova et al. (2021)
G. resinaceum	Miscanthus	Insulation materials	Luxembourg	Dias et al. (2021)
G. resinaceum, Megasporoporia minor, Oxyporus latermarginatus	Wheat straw	Building insulation materials	UK	Xing et al. (2018)
G. resinaceum, T. versicolor	Hemp hurds, beechwood sawdust	Construction	Belgium	Elsacker et al. (2021)
G. resinaceum, T. versicolor	Beech wood sawdust, hemp fibres	Biocomposites	Belgium	Van Wylick et al. (2022)
G. sessile, T. ochracea, T. versicolor	Wood chips of Apple, Vines	Design and architecture	Israel	Attias et al. (2019)
Ganoderma sp.	Cotton byproducts	Packaging materials	USA	Holt et al. (2012)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
Ganoderma sp.	Corn stover	Insulation materials	USA	Pelletier et al. (2019)
Ganoderma steyaertanum	Cardboard, coffee grounds	Biocomposites	Australia	Gough et al. (2024)
Irpex lacteus	Sawdust pulp of Alaska birch	Thermal Insulation material	USA	Yang et al. (2017a)
Lentinula edodes	Coconut powder, wheat bran	Packaging	Brazil	Matos et al. (2019)
L. edodes (spent mushroom)	Sawdust (birch)	Biocomposites	Sweden	Berglund et al. (2024)
L. edodes, Pleurotus eryngii	Bagasse fibre	Fire retardancy	Iran	Hemmati and Garmabi (2012)
L. edodes, P. ostreatus	Sengon wood sawdust, bagasse	Biocomposites	Indonesia	Christos et al. (2024)
Lentinus crinitus	Barley straw	Biocomposites	Mexico	César et al. (2021b)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
L. sajor-caju	Rubber tree sawdust, corn husk	Biocomposites	Thailand	Jinanukul et al. (2024)
L. sajor-caju	Corn husk, rubber sawdust, paper waste	Biocomposites	Thailand	Teeraphantuvat et al. (2024)
L. velutinus, P. albidus, Pycnoporus sanguineus	Pinus sawdust	Packaging biofoams	Brazil	Bruscato et al. (2019)
N/A	Rice husk, wheat grain	Biocomposites	Malaysia	Arifin and Yusuf (2013)
N/A	Soil	Architecture design	Germany	Colmo and Ayres (2020)
N/A	Hemp fibres	Designs	USA	Dessi-Olive (2022b)
N/A	Hemp fibres	Sound absorption	USA	Hsu and Dessi-Olive (2021)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
N/A	Rubber tree sawdust	Construction materials	India	Finu et al. (2023)
N/A	Clay, sugarcane colasses, rice bran, sawdust, coconut husks	Construction materials	Philippines	Maximino et al. (2020)
N/A	Not mentioned	Building materials and designs	Denmark	Özlü and Nicholas (2021)
N/A	Switch grass, rice straw, sorghum stalks, flax shive, kenaf, hemp	Acoustic absorption panels	USA	Pelletier et al. (2013)
N/A	Cotton burs, switch-grass, rice straw, sorghum stalks, corn stalks, kenaf	Insulation materials	USA	Pelletier et al. (2017)
N/A	Cotton hulls	Building materials	India	Santhosh et al. (2018)
N/A	Low-quality cotton, hemp shives	Biocomposites	Italy	Sisti et al. (2021)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
N/A	Corn stover	Biocomposites	USA	Tudryn et al. (2018)
N/A	N/A	Electronic parts	USA	Vasquez and Vega (2019b)
N/A	N/A	Wearables	USA	Vasquez and Vega (2019a)
N/A	N/A	Biocomposites	USA	Islam et al. (2017)
N/A	N/A	Biocomposites	USA	Islam et al. (2018)
N/A	Jute, hemp, cellulose	Biocomposites	USA	Jiang et al. (2017)
N/A	Wood particles of spruce, pine, fir, cellulose nanofibrils	Packaging and furniture applications	USA	Sun et al. (2019)
N/A	N/A	Pure mycelium mats	USA	Sun et al. (2021)
N/A	Cotton fibre, hemp pith	Biocomposites	USA	Ziegler et al. (2016)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
Oudemansiella radicata, P. ostreatus	Cotton stalk, wheat bran	Biocomposites	China	Gou et al. (2021)
Phanerochaete chrysosporium	Malt extract	Biomedical use	India	Khamrai et al. (2018)
P. chrysosporium	PDA, concrete	Construction materials	USA	Menon et al. (2019)
Phellinus igniarius	Corn cob, wheat bran	Biocomposites	China	Wang et al. (2019)
P. djamor	Northern bleached softwood kraft fibres	Filtration, packaging, bioremediation	Canada	Ahmadi et al. (2022)
P. eryngii	Hardwood sawdust	Packaging	Canada	Kao et al. (2022)
P. eryngii	Sawdust	Shoe products	USA	Wolfe and Cao (2024)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
P. eryngii, P. ostreatus, Pycnoporus sanguineus	Coconut powder, wheat bran	Packaging materials	Brazil	Teixeira et al. (2018)
Pleurotus florida	Spent mushroom, clay	Insulation materials	Egypt	Ali et al. (2023)
P. ostreatus	European beech sawdust	Biocomposites	Austria	Alaux et al. (2023)
P. ostreatus	Coffee husk, sawdust, sugarcane bagasse	Construction materials	Ethiopia	Alemu et al. (2022b)
P. ostreatus	Hemp hurds	Biocomposites	USA	Etinosa et al. (2024)
P. ostreatus	Bamboo fibers	Indoor applications	Singapore	Gan et al. (2022)
P. ostreatus	Oakwood pellets, wheat straw	Building materials	USA	Ghazvinian and Gürsoy (2022)
P. ostreatus	Straw, sawdust	Architecture design	USA	Ghazvinian et al. (2019)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
P. ostreatus	Sawdust, straw, hemp	Design, architecture	USA	Ghazvinian et al. (2022)
P. ostreatus	Glass wool, hemp wool	Biocomposites	Canada	Grenon et al. (2023)
P. ostreatus	Cotton seed hulls, carboxylated styrene butadiene rubber latex	Biocomposites	China	He et al. (2014)
P. ostreatus	Bagasse, sawdust, and wheat bran	Packaging, insulation, furniture	India	Joshi et al. (2020)
P. ostreatus	Spent coffee grounds, pineapple fibres	Biocomposites	Thailand	Kohphaisansombat et al. (2023)
P. ostreatus	Hemp stalks, rice straw, lacquer tree wood chips, oak wood chips	Air filtration panels	South Korea	Lee and Choi (2021)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
P. ostreatus	Crop residue *(Triticum* sp.), edible films (carrageenan, chitosan, xanthan gum)	Packaging	Mexico	López Nava et al. (2016)
P. ostreatus	Rice husks, sawdust	Biocomposites	Uganda	Mbabali et al. (2023)
P. ostreatus	Waste cardboard	Biocomposites	USA	Mohseni et al. (2023)
P. ostreatus	Sugarcane bagasse, sawdust, rice husk	Biofoams	Malaysia	Nashiruddin et al. (2022)
P. ostreatus	Wood chips, hemp fibres	Designs	Germany	Nguyen et al. (2022)
P. ostreatus	Rice straw, bagasse, coir-pith, sawdust, corn straw	Packaging materials	China	Peng et al. (2023)
P. ostreatus	Hemp fibre, peanut shell	Biocomposites	Argentina	Picco et al. (2024)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
P. ostreatus	Rice husk, wheat straw, rice husk powder, wood shaving, walnut shell	Biocomposites	Turkey	Sağlam and Özgünler (2022)
P. ostreatus	Vegetable peel, denim textile waste, coffee ground, synthetic textile waste	Biocomposites	Spain	Sangosanya and Pistofidou (2024)
P. ostreatus	Merino wool, paper cellulose, barley straw	Architecture design	UK	Scott et al. (2020)
P. ostreatus	Rubber wood sawdust	Biocomposites	Malaysia	Shakir et al. (2020)
P. ostreatus	Rubber wood sawdust	Biocomposites	Malaysia	Shakir et al. (2025)
P. ostreatus	Coir pith, sawdust	Packaging materials	India	Sivaprasad et al. (2021)
P. ostreatus	Cardboard, paper, newsprint	Sound absorption	USA	Walter and Gursoy (2022)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
P. ostreatus	Spent mushroom substrate (cotton seed hulls, corncobs, crayfish shells, wheatbrans	Particle boards	China	Lu et al. (2024)
P. ostreatus	Rye berries	Insulation materials	USA	Zhang et al. (2022a)
P. ostreatus (spent mushroom)	Wheat straw	Thermal insulation	Chile	Aravena et al. (2024)
P. ostreatus, Polyporus squamosus, Volvariella volvacea	Hemp fibre, wood chips	Biocomposites	USA	Etinosa (2019)
Pleurotus ostreatus, Schizophylllum commune, Trametes multicolor	Fern (*Azolla filiculoides*)	Biocomposites	Netherlands	Läkk et al. (2018)
P. ostreatus, T. hirsuta	Pine and spruce shavings	Biocomposites	Finland	Kuribayashi et al. (2022)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
P. ostreatus, T. ochracea	Beech sawdust, rapeseed straw, non-woven cotton fibre	Non-foam panels	Netherlands	Appels et al. (2019)
P. pulmonarius	Sugarcane bagasse, textile scraps	Sound absorption	Colombia	Garcia et al. (2023)
Polyporus brumalis, T. versicolor	Wheat straw, rice hulls, sugarcane bagasse, molasses	Nanofibers	Australia	Jones et al. (2019b)
Pycnoporus sanguineus	Coconut powder, wheat bran	Building materials	Brazil	Santos et al. (2021)
Schizophyllum commune	Minimal medium	Mycelium films	Netherlands	Appels et al. 2020
S. commune	Minimal medium	Pure mycelium mats	Netherlands	d'Errico et al. (2024)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
S. commune (GMO)	Agar minimal medium	Mycelium mats	Netherlands	Appels et al. (2018)
T. betulina	Rapeseed straw, recycled cellulose	Building materials	Netherlands	Livne et al. (2022)
T. pubescens, T. versicolor	Beechwood sawdust	Biocomposites	Germany	Nussbaumer et al. (2023)
T. versicolor	Flax, flax dust, flax long-treated fibres, flax long-un-treated fibres, flax waste, wheat straw dust, wheat straw, hemp fibres, pine softwood shavings	Thermal Insulation	Belgium	Elsacker et al. (2019)
T. versicolor	Hemp shives, sawdust (birch)	Insulation materials	Latvia	Irbe et al. (2024)
T. versicolor	Rice hulls	Fire-resistant panels	Australia	Jones et al. (2017)

Table 4.3 (continued)

Fungal Species	Main Substrates	Intended Application	Country	References
T. versicolor	Rice hulls, glass fines	Construction materials	Australia	Jones et al. (2018a)
T. versicolor	Wheat grains	Insulation materials	Australia	Jones et al. (2018b)
T. versicolor	Pulp and paper mill sludge	Insulation materials	Chile	Muñoz et al. (2024)
T. versicolor	Yellow birch wood veneers	Biocomposites	USA	Sun et al. (2022)
T. versicolor	Spruce wood particles	Biocomposites	Slovakia	Vidholdová et al. (2019)
T. versicolor	Hardwood chips, hemp shavings	Construction materials	Latvia	Zimele et al. (2020)

Note N/A = not available. The taxon name is provided in the same way as in the published paper.

4.3.3 Mushroom-Based Biomaterials

Mushroom-based biomaterials (MBs) are derived from mushroom fruiting bodies rather than culture mycelium (Bustillos et al., 2020). These materials are also biodegradable, lightweight, and renewable, requiring minimal energy for their production and leaving a smaller carbon footprint than synthetic plastics (Abhijith et al., 2018; Müller et al., 2021; Pylkkänen et al., 2023). MBs possess the structural properties of fungal tissues while exhibiting material characteristics comparable to mycelium-based biomaterials. They are composed of chitin, glucans, and protein that contribute to their mechanical strength, hydrophobicity, and thermal stability (Bustillos et al., 2020). Additionally, the intrinsic antifungal and antibacterial properties of mushrooms are exhibited in the MBs products, providing resistance to degradation caused by alien fungi and bacteria (Bustillos et al., 2020). These qualities make MBs a sustainable and efficient material and a promising candidate in biomaterial development and other fields.

In mushroom-based biomaterials (MBs) production, the mushroom fruiting bodies are initially harvested, then dried and processed into various desired forms, such as powders or composite materials (Porter & Naleway, 2022; Pylkkänen et al., 2023). These materials are then combined with biopolymers or natural fibres to create high-performance products. Alternatively, mushrooms can be cultivated directly in the mould until full growth, which is then harvested, dried, and treated. These MBs have also demonstrated significant potential in constructions, textiles, and medical fields (Hamlyn et al., 1994; Papp et al., 2017; Bustillos et al., 2020; Muhammad Rafiq et al., 2020; Müller et al., 2021; Porter & Naleway, 2022; Pylkkänen et al., 2023). However, cultivating mushrooms to produce large quantities of basidiomata requires significant resources and time. Product consistency is also a challenge, directly affecting the quality of final materials. Like other biomaterials, MBs also require additional treatments to enhance mechanical strength, hydrophobicity, and resistance to microbial degradation. Although research in this

field is minimal, based on published articles, some research on MBs is provided in Table 4.4.

Table 4.4 Fungal species (Basidiomata) utilised in the preparation of biomaterials

Fungal species	Part used	Target use	Country	References
Agaricus bisporus	Stipe	Wound dressing	UK	Hamlyn et al. (1994)
Agaricus bisporus, Ganoderma lingzhi, Grifola frondosa	Whole basidiomata	Biocomposites	USA	Porter and Naleway (2022)
Fomes fomentarius	Whole basidiomata	Biocomposites	Germany	Pylkkänen et al. (2023)
Fomes fomentarius	Whole basidiomata	Construction materials	Germany	Müller et al. (2021)
Fomes fomentarius, Piptoporus betulinus	Whole basidiomata	Ethnomycological and ethnomedicinal use	Hungary	Papp et al. (2017)
Ganoderma boninense	Whole basidiomata	Construction materials	Indonesia	Muhammad Rafiq et al. (2020)
Phellinus ellipsoideus	Whole basidiomata	Leather	USA	Bustillos et al. (2020)

4.3.4 Major Differences Between Mushroom-Based Biomaterials and Mushroom Mycelium-Based Biomaterials

The key differences between mushroom-based biomaterials (MBs) and mycelium-based biomaterials (MMBs) are outlined as follows:

Parts used*:* MBs use the fruiting bodies directly in the development of biomaterials, while MMBs involve mycelium cultivation in feeding substrates under sterile and controlled conditions (Bustillos et al., 2020).

Production method*:* MBs utilise the natural growth characteristics of fruiting bodies. In this approach, fruiting bodies are cultivated directly within moulds until the ultimate shape and size (Müller et al., 2021; Pylkkänen et al., 2023). In contrast, mycelium-based biomaterials (MMBs) allow for the vegetative growth phase of the fungus. Mycelium is allowed to fully colonise lignocellulosic substrates, after which the colonised substrates are broken down into fine particles and transferred into moulds to allow further mycelium growth, resulting in products with specific shapes and dimensions (Khyaju & Luangharn, 2024).

4.4 Challenges and Future Directions of Mycelium-Based Biomaterials

In the current context, the use of mushroom mycelium in materials science is a fascinating innovation. The MMBs have gained popularity as a sustainable measure in converting agricultural and forestry by-products into cost-effective, energy-efficient, and versatile materials. Consequently, these MMBs have been successfully applied to various sectors, including construction, packaging, architectural designs, textiles, and insulation (Al-Qahtani et al., 2023; Khyaju & Luangharn, 2024). Additionally, the potential growth and development of the MMB sector is reflected by the increasing number of patent acceptances (Cerimi et al., 2019). Despite recent scientific advancements that have enabled the development and application of MMBs, several challenges remain to their widespread adoption and scalability. Based on existing literature, some of the key limitations of MMBs are briefly discussed below:

4.4.1 Misleading Science

Research on MMBs is rapidly expanding, mainly in mycology and material science, and its constraints must be addressed (Ghazvinian & Gursoy, 2022b). Systematic identification of the mushroom species is crucial to ensure the reproducibility and reliability of results. Employing a polyphasic approach for species-level identification, along with the use of the latest legitimate names, is essential for conducting scientific research and scaling up industrial production. Additionally, the MMBs products are designed to be people-centric, in the form of packaging, indoor insulation, wearable, and electronic parts. Therefore, these products require basic attention from users, both regarding health concerns and safety. Furthermore, emerging opportunities for MMBs applications include genetic modification of mushroom strains (GMOs), such as CRISPR/Cas9-based systems, to enhance specific characteristics (Amobonye et al., 2023; Salichanh et al., 2025). However, the absence of an international standardised set of parameters for MMBs development and material testing creates challenges in understanding and comparing material properties (Aiduang et al., 2022b). Establishing international standards for MMBs fabrication and evaluation would significantly improve the consistency and scientific integrity of the field.

4.4.2 Limited Exploration of Mushroom Species

In the MMBs sector, research and industrial works focus on only a few mushroom species (Table 4.2). However, many recognised mushroom species are underexplored and underutilised for MMBs. Besides this, the hidden box of underexplored mushrooms in nature holds a huge opportunity. With the incorporation of phylogenetic analytical tools and micro- and macro-morphological characteristics, the discovery of novel fungal species has seen a sudden rise and is expected to be introduced (Jeewon & Hyde, 2016). Medicinal, edible, or saprobic mushrooms can be screened and utilised in experiments to develop desirable-quality

MMB products (Sydor et al., 2022). Diversifying the fungal species in MBBs may provide more efficient, sustainable, and economically viable solutions.

4.4.3 Substrate Concerns

MMBs development utilises agricultural residues and forest by-products as basic feeding substrates for mycelium, which are rich in lignin, cellulose, and hemicellulose. Excessive use of these resources for MMBs might create competition for feed in animal husbandry. However, the trend of increasing agricultural production can address the availability of these by-products. Additionally, exploring diverse lignocellulosic substrates, such as pineapple peel, forest shrubs, banana plant fibres, and cactus fibres, could be an additional alternative for MBBs.

4.4.4 Contamination Risks

A major challenge is contamination of MMBs by unwanted fungi or bacteria due to failure in maintaining a sterile environment. Sterilisation of substrates, equipment, moulds, and the workspace requires specific protocols and implementation. Sterile conditions require efficient equipment and technical expertise. The culture must be pure, viable, and vigorous. Some mushroom species feature the intrinsic antimicrobial properties in the final products (Alves et al., 2012; Amobonye et al., 2023). For instance, *Phellinus ellipsoideus* contains bioactive compounds that confer resistance to bacterial and fungal contamination, including protocatechuic acid, protocatechualdehyde, hispidin, hispolon, phelligridin, and inoscavin (Li et al., 2017; Amobonye et al., 2023). Selecting fungal species with strong antimicrobial behaviour can be considered to mitigate contamination risks.

4.4.5 Material Properties

MMBs are less effective regarding mechanical strength, flexibility, water resistance, and durability than plastic-based products (Alaneme et al., 2023). Additionally, without proper treatment, MMBs are less fire-resistant than some synthetic materials, restricting their use to semi-structural and non-structural applications (Alaneme et al., 2023). However, reinforcing MMBs with wood or

metals showed better performance (Almpani-Lekka et al., 2021). Treatments with plasticisers, crosslinking agents, or post-processing address some issues of MMBs (Almpani-Lekka et al., 2021; Elsacker et al., 2023). Moreover, the diversity of mushroom species offers an opportunity to overcome these challenges and improve material performance.

4.4.6 Scaling-Up Production

Producing MMBs in large quantities and maintaining consistency in their properties is a major challenge (Abhijith et al., 2018). This is feasible only by expanding the laboratory setup, which means industries. MMB production performs sound in controlled environmental conditions, such as temperature, humidity, aeration, incubation duration, and light exposure (Aiduang et al., 2024). Mycelium growth is slower than that of synthetic material. However, the establishment of several industries for MMBs production has been a benchmark for further expansion. Additionally, contamination by unwanted fungi and bacteria is another challenge, requiring strict safety protocols (Gandia et al., 2021). Importantly, research in modifying growth conditions, along with maintaining a sterile environment, could address this problem and enhance productivity. For instance, Crawford et al. (2024) introduced a method for cultivating mycelium leather on a paste medium, which could accelerate growth and ease harvesting.

4.4.7 Economic Viability

Financial investors invest their money and resources in a business, enterprise, or company, only under the conditions of getting profits over time. The total cost in a company refers to the combination of initial capital investment and operational or administrative costs. A primary raw input in MBBs production is low-cost agricultural residues and forest byproducts. However, other investments, such as land, labour, infrastructure, and equipment, also play a significant role in decision-making before startup. Additionally, market introduction and expansion of MBBs are still challenging due to stakeholder resistance from other companies with

similar final uses, such as synthetic packaging or building products. However, public demand for sustainable products provides strong support for the MBB industry. Improving the quality and scaling production of MMBs can address these cost-related limitations, making them more economically competitive in the market.

4.4.8 Regulatory and Market Acceptance

Animal-based leather production has a significant economic impact, with a market value of EUR 48 billion and 558,000 tons of production globally (FAO, 2016; European Commission, 2019). However, this industry causes greenhouse gas emissions and chemical pollution in the environment (Silva, 2021). On the other hand, MMBs production is struggling to meet the safety and performance standards for applications in construction, packaging, and leather products. In addition, shifting industry and consumer perceptions and acceptance of MMBs remains time-consuming (Abhijith et al., 2018). However, the demand for MMBs is increasing, and their effectiveness, such as thermal insulating biomaterials, is being recognised for maintaining suitable indoor environments (Al-Qahtani et al., 2023). With the success of MBB utilisation, they can expand market coverage and diversification.

4.4.9 Limited Applications

When compared to conventional plastic-based products or animal-based leather, the range of applications for MMBs remains relatively limited. MMBs are developed from liquid-state surface fermentation (LSSF) or solid-state fermentation (SSF). The harvested mycelium-based leather has not reached the quality of animal-based leather in terms of tensile strength, flexibility, and durability. Other parameters of MMBs, such as mechanical strength, are below the standards. However, the MMBs have been utilised in packaging, insulation, architectural designs, and leather substitutes (Gandia et al., 2021). Additionally, MMBs have also been successful in specialised fields, such as biomedical scaffolds and electronic parts (Vasquez & Vega, 2019b; Antinori et al. 2021; Danninger et al., 2022). Despite

the limitations, the ongoing intensive research and development in MMBs hold the potential to enhance their quality and increase their applications.

CHAPTER 5

FUNGALPEDIA – BASIDIOMYCOTA GENERA AND NOTES ON MUSHROOM MYCELIUM-BASED BIOMATERIALS

5.1 Introduction

Fungalpedia is an online portal run by Mushroom Research Foundation in collaboration with the Center of Excellence in Fungal Research, Mae Fah Luang University, Thailand (www.fungalpedia.org). It is a comprehensive database encompassing fungal taxa and terminologies, developed based on published scientific articles. Hyde et al. (2023) published "Fungalpedia, an illustrated compendium of the fungi and fungus-like taxa", highlighting the theme and significance of Fungalpedia-related publications. Fungalpedia significantly contributes to mycology by compiling and systematically presenting scattered information on fungal taxa into a common and accessible platform (Hyde et al., 2023).

This study is part of the Fungalpedia series, which focuses on fungal genera and higher taxa of Basidiomycota and on popular terms for mycelium-based biomaterials. The first section is attributed to notes on basidiomycota genera and higher taxa, while the second section provides notes on terms popular in mycelium-based biomaterials. Each genus entry includes a summary of original description, habit, host and lifestyle, type species, classification, morphological characteristics, phylogenetic genes used for identification, the latest taxonomic placement, closely related genera, unique characteristics, and their applications. The notes on key terminologies of mycelium-based biomaterials provide information relating to fungi and mycelium-based biomaterials.

The mycelium-based biomaterials are an innovative and sustainable material developed using fungal mycelium and lignocellulosic substrates and are an alternative to plastic and foam-based materials (Khyaju & Luangharn, 2024). Notably, the choice of

mushroom species has a pivotal role in determining the mechanical and overall properties of the final product. Therefore, description of fungal species with key features, including morphological characteristics, phylogenetic evidence, culture characteristics, decay type, and toxicity, aids in their screening in mycelium-based biomaterial applications (Sydor et al., 2022; Khyaju et al., 2025).

5.2 Methods

A systematic approach was followed to compile descriptions and illustrations for both fungal genera and mycelium-based biomaterial terminologies. Relevant information for preparing entries was gathered from peer-reviewed articles, monographs, books, journals, and various online portals, including Google Scholar (https://scholar.google.com/), PubMed (https://pubmed.ncbi.nlm.nih.gov/), ScienceDirect (https://www.sciencedirect.com/), Elsevier (https://www.elsevier.com/), and Semantic Scholar (https://www.semanticscholar.org/). Information on fungal taxa was gathered from online databases, such as Index Fungorum (https://www.indexfungorum.org/), MycoBank (https://www.mycobank.org/), GenBank (https://www.ncbi.nlm.nih.gov/), Facesoffungi (https://www.facesoffungi.org/), and UNITE (https://unite.ut.ee/index.php). In each genus entry, genetic markers, including ITS, LSU, SSU, *rpb1*, *rpb2*, *tub*, and *tef1-α*, used in the latest investigation on molecular phylogeny are provided, except for the genera lacking molecular evidence. The recent taxonomic status of fungal taxa followed the classification published by Hyde et al. (2024a). The terminologies related to mushroom mycelium-based biomaterials were selected based on the biomaterial development process, their relevance to material properties, and recurrent uses, and are sourced from published and available research publications.

Fungalpedia entries are presented in alphabetical order in both sections. Scientific taxa are hyperlinked to relevant publications and online databases for additional information. Figures are linked to external repositories to enable access to

complementary visual material or reference data. The original figures of basidiomata, equipment, and materials are used with permission from the authors.

5.3 Results and Discussions

5.3.1 Basidiomycota Genera Notes

Agaricomycetidae Parmasto

Agaricales Underw.

Agaricaceae Chevall., *Fl. gén. env. Paris* (Paris) 1: 121

Agaricaceae was established by F.F. Chevallier (1826), with *Agaricus* L. as the type genus, and includes diverse basidiomata forms, including agaricoid, secotioid, and gasteroid (Kooij et al., 2024). Based on morphology and phylogeny, the most recent classification recognised approximately 59 genera and 1,560 species within this family (Wijayawardene et al., 2022; Kooij et al., 2024). Members of this family are widely distributed, forming a monophyletic group of saprotrophs and exhibiting a broad range of basidiospore colour (Vellinga, 2004; Kooij et al., 2024). Kooij et al. (2024) followed and revised the classification of Singer (1986), dividing the *Agaricaceae* into tribes: *Agaricaceae*, *Coprineae* Kooij, *Cystolepioteae* Kooij, *Leucocoprineae*, *Lepioteae* Fayod ex Ulbr., *Lycoperdeae* Kooij, *Macrolepioteae* Kooij, and *Tulostomateae* Kooij. Members of this family are characterised by pluteoid, lepiotoid, or tricholomatoid basidiomata with free or rarely adnexed lamellae, the presence of a veil, hyaline to pigmented basidiospores, and a regular to subregular hymenophoral trama (Vellinga, 2004; Nascimento & Alves, 2014). Species belonging to *Agaricaceae* are distributed worldwide, including alpine, arctic, arid, temperate, and tropical regions (Vellinga, 2004; Kooij et al., 2024). It includes edible, medicinal, and poisonous species (Nascimento & Alves, 2014).

5.3.1.1 *Dictyocephalos* Underw. ex V.S. White

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.1

Classification: *Agaricaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Dictyocephalos was established by V.S. White (1901), with *D. attenuatus* as the type species (White, 1901). The genus remained monotypic for more than a century, until the description of a second species, *D. xinjinagensis* (Dios et al., 2002; Hyde et al., 2021). Species of *Dictyocephalos* are found in soil and are distributed worldwide (Long & Plunkett, 1940; He et al., 2019; Hyde et al., 2021).

Dictyocephalos is characterised by hypogeous basidiomata with a powdery cellular gleba, consisting of permanent cells, with dehiscence by irregular breaking away of the peridium, living persistent basidia and basidioles (White, 1901; Long & Plunkett, 1940; Hyde et al., 2021). The basidiomata are enclosed in a cup-like volva during early stages, which is persistent at the base of the stipe (White, 1901; Long & Plunkett, 1940). The stipe is stout, solid, and becomes woody with maturity (Long & Plunkett, 1940). The peridium is two-layered, comprising the outer roughened peridium and inner coriaceous to membranous endoperidium (Long & Plunkett, 1940). The gleba is a powdery, mesh-like, irregular tissue containing basidiospores and persistent fascicles of basidia (Long & Plunkett, 1940). Basidiospores are globose to subglobose, verrucose, and fulvous (Long & Plunkett, 1940; Hyde et al., 2021).

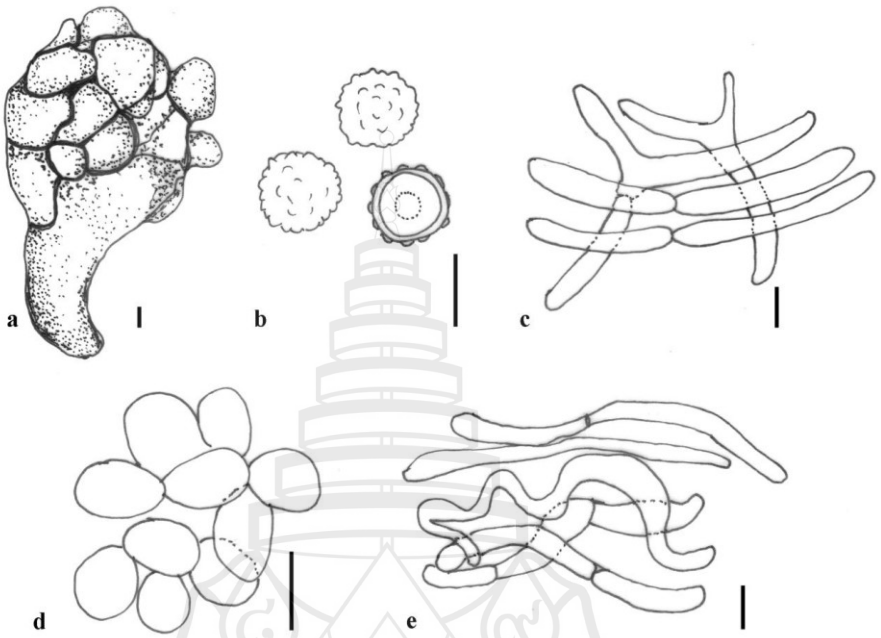
Hyde et al. (2021) described *D. xinjinagensis* based on a combination of morphological characteristics and phylogenetic analyses (ITS and LSU) of specimens collected in Xinjiang, China. *Dictyocephalos* is closely related to the genus *Phellorinia* Berk., but is distinguished by the presence of thin, membranous plates in the gleba, which remain divided into compartments (Long & Plunkett, 1940; Moreno et al., 1997; Dios et al., 2002). Additionally, the basidiomata of *Dictyocephalos* are generally larger and more robust than those of *Phellorinia* (Dios et al., 2002).

Synonymy: *Battarreopsis* Henn., *Podoloma* Clem., *Whetstonia* Lloyd

Type species: *Dictyocephalos attenuatus* (Peck) Long & Plunkett

Basionym: *Battarrea attenuata* Peck

Other accepted species: *Dictyocephalos xinjiangensis* R.L. Zhao, M.Q. He & J.Xin Li



Note a Basidiomata. b Basidiospores. c Exoperidial hyphae. d Group of globular elements. e Endoperidial hyphae. Scale bar: a = 1 cm, b–d = 5 µm, e = 2 µm.

Source Redrawn from Hyde et al. (2021). For original basidiomata, refer to Hyde et al. (2021).

Figure 5.1 *Dictyocephalos xinjiangensis* (HMAS255794, holotype)

Biannulariaceae Jülich, *Biblthca Mycol.* 85: 356

Biannulariaceae was established by W. Jülich (1981) with the type genus *Biannularia* Beck. Members of *Biannulariaceae* are characterised by tricholomatoid, collybioid, or pleurotoid basidiomata, with adnate or decurrent lamellae, a white spore print, and smooth hyaline basidiospores. The lamella-edges with or without cheilocystidia, the hymenium lacks true pleurocystidia, and pseudocystidia are rare. Lamellar trama is regular or bilateral, and the pileipellis is a cutis, ixocutis, or trichoderm-type. Hyphae are clampless (Ammirati et al., 2007; Sánchez García et al., 2016; Raj et al., 2019). The genera under *Biannulariaceae* are *Anupama* K.N.A. Raj,

K.P.D. Latha & Manim., *Callistosporium* Singer, *Catathelasma* Lovejoy, *Guyanagarika* Sánchez-García, T.W. Henkel & Aime, *Macrocybe* Pegler & Lodge, *Pleurocollybia* Singer, and *Pseudolaccaria* Vizzini, Contu & Z.W. Ge (He et al., 2019). Members of *Biannulariaceae* are distributed both in tropical and temperate regions and are either saprotrophic or ectomycorrhizal (Sánchez García et al., 2016; Raj et al., 2019). Some species of the genera *Catathelasma* Lovejoy, *Macrocybe* Pegler & Lodge, and *Pleurocollybia* Singer are considered edible (Ammirati et al., 2007).

5.3.1.2 *Catathelasma* Lovejoy

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.2

Classification: *Biannulariaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Catathelasma was established by Ruth Harrison Lovejoy with *C. evanescens* as the type species (Lovejoy, 1910; Ge et al., 2020). Species of *Catathelasma* are known to be ectomycorrhizal (Trappe, 1962; Tedersoo & Smith, 2013; Ge et al., 2020). *Catathelasma* was initially classified under *Tricholomataceae* R. Heim ex Pouzar and later reclassified into *Biannulariaceae* Jülich (Jülich, 1982; Singer, 1986; Ge et al., 2020). The type specimen was collected from open balsam and spruce woods occurring singly in sod on thick humus in Wyoming, USA (Lovejoy, 1910). The basidiomata are characterised by distinct tricholomatoid morphology, featuring decurrent to adnate to sinuate-adnexed lamellae, a double annulus, bilateral to subregular lamella trama, and a firm, white context (Lovejoy, 1910; Ge et al., 2020). The pileus is somewhat fleshy, initially convex, and then expands (Lovejoy, 1910; Ge et al., 2020). Basidiospores are white, oblong, smooth, amyloid, and acyanophilic (Ge et al., 2020). Clamp connections are present (Ge et al., 2020).

Catathelasma species were delineated using morphological characters, phylogenetic evidence (ITS, LSU, and *tef1-1α*), host preferences, and geographic distribution (Ge et al., 2020). Ge et al. (2020) revealed the presence of two monophyletic clades within *Catathelasma*, namely the imperiale clade and the subalpinum clade. *Catathelasma* forms a sister clade with *Cleistocybe* Ammirati, A.D. Parker & Matheny

(Ammirati et al., 2007). However, *Cleistocybe* has not been reported as ectomycorrhizal and is characterised by inamyloid basidiospores and a partial veil (Ammirati et al., 2007). Hyde et al. (2024a) recognised six species worldwide within *Catathelasma*. The edible mushroom *Catathelasma ventricosum* is reported to possess antidiabetic, antihyperglycemic, antihyperlipidemic, antibacterial, and antioxidant activities (Liu et al., 2013; Liu et al., 2016; Liu et al., 2017).

Synonymy: *Biannularia* Beck

Type species: *Catathelasma evanescens* Lovejoy

Other accepted species:

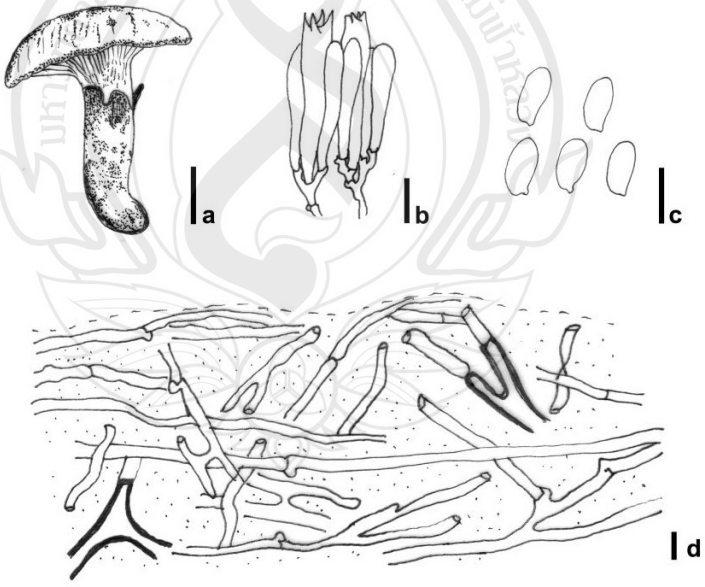
C. imperiale (P. Karst.) Singer

C. laorentou Z.W. Ge

C. singeri Mitchel & A.H. Sm.

C. subalpinum Z.W. Ge

C. ventricosum (Peck) Singer



Note a Basidiomata. b Basidia. c Basidiospores. d Pileipellis, oleiferous hyphae are indicated by thick-walled hyphae. Scale bar: a = 2.5 cm, b–d = 10 μm.

Source Redrawn from Ge et al. (2020). a = HKAS 92245, b−d = HKAS 105984

Figure 5.2 *Catathelasma laorentou*

Callistosporiaceae Vizzini, Consiglio, M. Marchetti & P. Alvarado, *Fungal Diversity* 101: 223

Callistosporiaceae was established by A. Vizzini, G. Consiglio, M. Marchetti, & P. Alvarado in 2020, with *Callistosporium* Singer as the type genus (Vizzini et al., 2020). The genera included in this family are *Callistosporium* Singer, *Anupama* K.N.A. Raj, K.P.D. Latha & Manim., *Guyanagarika* Sánchez-García, T.W. Henkel & Aime, *Macrocybe* Pegler & Lodge, *Pseudolaccaria* Vizzini, Contu & Z.W. Ge, and *Xerophorus* (Bon) Vizzini, Consiglio & M. Marchetti. Members of *Callistosporiaceae* have tricholomatoid, collybioid, or plerotoid basidiomata with adnate to adnexed, or emarginated-adnexed lamellae, regular to subregular hymenophoral trama, inamyloid basidiospores, and a lack of partial veil (Vizzini et al., 2020). *Callistosporiaceae* are either saprotrophic or ectomycorrhizal, found on soil or rotten wood (Vizzini et al., 2020).

5.3.1.3 *Callistosporium* Singer

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.3

Classification: *Callistosporiaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Callistosporium was established by Singer in 1944, with *C. palmarum* as the type species (Singer, 1986). The genus had undergone several taxonomic revisions, initially being placed in the family *Tricholomataceae* R. Heim ex Pouzar (Kaygusuz & Şengül 2021; Moncalvo et al., 2022). More recently, it was reclassified within the family *Entolomataceae* Kotl. & Pouzar based on rRNA data (Matheny et al., 2006; Kaygusuz & Şengül 2021). Sánchez-García et al. (2016) used phylogenetic inference to place the genus in the family *Catathelasmataceae* Wasser. Recently, Vizzini et al. (2020) reclassified it within the family *Callistosporiaceae*. *Callistosporium* are saprobic, growing on humus, litter, and wood debris, and are distributed worldwide (Singer, 1986; He et al., 2019; Vizzini et al., 2020; Kaygusuz & Şengül 2021).

The basidiomata of *Callistosporium* species exhibit a collybioid habit (Kaygusuz & Şengül 2021). The pileus is convex to applanate, with subdecurrent,

adnexed, or emarginated lamellae, and the central stipe is either eccentric or lateral (Vizzini et al., 2020; Kaygusuz & Şengül 2021). Lamellae are usually crowded, adnate, adnexed, or emarginated-adnexed, and veils are absent (Vizzini et al., 2020). Basidiospores are ellipsoid, smooth, inamyloid, indextrinoid, cyanophilous, and white in deposit (Singer,1986; Arnolds, 2006; Halama & Rutkowski, 2014; Jančovičová et al., 2016; Kaygusuz & Şengül 2021). Cheilocystidia, pleurocystidia, and clamp connections may or may not be present (Kaygusuz & Şengül 2021). The pileipellis and stipitipellis contain encrusted and intracellular pigmented hyphae (Kaygusuz & Şengül 2021). The context exhibits lilac, violet, and olive yellow staining in the KOH reaction (Kaygusuz & Şengül 2021). Hyphae are clampless (Jančovičová et al., 2016).

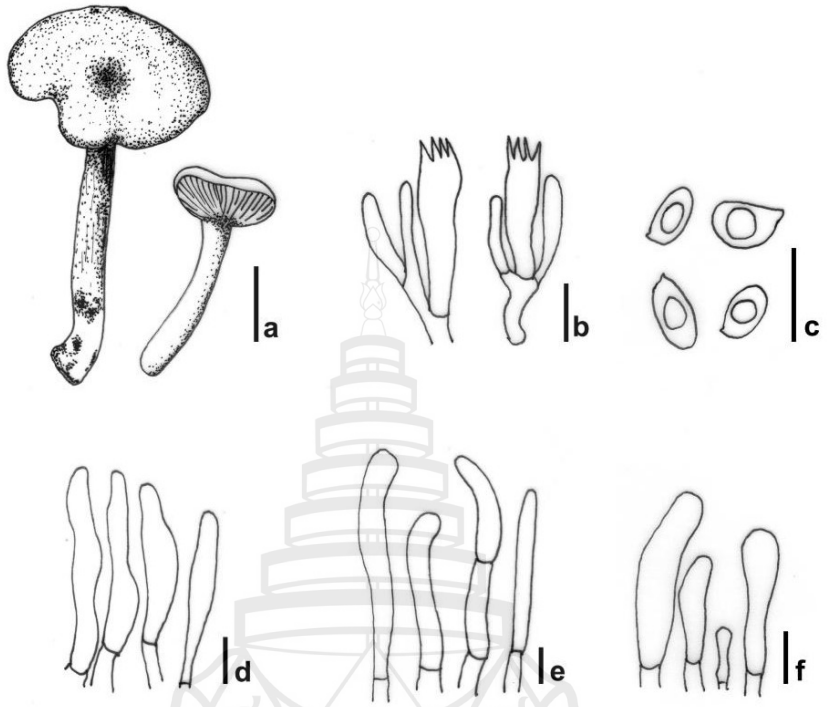
Species delineation within *Callistosporium* is based on combined morphological and phylogenetic analyses (ITS and LSU) (Kaygusuz & Şengül 2021). Index Fungorum (2025) reports 42 records under *Callistosporium*, but only 22 species are recognised in Species Fungorum (2025).

Synonymy: *Pleurocollybia* Singer

Type species: *Callistrosporium palmarum* (Murrill) Singer

Basionym: *Gymnopus palmarum* Murrill

Other accepted species: (Species Fungorum – search *Callistosporium*)



Note a Basidiomata. b Basidia and hymenial elements. c Basidiospores. d Cheilocystidia. e Pileipellis elements. f Caulocystidia. Scale bar: a = 1 cm, b−f = 10 µm.

Source Redrawn from Kaygusuz and Şengül (2021).

Figure 5.3 *Callistosporium luteo-olivaceum*

Clavariaceae Chevall., *Fl. gén. env. Paris* (Paris) 1: 102

Clavariaceae was established by F.F. Chevallier in 1826 with the type genus *Clavaria* Vaill. ex L. (Chevallier, 1826). Family *Clavariaceae* consists of the genera *Camarophyllopsis* Herink, *Clavaria* Vaill. ex L., *Clavicorona* Doty, *Clavulinopsis* Overeem, *Hirticlavula* J.H. Petersen & Læssøe, *Hodophilus* R. Heim, *Hyphodontiella* Å. Strid, *Lamelloclavaria* Birkebak & Adamčík, *Ramariopsis* (Donk) Corner, and *Setigeroclavula* R.H. Petersen (He et al., 2019). *Clavariaceae* comprise approximately 110 recognised species worldwide and are distributed mostly in temperate regions, some in tropical and subtropical regions (Corner, 1950; Birkebak et al., 2013; Furtado et al., 2016). Members of the family are characterised by clavate, coralloid, resupinate,

pendent-hydnoid, and hygrophoroid type basidiomata (Hibbett & Thorn, 2001; Birkebak et al., 2013; Furtado et al., 2016).

5.3.1.4 *Camarophyllopsis* Herink

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.4

Classification: *Clavariaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Camarophyllopsis was established by Herink in 1958, typified by *C. schulzeri* (Young & Wood, 1997). Members of *Camarophyllopsis* are solitary to sub-gregarious, terrestrial, biotrophic and saprobic, and distributed globally (Young & Wood, 1997; He et al., 2019). *Camarophyllopsis* was first classified under *Hygrophoraceae* Lotsy (Hesler & Smith, 1963; Arnolds, 1986a). Later, Matheny et al. (2006) transferred it to *Clavariaceae* Chevall. Species within *Camarophyllopsis* are polyphyletic and are categorised into two clades: *C.* subgen. *Camarophyllopsis* Herink and *C.* subgen. *Hodophilus* (R. Heim) Bon.

The basidiomata of *Camarophyllopsis* are agaricoid, characterised by thin to fleshy, grey to ochre or brown, convex to umbilicate, and hygrophanous pileus (Young & Wood, 1997; Zhang et al., 2019). Lamella are distant and broadly adnate to arcuate or decurrent (Young & Wood, 1997). Stipe is dry, often marked with small dots or pruinose punctate, and lacks a veil (Young & Wood, 1997). Basidia are narrowly clavate, typically four-spored (Young & Wood, 1997). Basidiospores are subglobose to broadly ellipsoidal, hyaline, smooth, inamyloid, and white in deposit (Young & Wood, 1997; Zhang et al., 2019). The pileipellis consists of erect, ascending, or repent, subcylindrical to ellipsoidal terminal cells (Arnolds, 1986a). Cystidia are either absent or inconspicuous (Young & Wood, 1997). Clamp connections may be present or absent (Young & Wood, 1997).

Species delineation within *Camarophyllopsis* used morphological and phylogenetic analysis (ITS and LSU) (Zhang et al., 2019). Index Fungorum (2025) reported 32 records under *Camarophyllopsis*; however, Hyde et al. (2024a) have recognised only 20 species worldwide. *Camarophyllopsis* can be distinguished from its phylogenetically related clades, *Hodophilus* R. Heim and *Lamelloclavaria* Birkebak & Adamčík, by its pileipellis structure, which is composed of chains of erect, ascending, or

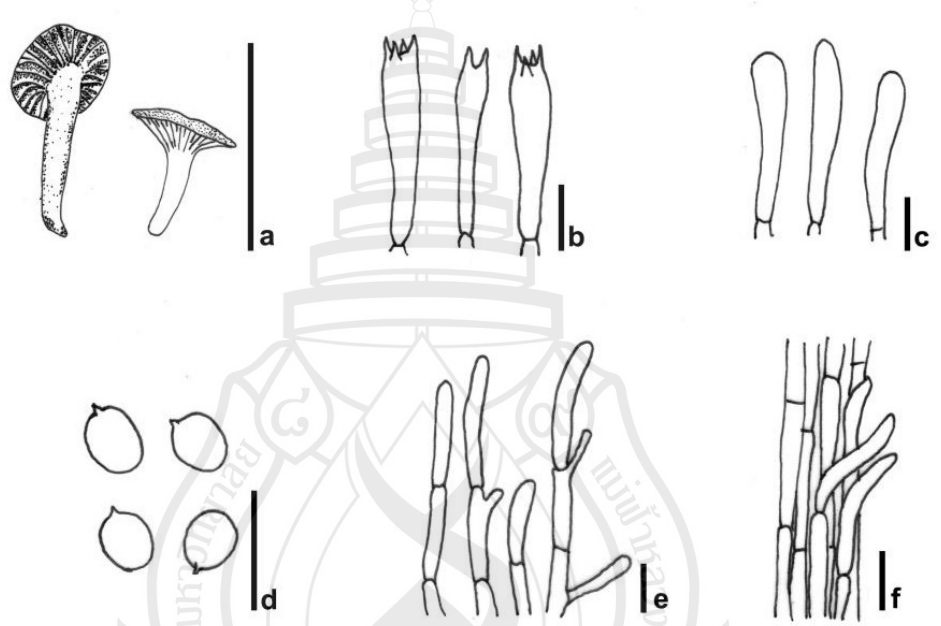
repent, subcylindrical to ellipsoid end cells and lacks inflated terminal elements (Birkebak et al., 2016).

Synonymy: *Hygrotrama* Singer

Type species: *Camarophyllopsis schulzeri* (Bres.) Herink

Basionym: *Hygrophorus schulzeri* Bres.

Other accepted species: (Species Fungorum – search *Camarophyllopsis*)



Note a Basidiomata. b Basidia. c Basidioles. d Basidiospores. e Hyphal terminations in pileipellis. f Stipitipellis. Scale bar: a = 2 cm, b–d = 10 μm, e–f = 20 μm.

Source Redrawn from Zhang et al. (2019).

Figure 5.4 *Camarophyllopsis olivaceogrisea* (GDGM44519, holotype)

5.3.1.5 *Ramariopsis* (Donk) Corner

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.5

Classification: *Clavariaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Ramariopsis was described by Donk in 1933 as *Clavaria* subgen. *Ramariopsis* Donk, with type species *Clavaria kunzei* Fr. (García-Sandoval et al., 2005). Corner

(1950) elevated subgenus *Ramariopsis* to the genus level, maintaining *Clavaria kunzei* [= *Ramariopsis kunzei* (Fr.) Corner] as the type species. Over time, classification within *Ramariopsis* has evolved. Petersen (1966) proposed dividing *Ramariopsis* into two subgenera: *Laevispora* for species with smooth basidiospores, and *Ramariopsis* for those with echinulate basidiospores (García-Sandoval et al., 2005). Later, Petersen (1978) proposed a new classification for the closely related genera *Ramariopsis*, *Clavulinopsis* Overeem, and *Clavaria* Vaill. Ex. L.

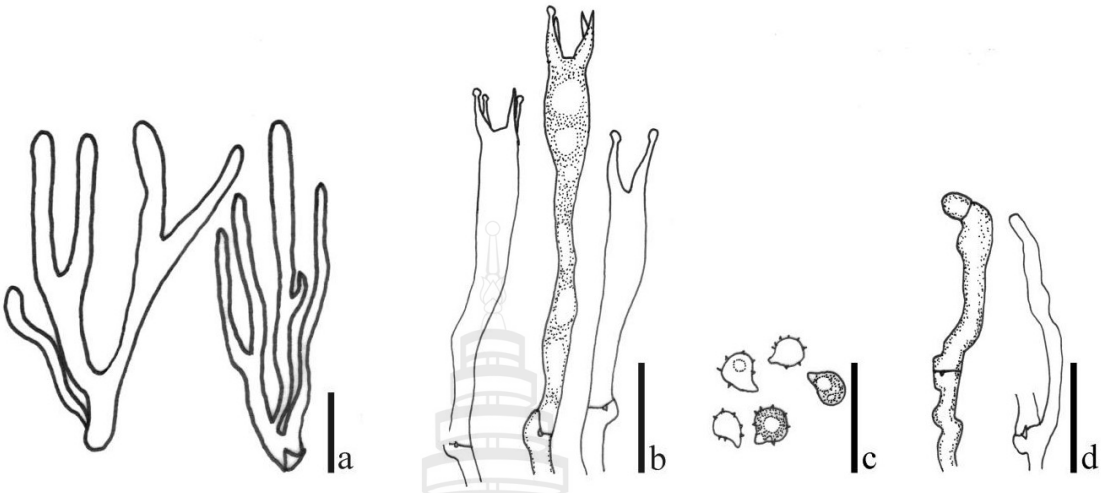
The basidiomata of *Ramariopsis* species are characterised by being small to medium-sized, branched or rarely simple, with a distinct stipe and usually slender, cylindrical branches (Corner, 1950, 1970; Hyde et al., 2016; Halama et al., 2017). Basidiospores are ellipsoid or subglobose, hyaline, and display finely verruculose to echinulate ornamentation (Corner, 1950, 1970; Hyde et al., 2016). Both basidia and tramal hyphae have clamp connections at their base (Corner, 1950, 1970; Hyde et al., 2016; Halama et al., 2017).

Phylogenetic studies based on the LSU show the monophyly of *Ramariopsis* species with ornamented basidiospores and clamps in the trama and branched basidiomata, while also showing paraphyletic lineages with remaining taxa that include smooth basidiospores (Kautmanová et al., 2012; Halama et al., 2017). Morphologically, species of *Ramariopsis* are similar to *Clavulinopsis* Overeem but can be distinguished by their echinulate basidiospores (Halama et al., 2017). Index Fungorum (2025) reported 84 records of *Ramariopsis*; however, Hyde et al. (2024a) recognised only 45 species worldwide. *Ramariopsis* species are terrestrial, saprotrophic, sometimes lignicolous, and can be solitary or gregarious (Corner, 1950, 1970; Petersen, 1978; Hyde et al., 2016).

Synonymy: *Clavaria* subgen. *Ramariopsis* Donk

Type species: *Ramariopsis kunzei* (Fr.) Corner

Other accepted species: (Species Fungorum – search *Ramariopsis*)



Note a Basidiomata. b Basidia. c Basidiospores. d Sterile elements of the hymenium. Scale bar: a = 0.5 cm, b−d = 15 µm.

Source Redrawn from Petersen (1964).

Figure 5.5 *Ramariopsis tenuiramosa*

Crepidotaceae (S. Imai) Singer, *Lilloa* 22: 584

Crepidotaceae was established by R. Singer in 1951 with the type genus *Crepidotus* (Fr.) Staude (Singer, 1951). Initially, Imai (1938) erected the monogeneric tribe *Crepidoteae* S. Imai to accommodate eccentric, lateral, or sessile agaric species with subdecurrent lamellae and ocherous or gerruginous basidiospores. Aime et al. (2005) conducted a molecular analysis of the agaric genera in this family to revise their traditional morphology-based classification, including genera from Singer (1986). Currently, the *Crepidotaceae* includes the genera: *Crepidotus* (Fr.) Staude, *Episphaeria* Donk, and *Nanstelocephala* Oberw. & R.H. Petersen, *Pellidiscus* Donk, *Pleuroflammula* Singer, and *Simocybe* P. Karst. (He et al., 2019). Species under *Crepidotaceae* are distinguished by either an ornamented or irregular outline, thick-walled, and a darker spore print (Petersen et al., 2010). *Crepidotaceae* are saprotrophic and are distributed worldwide (Aime et al., 2005).

5.3.1.6 *Nanstelocephala* Oberw. & R.H. Petersen

Index Fungorum, Facesoffungi, MycoBank, Fig. 5.6

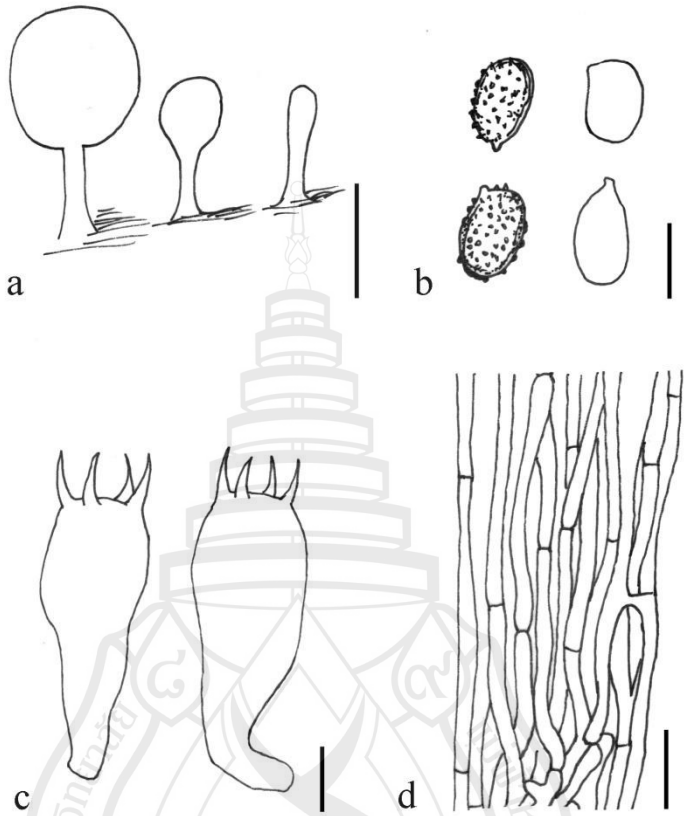
Classification: *Crepidotaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Nanstelocephala is a monotypic genus established by F. Oberwinkler, R.H. Peterson, and R.J. Bandoni in 1990 (Oberwinkler et al., 1990). The genus name is derived from Greek, with *nanos* meaning 'dwarf', *stele* meaning 'stalk', and *kephalos* meaning 'head' (Oberwinkler et al., 1990). The type species, *N. physalacrioides*, was collected on an unidentified fallen dead branch in North Carolina, USA (Oberwinkler et al., 1990). This species is saprobic and found only in the USA (Oberwinkler et al., 1990). Notably, the International Code of Nomenclature for algae, fungi, and plants has included this genus in the list of protected generic names for fungi (Kirk et al., 2013).

Nanstelocephala is characterised by its small, stalked-capitate basidiomata, which are white to cream, soft when fresh and become ochraceous and horny upon drying (Oberwinkler et al., 1990). Microscopically, the basidiospores are subglobose to ellipsoid, thick-walled, and warty, initially yellow to ochraceous in colour before maturity to brown (Oberwinkler et al., 1990). Basidia are clavate, apically swollen, and 4-spored (Oberwinkler et al., 1990). Cystidia are absent, while hyphidia are abundant, irregularly bent, thin-walled, and hyaline (Oberwinkler et al., 1990). The hyphal system is monomitic, smooth, thin-walled, and densely packed with hyphae (Oberwinkler et al., 1990).

Species delineation of *Nanstelocephala* from other genera is solely based on macro- and micro-morphology due to the lack of molecular sequences (He et al., 2019). *Nanstelocephala* is closely related to *Pellidiscus* Donk, with similar basidiospores, basidia, and hyphae (Oberwinkler et al., 1990). However, *Pellidiscus* is distinguished by its loose hyphal context (Donk, 1959; Oberwinkler et al., 1990). In addition, *Nanstelocephala* exhibits morphological resemblance to *Physalacria* Peck, but the latter has smooth, hyaline basidiospores and the presence of oleocystidia (Berthier, 1985; Oberwinkler et al., 1990).

Type species: *Nanstelocephala physalacrioides* Oberw. & R.H. Petersen



Note a Basidiomata. b Basidiospores. c Basidia. d Hyphal arrangement of the stalk. Scale bar: a = 200 μm, b–c = 5 μm, d = 10 μm.

Source Redrawn from Oberwinkler et al. (1990). For original basidiomata, refer to GBIF (2025).

Figure 5.6 *Nanstelocephala physalacrioides*

5.3.1.7 *Pleuroflammula* Singer

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.7

Classification: *Crepidotaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Pleuroflammula was established by R. Singer in 1946, with its type species *P. dussii* (Singer & Smith, 1946). *P. dussii* was originally described as *Crepidotus dussii* Pat., based on specimens collected from rotten wood in Guadeloupe, France (Patouillard,

1902). *Pleuroflammula* differs from *Flammula* (Fr.) P. Kumm. in its highly eccentric pileus, lateral stipe, or subsessile nature (Singer & Smith, 1946). Species of *Pleuroflammula* are either solitary or gregarious and are found in tropical, subtropical, and temperate regions across both hemispheres (Horak, 1978; Crous et al., 2021).

Species of *Pleuroflammula* are characterised by scaly, squamulose or squarrulose basidiomata, with a floccose-crenate to appendiculate margin formed from veil remnants (Horak, 1978). The stipe is squamulose below a sub-membranaceous or peronate annulus (Horak, 1978). Basidiospores are broadly ovate, smooth, thick-walled, rust-brown to yellow-brown, and lack germ pores (Horak, 1978). The basidia are typically 4-spored, rarely 2-spored (Horak, 1978). Chielocystidia are hyaline, clavate, rarely cylindrical or tapering towards the apex, and lack crystals (Horak, 1978). Notably, the yellow encrusting pigment in the basidiomata dissolves immediately when exposed to 3% KOH (Horak, 1978).

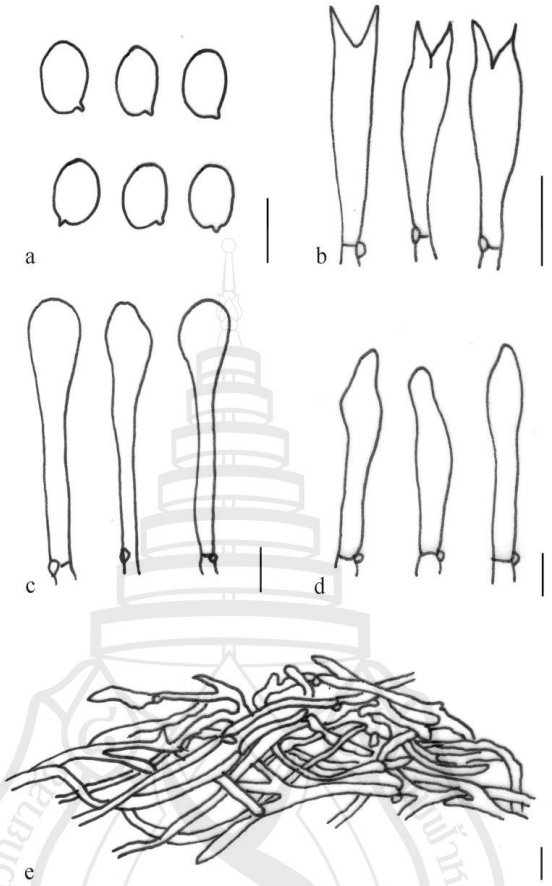
Pleuroflammula is morphologically similar to *Crepidotus* (Fr.) Staude, *Phaeomarasmius* Scherff., *Pholiota* (Fr.) P. Kumm., and *Simocybe* P. Karst. (Horak, 1978, 2018; Crous et al., 2021). However, it is distinct from *Crepidotus* by the absence of a veil (Horak, 1978). *Pleuroflammula* is distinguished from *Phaeomarasmius* by its KOH-soluble pigment, non-encrusted cheilocystidia, and smaller basidiospores (Crous et al., 2021).

Crous et al. (2021) described a new species, *P. pannonica* Polhorský, Kautmanová & Szabóová, based on specimens collected from fallen dead branches of *Quercus* sp., using morphological characteristics and phylogenetic analysis (ITS and LSU). Index Fungorum (2025) lists 28 records for *Pleuroflammula*, while Hyde et al. (2024a) have recognised only 20 species worldwide.

Type species: *Pleuroflammula dusii* (Pat.) Singer

Basionym: *Crepidotus dussii* Pat.

Other accepted species: (Species Fungorum – search *Pleuroflammula*)



Note a Basidiospores. b Basidia. c Cheilocystidia. d Pleurocystidia. e. Pileipellis. Scale bar: a−e = 10 μm.

Source Redrawn from Gierczyk and Kubinski (2019). For original basidiomata, refer to Gierczyk and Kubinski (2019).

Figure 5.7 *Pleuroflammula ragazziana*

Cyphellaceae Burnett, *Outl. Bot.* (London): 233

Cyphellaceae is a small monophyletic family established by G.T. Burnett in 1935 with the type genus *Cyphella* Fr. (Burnett, 1835). This family is characterised by agaricoid, cyphelloid, clavarioid, pleurotoid, corticioid, or stereoid basidiomata types (Vizzini et al., 2022; Zhang et al., 2024a). *Cyphellaceae* accommodates 16 genera: *Asterocyphella* W.B. Cooke, *Campanophyllum* Cifuentes & R.H. Petersen, *Catilla* Pat.,

Cheimonophyllum Singer, *Chondrostereum* Pouzar, *Cunninghammyces* Stalpers, *Cyphella* Fr., *Gloeocorticium* Hjortstam & Ryvarden, *Gloeostereum* S. Ito & S. Imai, *Granulobasidium* Jülich, *Hyphoradulum* Pouzar, *Incrustocalyptella* Agerer, *Phaeoporotheleum* (W.B. Cooke) W.B. Cooke, *Seticyphella* Agerer, *Sphaerobasidioscypha* Agerer, and *Thujacorticium* Ginns (He et al., 2019). Recently, Zhang et al. (2024a) described an additional new genus, *Stratocorticium* S.H. He, Y.P. Zhang & Nakasone, based on morphology and phylogenetic analyses (ITS and LSU). Members of *Cyphellaceae* are saprophytic and are distributed worldwide (Zhang et al., 2024a).

5.3.1.8 *Asterocyphella* W.B. Cooke

Index Fungorum, Facesoffungi, MycoBank

Classification: *Cyphellaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Asterocyphella was established by W.B. Cooke in 1961 to accommodate one new species, *A. floccose*, and two species transferred to the genus, *A. friesii* and *A. theiacantha* (Cooke, 1961). The type specimen of *A. floccose* was collected from dead branches of *Serjana fulta* in Tucuman, Argentina (Cooke, 1961). Species of *Asterocyphella* are distributed worldwide (Cooke, 1961; He et al., 2019).

Asterocyphella species are characterised by their receptacles, which can be either sessile or subsessile and are covered by a floccose network of surface hairs (Cooke, 1961). These hairs may branch and anastomose or be simple and elongated (Cooke, 1961). The receptacles consist of three tissue layers: a loose to compact layer of hyphae that produces the surface hairs, a compact layer of context tissue, and the hymenium, which is made up of basidia (Cooke, 1961). The basidiospores are brown, globose to ovate or asperulate (Cooke, 1961).

Identification of *Asterocyphella* species relies exclusively on macro- and micro-morphological features, as no molecular data have been reported (Cooke, 1961; He et al., 2019).

Type species: *Asterocyphella floccosa* W.B. Cooke

Other accepted species:

A. friesii (Quél.) W.B. Cooke

A. theiacantha (Syd. & P. Syd.) W.B. Cooke

5.3.1.9 *Catilla* Pat.

Index Fungorum, Facesoffungi, MycoBank, Fig. 5.8

Classification: *Cyphellaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

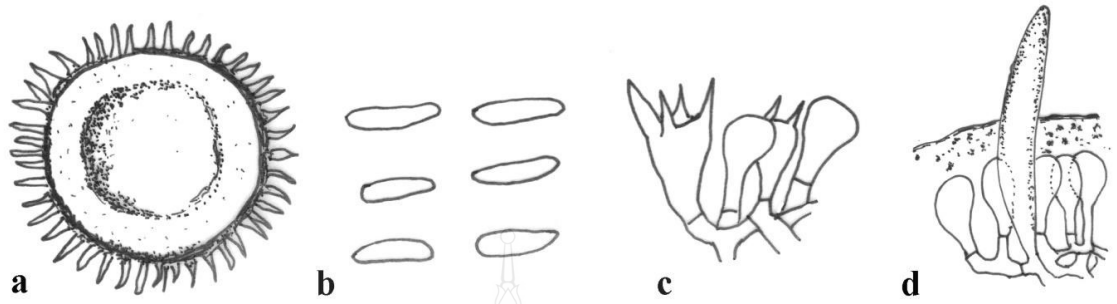
Catilla is a monotypic genus established by N. Patouillard in 1915 to accommodate its type species, *C. pandani* (Patouillard, 1915). The generic name *Catilla* is derived from "Catillus", which means small bowl (Patouillard, 1915). The type species was initially described as *Cyphella pandani* Pat., based on specimens collected from branches of *Pandanus* in Tuamotu, French Polynesia (Patouillard, 1906).

Catilla is characterised by small, cyphelliform, bowl-shaped basidiomata entirely covered with a gelatinous layer (Patouillard, 1915). A regular hymenium covers the inner concave surface part, while the margin is covered by a layer of basidiform cells that are rounded at the apical ends, attenuated into a stipitiform portion, and are mixed with hyaline and cystidioform hairs (Patouillard, 1915). Basidiospores are hyaline, narrow, and cylindrical, whereas basidia are hyaline, round to ovoid, with 2- or 4-spored subulate sterigmata (Patouillard, 1915). Hyphae are slender and sub-gelatinous (Patouillard, 1915).

Identification of *Catilla* solely depends on morphological characteristics due to the lack of molecular data (He et al., 2019), highlighting the need for molecular phylogenetic analyses to clarify the taxonomic placement of this genus.

Type species: *Catilla pandani* (Pat.) Pat.

Basionym: *Cyphella pandani* Pat.



Note a Basidiomata. b Basidiospores. c Basidia and basidioles. d Cystidiform hair and external cells immersed in gelatin. Scale bar: Not available in the original description.

Source Redrawn from Patouillard (1915).

Figure 5.8 *Catilla pandani*

5.3.1.10 *Cunninghammyces* Stalpers

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.9

Classification: *Cyphellaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Cunninghammyces was established by J.A. Stalpers in 1985 to accommodate its type species, *C. umbonatus.* This species was originally classified under the genus *Corticium* Pers. (Stalpers, 1985). The type specimen of *C. umbonatus* was first collected from the bark of dead stems in New Zealand (Cunningham, 1954). Subsequently, Boidin et al. (1993) described another species, *C. fuisporus*, based on a specimen from Réunion. In addition, species of *Cunninghammyces* have been reported in Venezuela, China, and Costa Rica (Hjortstam & Ryvarden, 1983; Boidin et al., 1993).

Species of *Cunninghammyces* are characterised by their annual, resupinate, effused basidiomata, which possess a pellicular to membranaceous texture (Stalpers, 1985). The hymenium is easily separable from the subiculum and the substrate (Stalpers, 1985). The basidiospores are hyaline, thin to slightly thick-walled, inamyloid, echinulate with a smooth suprahilar plage, and often contain large globules (Stalpers, 1985). Basidia are hyaline, thin-walled, and clavate to typically urniform. They can be terminal or

lateral, each bearing four sterigmata (Stalpers, 1985). The hyphae are hyaline, thin to somewhat thick-walled, and feature clamp connections (Stalpers, 1985).

Identification of *Cunninghammyces* species primarily relies on morphological characteristics due to a lack of molecular data (He et al., 2019). However, a few sequences have been uploaded to GenBank (2024), which are not supported by any valid publications.

Type species: *C. umbonatus* (G. Cunn.) Stalpers

Basionym: *Corticium umbonatum* G. Cunn.

Other accepted species: *C. fusisporus* Boidin & Gilles

Note a Stages of basidium development. b Basidiospores. Scale bar: a−b = 10 µm.

Source Redrawn from Stalpers (1985).

Figure 5.9 *Cunninghammyces umbonatus*

5.3.1.11 *Gloeocorticium* Hjortstam & Ryvarden

Index Fungorum, Facesoffungi, MycoBank, Fig. 5.10

Classification: *Cyphellaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Gloeocorticium, a monotypic genus, was established by K. Hjortstam and L. Ryvarden in 1986 (Hjortstam & Ryvarden, 1986). The type species, *G. cinerascens*, was based on specimens collected from bamboo in Misiones province, Argentina (Hjortstam & Ryvarden, 1986). This species is saprophytic and is distributed in Argentina and Brazil

(Hjortstam & Ryvarden, 1986, 2007). *Gloeocorticium* is characterised by resupinate, adnate, effused, medium-thick basidiomata, with a more or less dry, firm hymenium (Hjortstam & Ryvarden, 1986; Gorjón, 2020). Basidiospores are subglobose, smooth, thick-walled, inamyloid, indextrinoid, acyanophilic, and have a distinct lateral apiculus (Hjortstam & Ryvarden, 1986; Gorjón, 2020). Basidia are clavate, with four sterigmata and a basal clamp (Hjortstam & Ryvarden, 1986; Gorjón, 2020). Gloeocystidia are moniliform, thin-walled, and amyloid (Hjortstam & Ryvarden, 1986; Gorjón, 2020). The hyphal system is monomitic to dimitic, with thin-walled, long-celled hyphae that are hyaline, smooth, inamyloid, and have clamp connections (Hjortstam & Ryvarden, 1986; Gorjón, 2020).

Species delineation of *Gloeocorticium* is based solely on macro- and micro-morphological characteristics, as no molecular sequences are available (Hjortstam & Ryvarden, 1986; He et al., 2019). This genus is morphologically similar to *Radulomyces* M.P. Christ., sharing clavate basidia and ellipsoid basidiospores with a distinct apiculus (Hjortstam & Ryvarden, 1986). However, *Gloeocorticium* can be distinguished by its amyloid, moniliform gleocystidia, and laterally depressed basidiospores (Hjortstam & Ryvarden, 1986).

Type species: *Gloeocorticium cinerascens* Hjortstam & Ryvarden

Note a Basidiospores. b Basidia. c Cystidia. Scale bar: a = 5 µm, b–c = 10 µm.

Source Redrawn from Hjortstam and Ryvarden (1986). For original basidiomata, refer to GBIF (2025).

Figure 5.10 *Gloeocorticium cinerascens*

Cystostereaceae Jülich, *Biblthca Mycol.* 85: 362

Cystostereaceae is a small family established by W. Jülich in 1982 with *Cystostereum* Pouzar as the type genus (Jülich, 1982; Li et al., 2022a). He et al. (2019) reported seven genera in *Cystostereaceae*, namely *Cericium* Hjortstam, *Crustomyces* Jülich, *Cystidiodontia* Hjortstam, *Cystostereum*, *Parvobasidium* Jülich, *Parvodontia* Hjortstam & Ryvarden, and *Rigidotubus* J. Song, Y.C. Dai & B.K. Cui. However, later Li et al. (2022a) conducted phylogenetic analyses (ITS and LSU) and recognised only four genera, *Crustomyces*, *Cystostereum*, *Effusomyces*, and *Parvodontia*. Members of this family are characterised by effused to effused-reflexed basidiomata with smooth, odontoid, hydnoid, or poroid hymenium, monomitic or dimitic hyphal system, clamped generative hyphae, gloeocystidia or hyphidia, and smooth and inamyloid basidiospores (Li et al., 2022a). Members of *Cystostereaceae* are saprophytic on woody plants, causing white rot, and are distributed worldwide (Li et al., 2022a).

5.3.1.12 *Parvobasidium* Jülich

Index Fungorum, Facesoffungi, MycoBank, Fig. 5.11

Classification: *Cystostereaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Parvobasidium is a small genus established by W. Jülich, with its type species *P. cretatum* (Jülich, 1975; Li et al., 2022a). The type species was originally described as *Gloeocystidium cretatum*, based on specimens collected on rotten rachis of *Polystichum felix-femina* and *Polystichum spinulosum* in France (Jülich, 1975). *Parvobasidium* is a wood-rotting genus with a widespread distribution, mainly across Europe, including the Netherlands, Spain, Portugal, and Italy (Stalpers, 1985; Telleria & Duenas, 1986; Saitta et al., 2011; He et al., 2019).

Species of *Parvobasidium* are characterised by resupinate basidiomata, which are effused, adnate, and membranous (Jülich, 1975). The hymenial surface is smooth and cream-coloured (Jülich, 1975). Basidiospores are smooth, hyaline, small, thin-walled, and inamyloid (Jülich, 1975; Li et al., 2022a). Basidia are hyaline, small, and thin-walled and

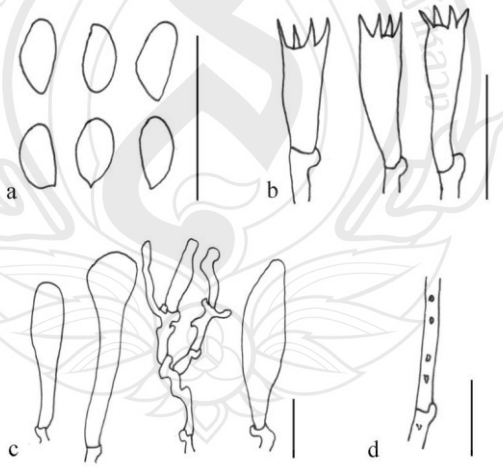
possess a basal clamp (Jülich, 1975). Gloeocystidia are present and are hyaline and clavate (Jülich, 1975). The hyphal system is monomitic, consisting of clamped generative hyphae (Jülich, 1975; Li et al., 2022a). The hypha is hyaline and thin-walled (Jülich, 1975).

Species delineation within *Parvobasidium* is based solely on macro- and micro-morphological characteristics due to the lack of molecular sequences (He et al., 2019). Jülich (1979) proposed a new combination, *P. lundellii* (Ryv. & Solheim) Jülich, for *Physodontia lundellii* Ryvarden & H. Solheim, but it is currently not accepted (Species Fungorum, 2024). Stalpers (1985) introduced another new combination, *P. lianicola*, based on a specimen originally classified as *Corticium lianicola* G. Cunn. Index Fungorum (2025) lists three records of *Parvobasidium,* while Hyde et al. (2024a) recognised only two species.

Type species: *Parvobasidium cretatum* (Bourdot & Galzin) Jülich

Basionym: *Gloeocystidium cretatum* Bourdot & Galzin

Other accepted species: *P. lianicola* (G. Cunn.) Stalpers



Note a Basidiospores. b Basidia. c Gloeocystidia. d Hyphae with clamp connection. Scale bar: a–d = 10 μm.

Source Redrawn from Jülich (1975). For original basidiomata, refer to Banco de setas (www.bancodeseteas.es).

Figure 5.11 *Parvobasidium cretatum*

Hydnangiaceae Gäum. & C.W. Dodge, *Comp. Morph. Fungi* (London): 485

Hydnangiaceae was established by E.A. Gäum. and C.W. Dodge in 1928 with *Hydnangium* Wallr. as the type genus (Gäumann & Dodge, 1928). The family consists of four genera: *Hydnangium*, *Laccaria* Berk. & Broome, *Maccagnia* Mattir., and *Podohydnangium* G.W. Beaton, Pegler & T.W.K. Young (He et al., 2019). *Hydnangiaceae* accommodates approximately 114 recognised species distributed worldwide and are ectomycorrhizal with several hosts, including *Betulaceae*, *Dipterocarpaceae*, *Fagaceae*, *Myrtaceae*, *Pinaceae*, *Salicaceae*, and *Tiliaceae* (Ramos et al., 2017; Hyde et al., 2024a; Thapa et al., 2024a). Some species, such as *L. amethystina* Cooke, *L. aurantia* Popa, Rexer, Donges, Zhu L. Yang & G. Kost, *L. bicolor* (Maire) P.D. Orton, *L. moshuijun* Popa & Zhu L. Yang, *L. vinaceoavellanea* Hongo, are edible and widely consumed (Wu et al., 2019a; Zhang et al., 2023a; Thapa et al., 2024a). Ecologically, some *Laccaria* species grow in heavy metal-polluted areas and play a key role in the ecological progression of forest ecosystems (Zhang et al., 2023a; Thapa et al., 2024a).

5.3.1.13 *Maccagnia* Mattir

Index Fungorum, Facesoffungi, MycoBank

Classification: *Hydnangiaceae*, *Agaricales*, *Agaricomycetidae*, *Agaricomycetes*, *Agaricomycotina*, *Basidiomycota*, Fungi

Maccagnia is a monotypic gasteroid genus erected by Mattirolo in 1922 (Dodge & Zeller, 1936). The only known species and generic type is *Maccagnia carnica* Mattirolo, collected in Italy (Singer, 1959a).

Maccagnia is morphologically characterised by small, spherical fructifications that dry hard and horny, a highly developed columella, and abundant lactiferous ducts (Dodge & Zeller, 1936). The cavities are filled with small hyaline, thick-walled basidiospores on zig-zag hyphae, which soon form a gel where the basidia and basidiospores are later borne (Dodge & Zeller, 1936). These basidiospores are subglobose to short-ellipsoid, oblong, or spherical and vaguely angular in polar view (Singer, 1959a). They are rather small and echinate, with a thick epispore (Dodge &

Zeller, 1936). The hilar appendage is symmetrically attached or slightly off-centre (Singer, 1959a). These basidiospores are hyaline to pale honey-colored, featuring fine spinules or low warts that give them a rough texture under oil immersion. Their ornamentation is non-amyloid and resembles that found in *Lepista* (Fr.) Sm. (Singer, 1959a). The basidia are clavate and bear four slender, straight sterigmata. There are no cystidia or pseudocystidia (Singer, 1959a). The subhymenium lacks cellular differentiation, while the hymenophoral trama is composed of interwoven filamentous hyphae, some of which are swollen (Singer, 1959a). These elements are mostly hyaline, with some exhibiting a honey-colored pigment (Singer, 1959a). Unlike *Russulaceae* Lotsy, or *Arcangeliella* Cavara, the oleiferous hyphae do not contain true oleiferous or laticiferous structures but may turn greenish in iodine (Singer, 1959a). The peridium consists of tangentially arranged filamentous hyphae interwoven with spherocyst-like elements, but does not exhibit the heteromerous structure seen in *Russula* Pers. (Singer, 1959a). The columella is composed of interwoven filamentous and spherocyst-like hyphae, appearing denser rather than distinctly gelatinous (Singer, 1959a). Clamp connections are present, and none of the hyphal structures exhibit amyloid or amylaceous properties (Singer, 1959a). *Maccagnia* appears intermediate between *Sclerogaster* Hesse, *Leucogaster*, and *Arcangeliella*, having the spores and texture of a *Sclerogaster*, the general ontogeny of a *Leucogaster*, and the columella and lactiferous ducts of an *Arcangeliella* (Dodge & Zeller, 1936).

Type species: *Maccagnia carnica* Mattir.

5.3.1.14 *Podohydnangium* G.W. Beaton, Pegler & T.W.K. Young

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.12

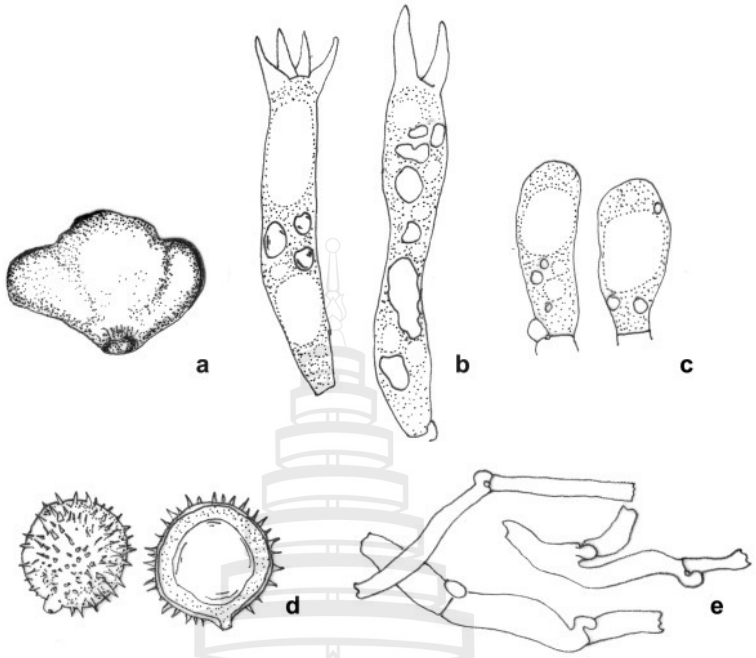
Classification: *Hydnangiaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Podohydnangium is a monotypic gasteroid genus established by G.W. Beaton, Pegler & T.W.K. Young, with *P. australe* as the type species (Beaton et al., 1984). The type specimen of *Podohydnangium* was collected under litter in a wet *Eucalyptus* forest in Victoria, Australia (Beaton et al., 1984). The basidiomata are subepigeal,

hemiangiocarpic, small, globose to turbinate or stipitate, with gleba progressively exposed towards the base (Beaton et al., 1984). The peridium is very thin, membranous, and pale, and eventually flakes away (Beaton et al., 1984). Gleba is concolourous, non-gelatinised, and consists of radially arranged chambers (Beaton et al., 1984). Chambers are small, irregular, anastomosing, and hollow (Beaton et al., 1984). Columella is present, ranging from partially to completely percurrent (Beaton et al., 1984). Hymenophoral trama are regular and hyaline (Beaton et al., 1984). Peridiopellis is composed of undifferentiated, agglutinated hyphae (Beaton et al., 1984). Basidia are elongated and bear 2 or 4 sterigmata (Beaton et al., 1984). Spore deposit is white to cream (Beaton et al., 1984). Basidiospores are orthotropic, statismosporic, globose, hyaline, inamyloid, and non-dextrinoid, with crowded and hyaline spine ornamentation (Beaton et al., 1984). Clamp connections are present in all hyphae (Beaton et al., 1984).

Both morphological and phylogenetic analyses (ITS, *rpb2,* and *tef-1α*) have been employed to delimit *Podohydnangium* species and *Hydnangium* and *Laccaria* (Sheedy et al., 2013). *Podohydnangium* is an intermediate genus between the agaricoid genus *Laccaria* Berk. & Broome (*Tricholomataceae*) and the gasteroid genus *Hydnangium* Wallr. (Beaton et al., 1984). The basidiomata of *Hydnangium* (hypogeous or subepigeous, angiocarpous, truffle-like) and *Laccaria* (epigeous, hemiangiocarpous, agaricoid) differ from those of *Podohydnangium* (Beaton et al., 1984; Bougher et al., 1993). *Podohydnangium* differs from *Laccaria* in its lack of lamellate hymenophore and poorly developed stipe (Beaton et al., 1984). Basidiospores are forcibly ejected in *Laccaria*, a feature absent in the other two genera (Bougher et al., 1993).

Type species: *Podohydnangium australe* G.W. Beaton, Pegler & T.W.K. Young



Note a Basidiomata, ×1. b Basidia, ×1000. c Basidioles, ×1000. d Basidiospores, ×1750. e Glebal hyphae, ×500.

Source Redrawn from Beaton et al. (1984).

Figure 5.12 *Podohydnangium australe* (Beaton 48)

Hygrophoraceae Lotsy, *Vortr. bot. Stammesgesch.* 1: 705

Hygrophoraceae was established by J.P. Lotsy in 1907 with the type genus *Hygrophorus* Fr. (Lotsy, 1907). Lodge et al. (2014) reported 25 genera with over 600 species. However, Hyde et al. (2024a) recognised only 86 species worldwide, distributed in six genera: *Aeruginospora* Höhn., *Haasiella* Kotl. & Pouzar, *Hygrocybula* De la Peña-Lastra, A. Mateos & Plaza, *Hygrophorus*, *Melanomphalia* M.P. Christ., and *Semiomphalina* Redhead. *Hygrophoraceae* is characterised by gymnocarpous or secondarily mixangiocarpous basidiomata, with subdecurrent to deeply decurrent lamellae, divergent or bidirectional hymenophoral trama, and a pachypodial structure below the active hymenium (Vizzini et al., 2024). Basidiospores are thin- or thick-walled, inamyloid, metachromatic or not, hyaline or lightly pigmented (Vizzini et al., 2024).

Hygrophorus forms either saprotrophic or ectomycorrhizal associations with trees (Tedersoo et al., 2010; Seitzman et al., 2011). Some genera form lichens with green algae or cyanobacteria, while others associate with ferns, grasses, and bryophytes (Lawrey et al., 2009; Lodge et al., 2014). Species of *Hygrophoraceae* are distributed worldwide (He et al., 2019).

5.3.1.15 *Cantharellula* Singer

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.13

Classification: *Hygrophoraceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Cantharellula was established by Rolf Singer in 1936, with *C. umbonata* as its type species (Singer, 1938). These fungi are gregarious and form ectomycorrhizal associations, primarily with bryophytes (Singer, 1938; Lawrey et al., 2009; Lodge et al., 2014). Species of *Cantharellula* are distributed globally, mainly in temperate regions (He et al., 2019). Index Fungorum (2025) lists 18 records of *Cantharellula*, but Hyde et al. (2024a) have recognised only ten species worldwide. The classification of *Cantharellula* under Index Fungorum and GenBank lists it under the family *Hygrophoraceae*, whereas MycoBank and Hyde et al. (2024a) have classified it under the family *Cantharellulaceae* (Lodge, Redhead & Desjardin) Vizzini, Consiglio & P. Alvarado.

Cantharellula is characterised by clitocyboid basidiomata, which feature a convex, indented, or infundibuliform, opaque pileus (Lodge et al., 2014). The surface of the pileus and stipe is typically yellowish or greyish brown (Lodge et al., 2014). The lamellae are decurrent, frequently forked, and often turn reddish-brown when stained (Lodge et al., 2014). The stipe is either fleshy or fleshy-fibrous (Lodge et al., 2014). Basidiospores are smooth, hyaline, cylindrical or ellipsoid-oblong, amyloid, acyanophilic, and produce a white deposit (Lodge et al., 2014). The basidia are four times longer than the basidiospores, and both cheilocystidia and pleurocystidia are absent (Lodge et al., 2014). The lamellar trama is sub-gelatinised at the edge, featuring a subregular central strand, tridirectional lateral strands, and hyphae that are interwoven with vertically oriented hyphae and others that diverge perpendicularly from the vertical

ones (Lodge et al., 2014). The subhymenium consists of short or long-celled, mostly parallel hyphal segments aligned with the basidia (Lodge et al., 2014). Clamp connections are present (Lodge et al., 2014).

In addition to the morphological traits, phylogenetic analyses (ITS, LSU, SSU, and *rpb2*) result in strong support for *Cantharellula* as a sister clade to *Pseudoarillariella* (Singer) Singer (Lodge et al., 2014). Morphologically, both genera share long, smooth amyloid basidiospores and tridirectional lamellar trama (Lodge et al., 2014). However, *Cantharellula* is distinct from *Chrysomphalina* in its amyloid spore reaction and the presence of clamp connections (Lodge et al., 2014). Additionally, *Cantharellula* differs from *Chrysomphalina* and *Pseudoarmillariella* in lacking encrusting pigments on the cuticular hyphae while exhibiting bright ochraceous pigments in the hymenium (Lodge et al., 2014).

Type species: *Cantharellula umbonata* (J.F. Gmel.) Singer

Basionym: *Merulius umbonatus* J.F. Gmel.

Other accepted species:

C. alpina G. Stev.

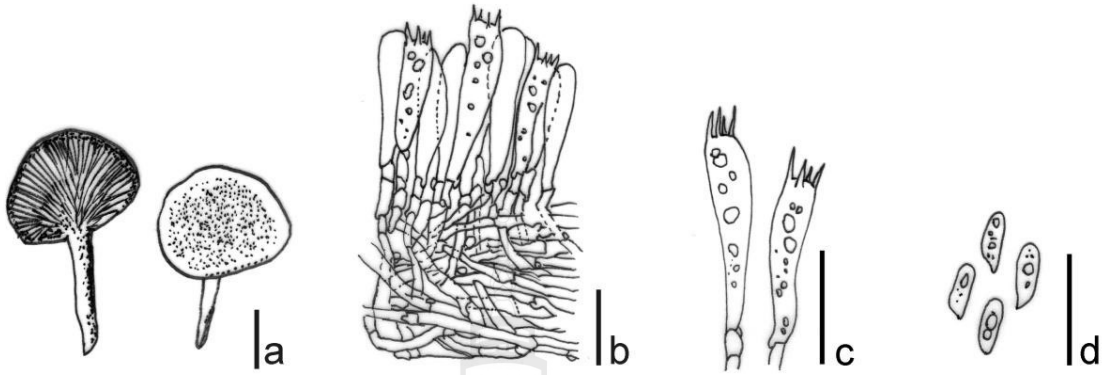
C. coprophila (Speg.) Singer

C. felleoides (Kauffman) Singer

C. infundibuliformis Singer

C. oregonensis (Murill) Singer

C. waiporiensis (G. Stev.) E. Horak



Note a. Basidiomata. b Cross-section of lamella. c Basidia. d Basidiospores. Scale bar: a = 1 cm, b−d = 20 µm.

Source Redrawn from Lodge et al. (2014).

Figure 5.13 *Cantharellula umbonata* (RDY-1366)

5.3.1.16 *Gliophorus* Herink

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.14

Classification: *Hygrophoraceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Gliophorus was established by J. Herink, with *G. psittacinus* as its type species (Herink, 1958; Lodge et al., 2014). This species was initially described based on specimens collected in Germany and classified as *Agaricus psittacinus* (Herink, 1958; Lodge et al., 2014). *Gliophorus* are saprotrophic and have a global distribution (He et al. 2019). This fungus is commonly found in grasslands (Ainsworth et al., 2013). They are often referred to as waxcap fungi due to their waxy or slimy texture and frequently vibrant colours (Ainsworth et al., 2013). Based on morphological characteristics and phylogenetic analyses, *Gliophorus* has been divided into three sections: *Gliophorus* Herink, sect. *Glutinosae* (Kühner) Lodge & Padamsee, and sect. *Unguinosae* Herink (Lodge et al., 2014). Species in sect. *Gliophorus* are characterised by conico-campanulate to convex pileus, some plano-convex with or without umbo, and colours typically green, purple, salmon or brick red (Lodge et al., 2014). Species of sect. *Unguinosae* have a grey-

brown pileus, while sect. *Glutinosae* have conico-campanulate or convex pileus (Lodge et al., 2014).

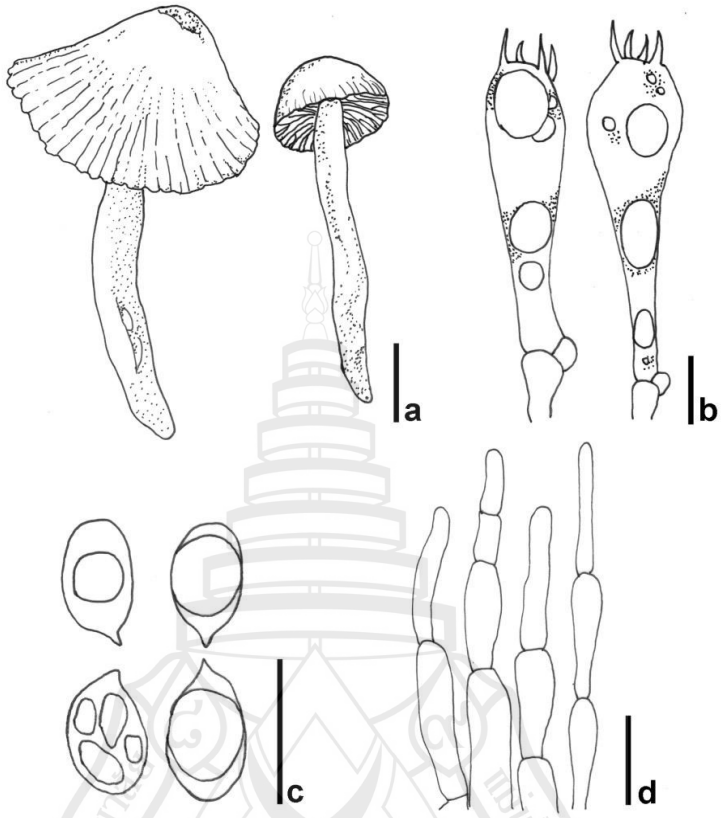
The basidiomata of *Gliophorus* display a variety of colours, including blue, violet, pink, salmon, green, ochre yellow, yellow, brick red, grey-brown, or their combination, but not bright red (Lodge et al., 2014). The pileus surface is viscid to glutinous (Lodge et al., 2014). Basidiospores are smooth, hyaline, thin-walled, inamyloid, and typically ellipsoid to ovoid, occasionally constricted, and not metachromatic (Lodge et al., 2014; Singh et al., 2017; Chakraborty et al., 2018). The basidia are primarily 4-spored, with basal clamp connections, and are about five times longer than the basidiospores (Lodge et al., 2014). Lamellae are narrowly or broadly attached, sinuate or decurrent, and sometimes gelatinised at the edges (Lodge et al., 2014; Singh et al., 2017; Chakraborty et al., 2018). Ixocheilocystidia may or may not be present, and tramal hyphae are subregular (Lodge et al., 2014; Singh et al., 2017; Chakraborty et al., 2018). The pileipellis is an ixotrichoderm with toruloid clamps. Clamp connections are present but occasionally rare in the trama (Lodge et al., 2014). Odour is absent or has a smell resembling burned rubber (Lodge et al., 2014).

Chakroborty et al. (2018) used morphological characteristics and phylogenetic analyses (ITS) to delineate species within *Gliophorus*. Index Fungorum (2025) lists 56 records of *Gliophorus,* while Hyde et al. (2024a) recognised only 15 species worldwide. Ecologically, *Gliophorus* is valued as a bio-indicator of the conservation status of grasslands or meadows (Adamčík & Kautmanová, 2005; Fuljer et al., 2019).

Type species: *Gliophorus psittacinus* (Schaeff.) Herink

Basionym: *Agaricus psittacinus* (Schaeff.) Herink

Other accepted species: (Species Fungorum – search *Gliophorus*)



Note a Basidiomata. b Basidia. c Basidiospores. d Terminal elements of pileipellis. Scale bar: a = 10 mm, b–c = 10 µm, d = 25 µm.

Source Redrawn from Singh et al. (2017).

Figure 5.14 *Gliophorus flavoviridis* (US 1367, holotype)

5.3.1.17 *Humidicutis* (Singer) Singer

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.15

Classification: *Hygrophoraceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Humidicutis was established by Rolf Singer in 1959 with *H. marginata* as the type species. This genus was originally described based on specimens collected from soil in New York, USA, and classified as *Hygrophorus marginatus* Peck (Singer, 1958a).

Species of *Humidicutis* have a global distribution and are saprotrophic in habitat (He et al., 2019).

Species of *Humidicutis* are characterised by sub-hygrophanous, moist, occasionally viscid basidiomata, which are often brightly coloured or greyish brown (Lodge et al., 2014; Yuan et al., 2020). The pilei are typically convex, convex-umbonate, or conic, with margins that are rarely or not deeply splitting (Lodge et al., 2014; Yuan et al., 2020). Lamellae are thick, sinuate or broadly adnate, often featuring a decurrent tooth (Lodge et al., 2014; Yuan et al., 2020). Basidiospores are ellipsoid to broadly ellipsoid, hyaline, thin-walled, inamyloid, non-constricted, and not metachromatic (Lodge et al., 2014; Yuan et al., 2020). Basidia are usually five or more times longer than basidiospores (Lodge et al., 2014; Yuan et al., 2020). Lamellar trama are sub-regular or regular, rarely tapered, and possess right-angled septa (Lodge et al., 2014; Yuan et al., 2020). The cuticular hyphae usually contain carotenoid pigments and may also exhibit encrusting pigments that are insoluble in alkaline solutions (Lodge et al., 2014; Yuan et al., 2020). Pileipellis hyphae are parallel, prostrate, and cylindrical (Lodge et al., 2014; Yuan et al., 2020). Clamp connections are absent in context and pellis but are present as toruloid clamps at the base of basidia and/or basidioles (Lodge et al., 2014; Yuan et al., 2020). These fungi have either no odour or a mildly disagreeable one (Lodge et al., 2014; Yuan et al., 2020).

Humidicutis is distinct from *Hygrocybe* (Fr.) P. Kumm., due to clamp connections only at the base of basidia and differences in pigment composition (absence of muscaflavin in basidiomata) (Desjardin & Hemmes, 1997). Index Fungorum (2025) lists 34 records of *Humidicutis*, while Hyde et al. (2024a) recognised 22 species worldwide.

Reschke et al. (2021) described a new species, *H. roseorubra* Reschke & C.W. Fisch., based on morphological and phylogenetic analyses. This species is distinct from other species of *Humidicutis* by the combination of conical, rose-red basidiomata, basidia with long sterigmata, and ellipsoidal to ovoid basidiospores (Reschke et al., 2021). Cardoso et al. (2023) described another new species, *H. pindorama* J.S. Cardoso,

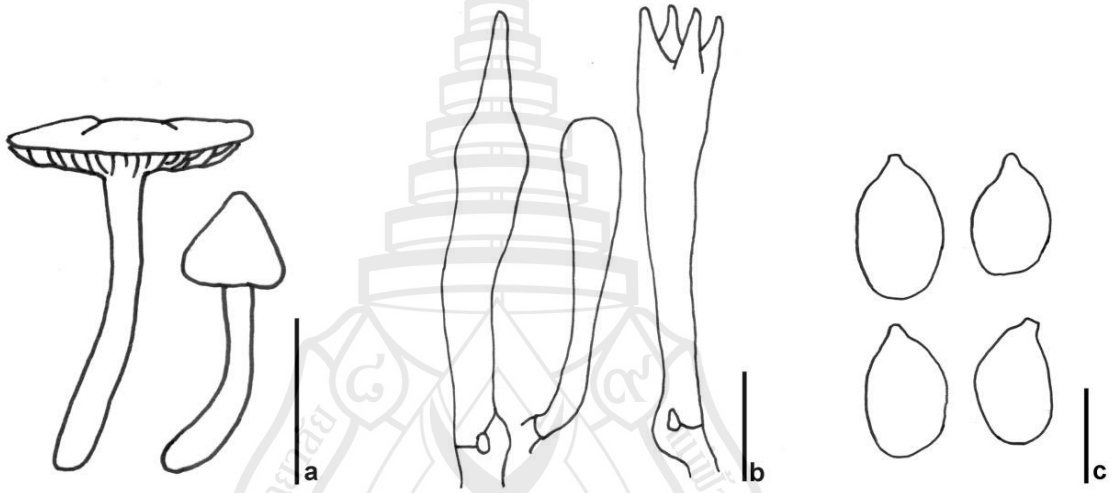
M.A. Neves & J.S. Oliveira, based on morphological characteristics and phylogenetic analyses (ITS).

Synonymy: *Tricholoma* subgen. *Humidicutis* Singer

Type species: *Humidicutis marginata* (Peck) Singer

Basionym: *Hygrophorus marginatus* Peck

Other accepted species: (Species Fungorum – search *Humidicutis*)



Note a Basidiomata. b Basidia and basidioles. c Basidiospores. Scale bar: a = 10 mm, b = 5 µm, c = 10 µm.

Source Redrawn from Desjardin and Hemmes (1997). a = DED 5506, b–c = DEH 492.

Figure 5.15 *Humidicutis peleae*

5.3.1.18 *Hygroaster* Singer

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.16

Classification: *Hygrophoraceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Hygroaster was established by R. Singer in 1955, with *H. nodulisporus* as its type species (Singer, 1955). This specsies was originally described from soil samples collected in Trinidad and Tobago (Singer, 1955). Subsequently, Lodge et al. (2014) revised the genus, excluding temperate species with bright pigments and sub-angular

basidiospores. In addition, the initial combination of *Hygrophorus nodulisporus* under *Hygroaster* was invalid and later formally validated (Ralaiveloarisoa et al., 2020). Members of this genus are saprobic and are found in tropical forests across Argentina, Brazil, China, Colombia, India, Madagascar, and Sweden (Niveiro & Alberto, 2012; He et al., 2019; Ralaiveloarisoa et al., 2020). The classification of *Hygroaster* is under *Hygrophoraceae* in Index Fungorum and GenBank; however, MycoBank and Hyde et al. (2024a) have synonimised the genus with another genus *Hygrocybe* (Fr.) P. Kumm., under the family *Hygrocybaceae* (Padamsee & Lodge) Vizzini, Consiglio & P. Alvarado.

Hygroaster is characterised by basidiomata with an indented, non-viscid pileus that is fuscous or white, lacking bright pigments (Lodge et al., 2014; Ralaiveloarisoa et al., 2020). The lamellae are thick, decurrent, and either distant or subdistant (Lodge et al., 2014; Ralaiveloarisoa et al., 2020). Lamellar trama is subregular, with pigmentation present in the central strand of the pigmented species (Lodge et al., 2014; Ralaiveloarisoa et al., 2020). Basidiospores are subglobose to globose, with long, conical spines that have blunt or acute apices, hyaline, inamyloid, and not cyanophilous (Lodge et al., 2014; Ralaiveloarisoa et al., 2020). Basidia are clavate, hyaline, and bear 2–4 sterigmata (Ralaiveloarisoa et al., 2020). Pileipellis hyphae are lightly encrusted and lack cystidia; clamp connections are absent (Lodge et al., 2014; Ralaiveloarisoa et al., 2020).

Ralaiveloarisoa et al. (2020) described two new species, *H. madagascarensis* and *H. andasibensis*, from Madagascar using morphological characteristics and phylogenetic analyses (ITS). Index Fungorum (2025) lists 17 records of *Hygroaster*, whereas Species Fungorum (2025) recognises only 10 species worldwide. *Hygroaster* is closely related to *Hygrocybe* (Fr.) P. Kumm. However, the latter is distinct by having smooth basidiospores and the presence of clamp connections (Ralaiveloarisoa et al., 2020).

Type species: *Hygroaster nodulisporus* (Dennis) Singer

Basionym: *Hygrophorus nodulisporus* Dennis

Other accepted species:

H. agrumbensis Sathe & S.M. Kulk.

H. albellus Singer

H. andasibensis Ralaiv., Niskanen & Liimat.

H. cleefii Franco-Mol. & López-Quint.

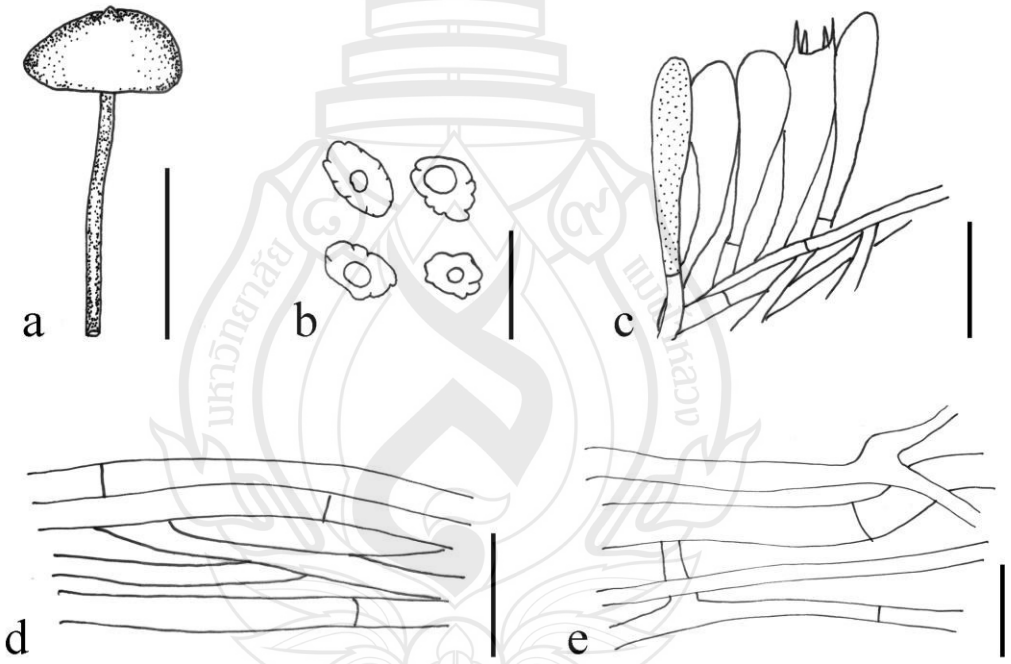
H. iguazuensis B.E. Lechner & J.E. Wright

H. lacteus E. Ludw. & Ryberg

H. madagascarensis Ralaiv., Niskanen & Liimat.

H. sulcatus (Z.S. Bi) T.H. Li & Z.S. Bi

H. trachysporus Z.S. Bi



Note a Basidiomata. b Basidiospores. c Basidia, basidioles, pseudocystidia. d Pileipellis. e Hyphae from the context. Scale bar: a = 1.5 cm, b = 20 µm, c–e = 10 µm.

Source Redrawn from Lechner et al. (2005). For original basidiomata, refer to Lechner et al. (2005).

Figure 5.16 *Hygroaster iguazuensis*

5.3.1.19 *Hygrophorus* Fr.

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.17

Classification: *Hygrophoraceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Hygrophorus was originally described by Fries (1836) as the type genus of the family *Hygrophoraceae* Lotsy. (Fries, 1836a; Lodge et al., 2014). The type species, *H. eburneus*, was initially described as *Agaricus eburneus* Bull. (Bulliard, 1783). Singer (1986) provided the authentic generic concept of *Hygrophorus* within *Hygrophoraceae*, as divergent tramenophoral trama, ectomycorrhizal habit, and commonly clamped hyphae. Members of *Hygrophorus* are ectomycorrhizal with a worldwide distribution, mainly in temperate regions of the Northern Hemisphere (Endo et al., 2018; He et al., 2019).

The genus has undergone several taxonomic revisions. Fries (1836a) divided it into three subgenera: subg. *Hygrophorus* Fr., subg. *Colorate* (Bataille) E. Larss., and subg. *Camarophylli* Fr. Hesler and Smith (1963) further subdivided the genus into eight subsections based on morphology. Later, taxonomic arrangements have been changed by several authors (Bresinsky & Huber, 1967; Arnolds, 1986b; Singer, 1986; Horak, 1990; Kovalenko, 2012). Based on molecular analyses, *Hygrophorus* has a monophyletic lineage (Lodge et al., 2014; Endo et al., 2018). Index Fungorum (2025) lists 1033 records of *Hygrophorus*; however, He et al. (2019) recognised only 200 species worldwide. Wang et al. (2023a) described 26 new species, based on a combination of morphological characteristics and phylogenetic analyses (ITS, LSU, *rpb2*, and *tef1-α*).

Members of *Hygrophorus* are characterised by tricholomatoid, collybioid, clitocyboid, or omphalinoid basidiomata, ranging from small to large, thin to fleshy, and dry to very glutinous or viscid (Singer, 1986; Kovalenko, 2012; Sesli et al., 2018). The pileus varies in colour from whitish, grey, brownish, yellowish, orange, or reddish, and is dry to moderately sticky (Singer, 1986; Kovalenko, 2012; Sesli et al., 2018). The lamellae are adnate to decurrent, thick, waxy, and usually whitish, sometimes yellowish or pinkish (Singer, 1986; Kovalenko, 2012; Sesli et al., 2018). The stipe is dry to

glutinous, glabrous to fibrillose, and often pruinose or granulose (Singer, 1986; Kovalenko, 2012; Sesli et al., 2018). The basidia are narrowly clavate, while basidiospores are hyaline, smooth, and inamyloid (Singer, 1986; Kovalenko, 2012; Sesli et al., 2018).

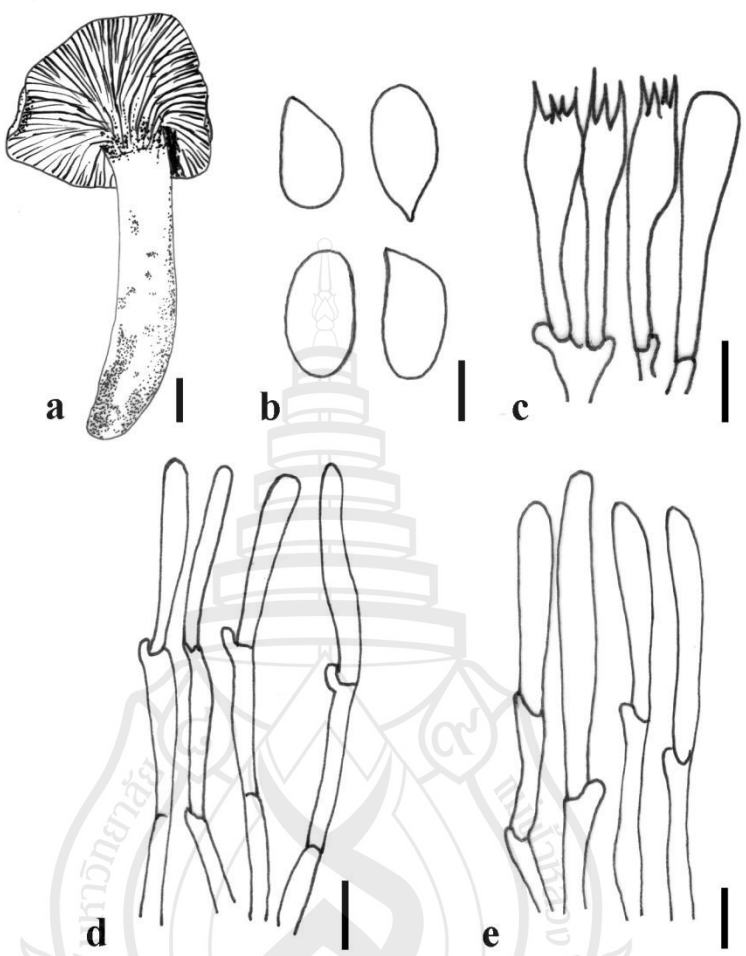
Members of *Hygrophorus* have ecological and economic significance. Several species, such as *H. annulatus* C.Q. Wang & T.H. Li, *H. eburneus* (Bull.) Fr., and *H. yukishiro* N. Endo, Tokoo & A. Yamada are edible (Yamada, 2002). *Hygrophorus eburneus* has also been reported to exhibit medicinal properties, including neuroprotective, antimicrobial, antioxidative, and anticancer activities (Kosanic et al., 2020). Additionally, bioactive compounds have been isolated from species of this genus. For example, acylcyclopentenedione derivatives with antifungal activity were obtained from *H. chrysodon* (Batsch) Fr. (Gilardoni et al., 2007).

Synonymy: *Agaricus* + *Camarophyllus* Fr. ex Rabenh., *Agaricus* +++ *Limacium* Fr. ex Rabenh., *Agaricus* subtrib. *Camarophylli* Fr., *Agaricus* trib. *Limacium* Fr., *Camarophyllus* (Fr.) P. Kumm., *Hygrophorus* subgen. *Camarophyllus* Fr., *Hygrophorus* subgen. *Limacinus* Quél., *Limacinus* (Quél.) Marchand, *Limacium* (Fr. ex Rabenh.) P. Kumm.

Type species: *Hygrophorus eburneus* (Bull.) Fr.

Basionym: *Agaricus eburneus* Bill.

Other accepted species: (Species Fungorum – search *Hygrophorus*)



Note a Basidiomata. b Basidiospores. c Basidia and basidioles. d Pileipellis. e Stipitipellis. Scale bar: a = 1.5 cm, b = 4.5 µm, c = 2 µm. d = 13.7 µm. e = 7.8 µm.

Source Redrawn from Naseer et al. (2019). For original basidiomata, refer to Naseer et al. (2019).

Figure 5.17 *Hygrophorus alboflavescens* (LAH35243, holotype)

5.3.1.20 *Pseudoarmillariella* (Singer) Singer

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.18

Classification: *Hygrophoraceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Pseudoarmillariella is a small genus established by R. Singer in 1956, with *P. ectypoides* as its type species (Singer, 1956). The classification of this genus remained unclear until Norvell et al. (1994) and Redhead et al. (2002) clarified its genetic boundaries. Subsequent phylogenetic studies confirmed its placement within *Hygrophoraceae* (Matheny et al., 2006; Lawrey et al., 2009; Yang et al., 2013). Lodge et al. (2014) revised the genus to include species characterised by tri-directional lamellar trama and an incipient pachypodial hymenial palisade. Members of this genus are lignicolous and are found across North and Central America and Asia, including the USA, New Zealand, and China (Horak, 1971; Singer, 1986; Kirk et al., 2008; Yang et al., 2013; Lodge et al., 2014). The taxonomic classification of *Pseudoarmillariella* is under *Hygrophoraceae* in Index Fungorum; however, MycoBank and Hyde et al. (2024a) have placed it under *Cantharellulaceae* (Lodge, Redhead & Desjardin) Vizzini, Consiglio & P. Alvarado.

Pseudoarmillariella is characterised by omphalinoid basidiomata with deeply infundibuliform, opaque pileus and a yellowish or greyish brown, appressed-fibrillose stipe surface (Lodge et al., 2014). The lamellae are decurrent, repeatedly forked, and exhibit a deep ochraceous or yellowish clay colouration (Lodge et al., 2014). The stipe is either central or eccentric (Lodge et al., 2014). Basidiospores are smooth, hyaline, amyloid, and acyanophilic, and appear white in deposit (Lodge et al., 2014). Both cheilocystidia and pleurocystidia are absent (Lodge et al., 2014). Pileipellis hyphae are nodulose-encrusted, while lamellar trama is sub-gelatinised at the lamellar edge with a sub-regular central strand toward the pileus and adjacent pileus context (Lodge et al., 2014). The lamellar context features tridirectional strands, with some hyphae parallel to the lamellar edge and others diverging more or less perpendicularly from the vertical hyphae (Lodge et al., 2014). Clamp connections are also present (Lodge et al., 2014).

Yang et al. (2013) described a new species, *Pseudoarmillariella bacillaris,* from China based on morphological characteristics and phylogenetic analyses (ITS and LSU). Currently, the genus includes three recognised species worldwide (He et al., 2019). Morphologically, this genus resembles *Cantharellula* Singer and *Chrysomphalina*

Clémençon (Lodge et al., 2014). However, *Cantharellula* is distinguished by the presence of encrusting pigments on the cuticular hyphae and the presence of bright ochraceous pigments in the hymenium (Lodge et al., 2014). Similarly, *Chrysomphalina* differs from *Pseudoarmillariella* due to the amyloid reaction of its basidiospores and the presence of encrusting pigments on the cuticular hyphae (Lodge et al., 2014).

Synonymy: *Cantharellula* subgen. *Pseudoarmillariella* Singer

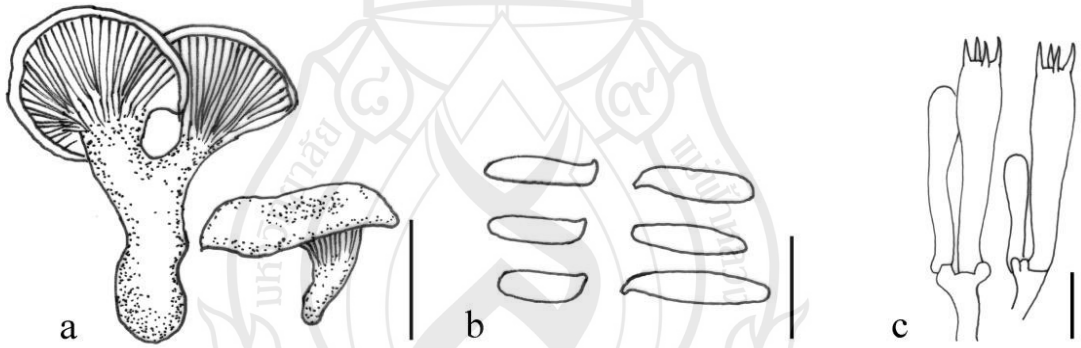
Type species: *P. ectypoides* (Peck) Singer

Basionym: *Agaricus ectypoides* Peck

Other accepted species:

P. bacillaris Zhu L. Yang, B. Feng & Y.J. Hao

P. fistulosa (G. Stev.) E. Horak



Note a Basidiomata. b Basidiospores. c Basidia and basidioles. Scale bar: a = 2 cm, b–c = 10 µm.

Source Redrawn from Yang et al. (2013). For original basidiomata, refer to Yang et al. (2013).

Figure 5.18 *Pseudoarmillariella bacillaris*

Incertae sedis

5.3.1.21 *Calyptella* Quél.

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.19

Classification: *Incertae sedis, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Calyptella was established by Licien Quélet in 1886, although no type species was indicated (Quélet, 1886). In 1951, M.A. Donk designated *C. capula* (Holmsk.) Quél. as the type species, based on a specimen collected in Sweden (Donk, 1952). Species within the genus *Calysptella* are worldwide distributed and are primarily saprobic (He et al., 2019). The taxonomic classification of *Calyptella* is under *Incertae sedis* in Index Fungorum; however, GenBank and Hyde et al. (2024a) have placed it under *Porotheleaceae* Murrill.

Calyptella is characterised by its delicate, stipitate-cupulate, wine-glass-shaped basidiomata (Reid, 1961). To the unaided eye, these appear smooth, but under magnification, they are often sparsely and minutely tomentose (Reid, 1961). The basidiospores are elliptical to pip-shaped, hyaline or subcylindrical (Reid, 1961). Its hyphal system is monomitic, composed of thin-walled, branched, hyaline generative hyphae that are inflated and clamped (Reid, 1961). The outermost hyphae develop small, wart-like swellings along their length, which extend into well-developed, highly branched coralloid structures that cover the external surfaces of the basidiomata (Reid, 1961).

Bodensteiner et al. (2004) combined morphological characteristics with phylogenetic analyses (ITS and LSU) to delineate species within *Calyptella*. Index Fungorum (2025) lists 60 records of *Calyptella*, whereas Species Fungorum (2024) recognises only 29 species worldwide. The classification of *Calyptella* as *Incertae sedis, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* is in agreement with Index Fungorum (2025), UNITE, He et al. (2019), and Wijayawardene et al. (2022). However, the genus has been reclassified under *Porotheleaceae* Murrill (He et al., 2024; Hyde et al., 2024a).

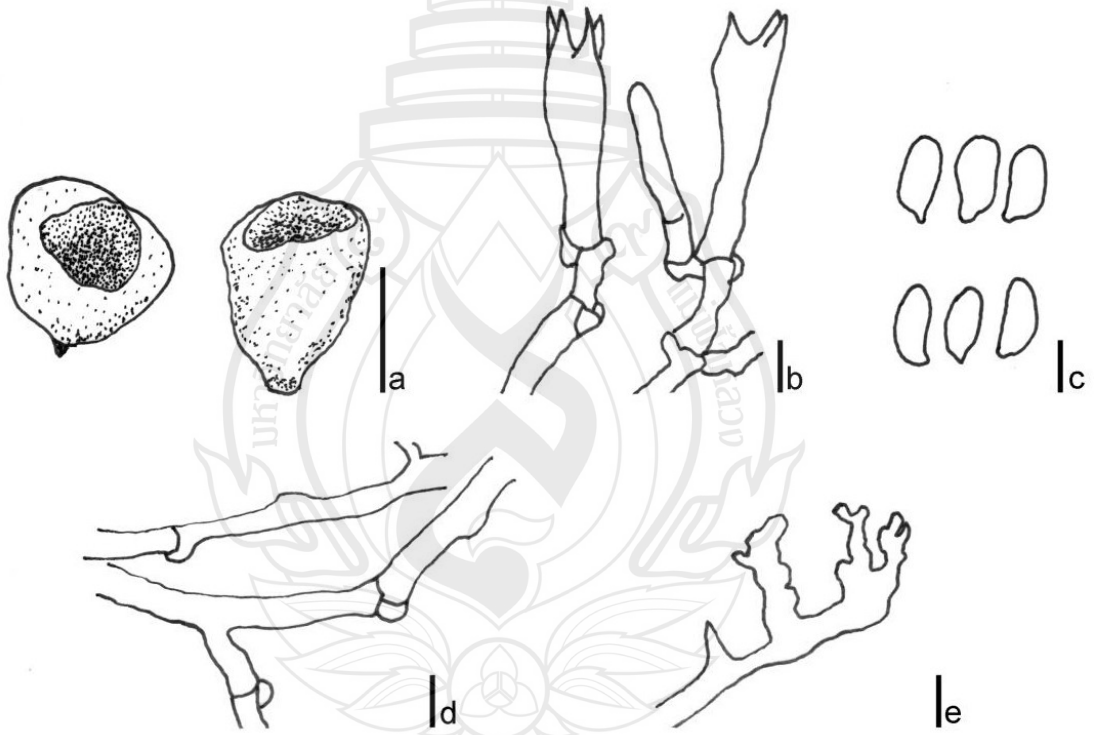
Species of *Calyptella* share similarities with *Stigmatolemma* Kalchbr. and *Resupinatus* Nees ex Gray in the general branching pattern of the surface hyphae (Bodensteiner et al., 2004). However, it is distinguished from these genera by the slight gelatinosity of its basidiomata and the absence of globule-bearing structures (Bodensteiner et al., 2004).

Calyptella campanula has a significant economic impact by causing substantial yield losses in tomatoes (*Lycopersicon esculentum*). Root rot disease in glasshouse-grown tomatoes was first reported in northern England in 1983 (Sandys-Winsch & Jeves, 1992). Additionally, it is known to grow on the stem bases of herbaceous plants across Europe, Russia, and the USA (Cooke, 1961; Sandys-Winsch & Jeves, 1992).

Type species: *C. capula* (Holmsk.) Quél.

Basionym: *Peziza capula* Holmsk.

Other accepted species: (Species Fungorum – search *Calyptella*)



Note a Basidiomata. b Basidia. c Basidiospores. d Generative hyphae. e Hyphal end of a generative hyphae. Scale bar: a = 1 mm, b−e = 5 µm.

Source Redrawn from Lee et al. (2009).

Figure 5.19 *Calyptella capula* (HCCN00010)

5.3.1.22 *Conchomyces* Overeem

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.20

Classification: *Incertae sedis, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

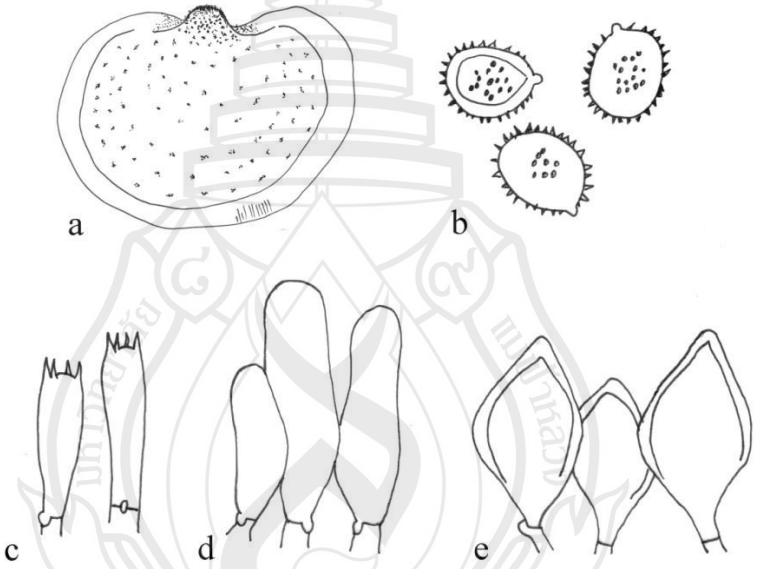
Conchomyces was established by Casper van Overeem in 1927, with its type species, *C. verrucisporus* (Heyne, 1927). The type species was described based on specimens collected from rotten wood in Java, Indonesia (Heyne, 1927). In 1981, Horak reclassified *Agaricus bursiformis* Berk. as *C. bursiformis* (Berk.) E. Horak, with the species collected from bark in Tasmania, Australia (Hooker, 1860; Horak, 1981). Species of *Conchomyces* are saprophytic and distributed across Australasia and southern South America, including New Zealand, New Caledonia, Papua New Guinea, and Chile (Horak, 1981). The classification of this genus has undergone several revisions (Henrici, 2003). Notably, Reid (1963b) transferred *Agaricus bursiformis* to *Hohenbuehelia* Schulzer due to its gelatinous pileus layer and metuloidal pleurocystidia. In 1969, Singer established a new subgenus, *Reidia*, within *Hohenbuehelia,* to accommodate this species, along with his collection from Chile (Horak, 1981). It was also synonymized with *Crepidotus* (Fr.) Staude (Henrici, 2003). However, this genus was revived after the new combination, *Conchomyces bursiformis,* was recognised (Horak, 1981; Henrici, 2003). Phylogenetic analyses (LSU) further supported *Conchomyces* as a distinct genus, separate from others (Moncalvo et al., 2002). The taxonomic classification of *Conchomyces* is under *Incertae sedis* in Index Fungorum and GenBank; however, MycoBank and Hyde et al. (2024a) have placed it under *Fayodiaceae* Jülich.

Species of *Conchomyces* are characterised by a polymorphic shape, starting convex when immature and becoming conchate or fan-shaped upon maturity (Horak, 1981). Stipe is absent, rudimentary or cylindrical in an eccentric position, and concolourous with the pileus (Horak, 1981). Basidiospores are ellipsoid to broadly ovate to subglobose and spinulose, and produce a white spore print (Horak, 1981). Basidia are 4-spored and possess basal clamp connections (Horak, 1981). Chielocystidia are vesiculose, clavate, or uteriform, hyaline, and have thin-walled membranes (Horak,

1981). Pleurocystidia are fusoid, with the apex either pointed or rounded (Horak, 1981). Hyphae exhibit clamp connections (Horak, 1981). Both taste and odour are negligible (Petersen & McCleneghan, 1995). *Conchomyces* shares macro-morphological similarities with *Hohenbuehelia*, *Pleurotopsis* (Henn.) Earle and *Resupinatus* Nees ex Gray (Horak, 1981; Peterson & McCleneghan, 1995). However, they differ by having smooth basidiospores (Horak, 1981).

Type species: *Conchomyces verrucisporus* Overeem

Other accepted species: *C. bursiformis* (Berk.) E. Horak



Note a Basidiomata. b Basidiospores. c Basidia. d Cheilocystidia. e Pleurocystidia.

Source Redrawn from Horak (1981). For original basidiomata, refer to GBIF (2025).

Figure 5.20 *Conchomyces bursiformis* (ZT 72/260)

5.3.1.23 *Cymatella* Pat.

Index Fungorum, Facesoffungi, MycoBank, Fig. 5.21

Classification: *Incertae sedis, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Cymatella was established by N.T. Patouillard in 1899, with its type species, *C. minima* (Patouillard, 1899). This species was described based on specimens collected

from rotten wood in the Antilles, Guadeloupe, France (Patouillard, 1899). In the same year, Patouillard also transferred two species from *Craterellus* Pers. to *Cymatella*, namely *Cymatella marasmioides* (Berk. & M.A. Curtis) Pat. and *Cymatella pulverulenta* (Berk. & M.A. Curtis) Pat. (Patouillard, 1899). In 1944, Martin described another new species, *C. longipes*, later reclassified as *Marasmius martini* Singer (Martin, 1944; Singer, 1958a). Members of *Cymatella* are saprophytic and are predominantly found in tropical regions, including Argentina, Bolivia, Brazil, Cuba, Ecuador, Ghana, Guadeloupe, Puerto Rico, the USA, and Venezuela (Burt, 1924; GBIF, 2025).

Cymatella is characterised by minute, marasmioid, stipitate basidiomata, which revive upon exposure to moisture (Patouillard, 1899; Burt, 1924). Pileus lacks a pellicle, and the hymenium is inferior, lacks lamellae, and is either even or slightly wavy (Burt, 1924). The stipe is filiform, glabrous, black, thickened somewhat towards the base, and eccentrically inserted (Patouillard, 1899). Basidiospores are ovoid, smooth, and hyaline, while basidia are clavate with four sterigmata (Patouillard, 1899). Cystidia are absent (Patouillard, 1899).

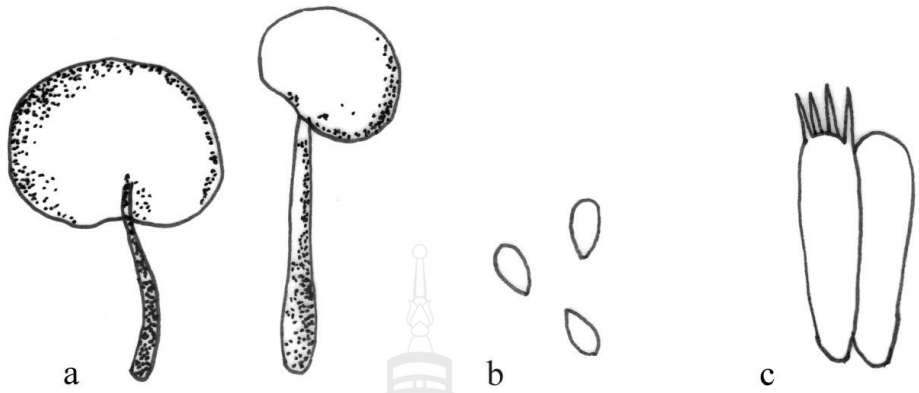
Morphologically, this genus is closely related to *Marasmius* Fr. (Burt, 1924). Species delineation of *Cymatella* from other genera is solely based on macro- and micro-morphology due to the lack of molecular sequences (He et al., 2019). Index Fungorum (2025) lists four records of *Cymatella,* while Hyde et al. (2024a) recognised only one species worldwide.

Type species: *Cymatella minima* Pat.

Other accepted species:

C. marasmioides (Berk. & M.A. Curtis) Pat.

C. pulverulenta (Berk. & M.A. Curtis) Pat.



Note a Basidiomata. b Basidiospores. c Basidia and basidiole.

Source Redrawn from Patouillard (1899). For original basidiomata, refer to GBIF (2025).

Figure 5.21 *Cymatella minima*

5.3.1.24 *Cyphellocalathus* Agerer

Index Fungorum, Facesoffungi, MycoBank, Fig. 5.22

Classification: *Incertae sedis, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Cyphellocalathus is a monotypic genus established by R. Agerer in 1981 with its type species, *C. cecropiae* (Agerer, 1981). Initially, the species was classified within *Lachnella* Fr. as *L. cecropieae* and placed in *Lachnella* sect. *Metuloidifera* Sing. (Singer, 1962a, 1966). This species was first described based on a specimen collected from leaves of *Cecropia* in Bolivia (Agerer, 1981). Additionally, the species has been reported from Colombia (Vasco-Palacios & Franco-Molano, 2013).

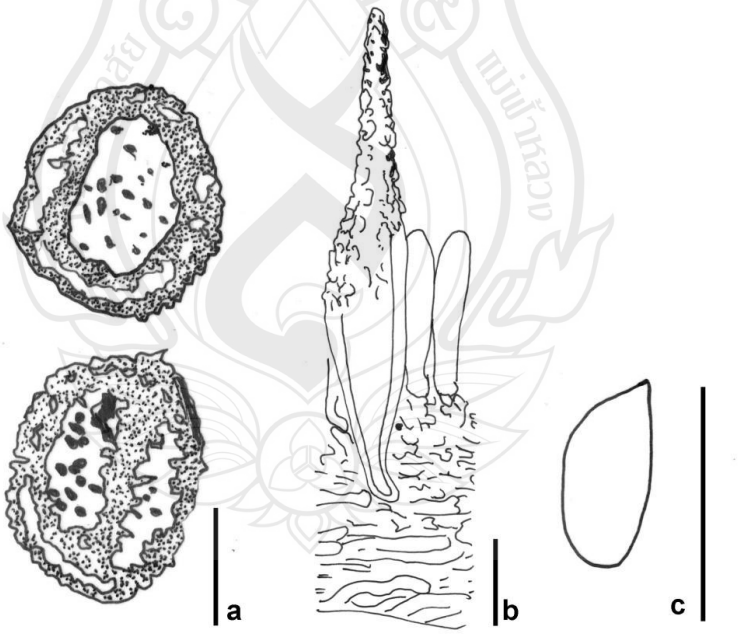
Species of *Cyphellocalathus* are characterised by their white, cup-shaped basidiomata, which may or may not have a stipe (Agerer, 1981). The surface hairs are thick-walled, either scarcely encrusted or without encrustation, and exhibit dextrinoid reactions (Agerer, 1981). The terminal cells of these hairs are rounded (Agerer, 1981). The hymenium features dextrinoid metuloids encrusted with granular, angular crystals or amorphous mass (Agerer, 1981). Notably, crystals found on the surface hairs and hymenium dissolve rapidly in concentrated HCl and slowly in 10% KOH (Agerer, 1981).

Basidiospores are smooth, thin-walled, hyaline, asymmetrically ellipsoidal or ovoidal, and neither amyloid nor dextrinoid (Agerer, 1981). Basidia are suburniform and do not exceed 50 µm long (Agerer, 1981).

The identification of *Cyphellocalathus* species relies entirely on macro- and micro-morphological characteristics due to a lack of molecular sequence (Agerer, 1981; He et al., 2019). *Cyphellocalathus* is distinct from other members of cyphellaceous taxa; *Lachnella australis* Speg., *Chaetocalathus craterellus* (Durieu & Lév.) Singer, *Chaetocalathus liliputianus* (Mont.) Singer, *Crinipellis stipitaria* (Fr.) Pat. and *Rectipilus davidii* (D.A. Reid) Agerer by dextrinoid metuloids in the hymenium (Agerer, 1981). Additionally, it is distinct from *Chaetocalathus* Singer by the absence of gills (Agerer, 1981).

Type species: *Cyphellocalathus cecropiae* (Singer) Agerer

Basionym: *Lachnella cecropiae* Singer



Note a Basidiomata. b Section through basidiomata. c Basidiospores. Scale bar: a = 0.6 mm, b–c = 20 µm.

Source Redrawn from Agerer (1981).

Figure 5.22 *Cyphellocalathus cecropiae* (BAFC, holotype)

5.3.1.25 *Lycogalopsis* E. Fisch.

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.23

Classification: *Incertae sedis, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Lycogalopsis was established by Edouard Fischer (1886) with *L. solmsii* as the type species (Fischer, 1886a). The type is considered rare and was described from specimens collected on the fruit of *Parinari scabra* and a tree trunk in Java (Fischer, 1886a; Demoulin et al., 2013). Members of the genus are lignicolous and distributed in tropical regions, including Brazil, Costa Rica, Mexico, and Venezuela (Calonge et al., 2005; He et al., 2019). Currently, Species Fungorum (2025) recognises nine species of *Lycogalopsis*.

Members of *Lycogalopsis* are characterised by gasteroid basidiomata (Demoulin et al., 2013). The base of the basidiomata is sterile and becomes highly developed at maturity (Dodge & Zeller, 1936). A well-developed subiculum is present on firm wood but conspicuous on plant debris (Demoulin et al., 2013). Basidiospores are globose, elongated, or somewhat irregular (Fischer, 1886a; Martin, 1939). Basidia are elongated and 6–7-spored (Fischer, 1886a; Demoulin et al., 2013).

The taxonomic placement of *Lycogalopsis* remains unresolved, and the genus is currently treated as *incertae sedis* (He et al., 2019). In the tenth edition of the Dictionary of Fungi, it was placed in *Agaricaceae* Chevall. (Kirk et al., 2008). Hosaka (2005) suggested placement of *Lycogalopsis* in the gomphoid-phalloid clade, while LSU-based phylogenetic analysis by Demoulin et al. (2013) indicated a closer relationship to *Phallales* E. Fisch. and *Hysterangiales* K. Hosaka & Castellano than to *Geastrales* K. Hosaka & Castellano or *Gomphales* ss Jülich. However, limited sequence data from *Lycogalopsis* has been a limitation for its accurate classification (Demoulin et al., 2013).

Synonymy: *Enteromyxa* Ces.

Type species: *Lycogalopsis solmsii* E. Fisch.

Other accepted species:

L. africana Har. & Pat.

L. dussii Pat.

L. hypostratosa Rick

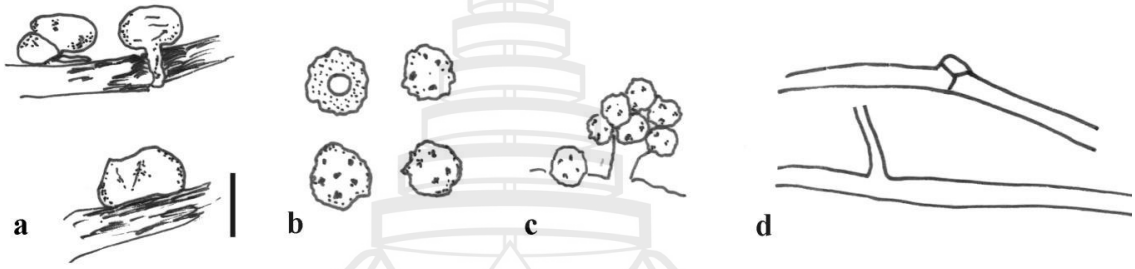
L. hypoxilinoides Rick

L. leopoldensis Rick

L. reticulata Lloyd

L. subiculosa Lloyd

L. zeylanica Petch



Note a Basidiomata. b Basidiospores (×1620). c Basidia with basidiospores (×952). d Hypahe from basal pad of mycelium (×810). Scale bar: a = 1 cm.

Source Redrawn from: a = from Kotlaba and Zehnalek (2018), b–d = Coker and Hill (1930).

Figure 5.23 *Lycogalopsis solmsii*

5.3.1.26 *Skepperiella* Pilát

Index Fungorum, Facesoffungi, MycoBank, Fig. 5.24

Classification: *Incertae sedis, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota*, Fungi

Skepperiella was established by Pilát in 1927, with *S. spathularia* as the type species (Pilát, 1927). The type species was initially classified as *Craterellus spathularius*, described based on specimens collected from dead wood in Cuba (Berkeley & Curtis, 1869). Species of *Skepperiella* are lignicolous saprobes and are distributed in tropical regions (Pegler, 1973). The classification of *Skepperiella* remains uncertain, although Pegler (1973) proposed its inclusion in the family *Tricholomataceae* R. Heim ex Pouzar

(*Agaricales*) based on morphological features such as a monomitic hyphal system with inflated hyphae and the presence of a *Rameales*-type structure on the pileal surface.

Skepperiella is characterised by nutant basidiomata with mesopodal to pleuropodal attachment, featuring a dorsally inserted pseudostipe and a hanging pileus (Pegler, 1973). The pileus is an inverted cupulate, ranging from fleshy-firm to coraceous in texture, convex, smooth to finely pruinose, and varies in colour from white to pale greyish or yellowish (Pegler, 1973). Pileal surface is variable, consisting of repentant to erect hyphal terminations, sometimes forming a *Rameales*-type structure or presenting inflated hyphae (Pegler, 1973). The margin is entire or crenate, straight, inflexed, or reflexed (Pegler, 1973). The hymenium is initially smooth, then becomes plicate or forms anastomosis ridges, and eventually develops a strongly merulioid structure (Pegler, 1973). The stipe is dorsally attached, centrally with strongly excentric attachment, filiform, solid, and ranges from pruinose to glabrous (Pegler, 1973). The context is thin and firm (Pegler, 1973). The hyphal system is monomitic, consisting of clamped generative hyphae that are hyaline, non-gelatinised, non-dextrinoid, and inamyloid (Pegler, 1973). Basidiospores are minute, ovoid to ellipsoid, hyaline, thin-walled, inamyloid, and white in spore print (Pegler, 1973). Basidia are narrowly clavate, typically 4-spored, and occasionally 2-spored (Pegler, 1973). Hymenial cystidia originate from the tramal, emergent, hyaline, thin-walled, and stain positive with aniline blue (Pegler, 1973). Dermatocystidia are scattered across both the pileal and stipe surfaces (Pegler, 1973). The sub-hymenium layer is well-developed, composed of tightly interwoven hyphae (Pegler, 1973).

The identification of *Skepperiella* species is currently based on morphological characteristics, as molecular data remain unavailable (Pegler, 1973; He et al., 2019). Currently, *Skepperiella* accommodates four accepted species worldwide (He et al., 2019). *Skepperiella* is closely related to *Rhodoarrhenia* Singer, but the latter can be distinguished by its gelatinised context and the lack of hymenial cystidia (Pegler, 1973).

Type species: *Skepperiella spathularia* (Berk. & M.A. Curtis) Pilát

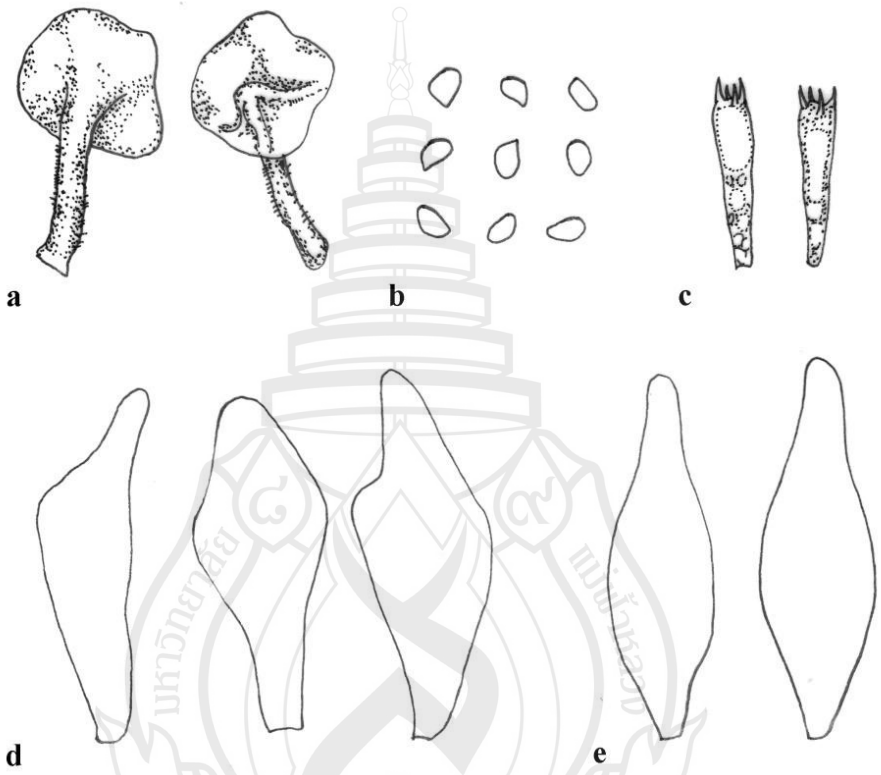
Basionym: *Craterellus spathularius* Berk. & M.A. Curtis

Other accepted species:

S. cochlearis Pegler

S. merulioides (R. Heim) Pegler

S. populi Singer



Note a Basidiomata. b Basidiospores. c Basidia. d Hymenial cystidia. e Pileocystidia. Scale bar: a = ×6, c–e = ×1000.

Source Redrawn from Pegler (1973).

Figure 5.24 *Skepperiella spathularia*

Lycoperdaceae Bercht. & J. Presl, *O Přirozenosti rostlin, aneb Rostlinář* 1: 273

Lycoperdaceae was established by F. Berchtold and J.S. Presl (1820) with *Lycoperdon* Pers. as the type genus (Berchtold & Presl, 1820). He et al. (2019) reported around 430 recognised species in eight genera: *Apioperdon* (Kreisel & D. Krüger)

Vizzini, *Bovista* Pers., *Bryoperdon* Vizzini, *Calbovista* Morse ex M.T. Seidl, *Calvatia* Fr., *Gastropila* Homrich & J.E. Wright, *Lycoperdon*, and *Morganella* Zeller. However, a recent comprehensive study by Yang et al. (2025) divided the family into 19 genera, based on morphological characteristics, phylogenetic analyses (ITS+LSU+*rpb2*+*tef1-α*), and divergence time analyses. *Lycoperdaceae*, commonly known as puffballs, is characterised by globose to subglobose basidiomata, with mature gleba and releasing a powdery mass of basidiospores passively through the apical opening of the endoperidium (Krüger et al., 2001; Yang et al., 2025). Members of *Lycoperdaceae* are distributed worldwide and are found on forest floors, decaying wood, or meadows (Yang et al., 2025). Some species are used in culinary and medicinal purposes, including *Calvatia craniiformis* (Schwein.) Fr. ex De Toni and *C. cyathiformis* (Bosc) Morgan (Yang et al., 2025).

5.3.1.27 *Gastropila* Homrich & J.E. Wright

Index Fungorum, Facesoffungi, MycoBank, Fig. 5.25

Classification: *Lycoperdaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Gastropila, established by Homrich and J. E. Wright in 1973, was originally classified as *Pila* Speg. (Homrich & Wright, 1973). The type species, *Gastropila fragilis* (≡ *Mycenastrum fragile* Lév.), was based on a specimen collected on soil in Uruguay (Homrich & Wright, 1973). Later, Ponce de Leon (1976) described three new species, *G. fumosa*, *G. hesperia*, and *G. subcretacea*. These species are found solitary or gregarious in soil, typically among grasses or under spruce and fir trees (Ponche de Leon, 1976). Members of the genus *Gastropila* are globally distributed, mainly in Asia, Europe, and North and South America, though they are considered rare (Rebriev & Assyov, 2012; He et al., 2019).

Gastropila species are characterised by globose basidiomata with irregular apical openings that form radiate-stellate structures (Diego Calonge & Martin, 1990). The peridium is thick, smooth, sparsely branched, and externally fragile but corky-spongy internally (Homrich & Wright, 1973; Diego Calonge & Martin, 1990). It is composed of

three layers: a very thin outer layer, a fragile middle layer, and an extremely thick and fragile inner layer (Homrich & Wright, 1973). The subgleba is absent in this genus (Diego Calonge & Martin, 1990). Basidiospores are small, smooth, and ovoid (Diego Calonge & Martin, 1990). The capillitium consists of smooth, sparsely branched threads that are highly entangled but not easily broken (Homrich & Wright, 1973).

In the delineation of *Gastropila* species, only macro- and micro-morphological characteristics have been documented, as molecular data are currently unavailable (He et al., 2019). Although members of *Gastropila* are morphologically similar, the exoperidium in *G. fragilis*, *G. fumosa*, and *G. hesperia* is smooth, while in *G. subcretacea* it is covered with polygonal warts (Ponche de Leon, 1976). The capillitium in *G. fragilis* contains round pits, whereas *G. fumosa* and *G. hesperia* feature pit-like structures (Ponche de Leon, 1976). Basidiospores in *G. fumosa* are echinate, while those in *G. hesperia* are smooth (Ponche de Leon, 1976). *Gastropila* shares similarities with *Calvatia,* but it differs in spore morphology and the presence or absence of the subgleba (Diego Calonge & Martin, 1990).

Synonymy: *Pila* Speg.

Type species: *Gastropila fragilis* (Lév.) Homrich & J.E. Wright

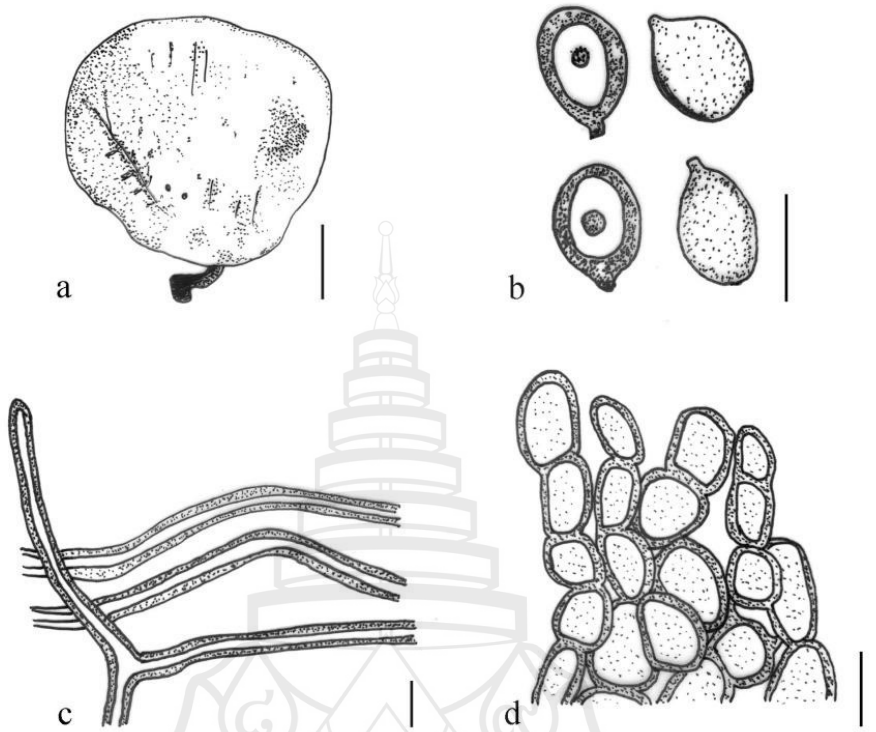
Basionym: *Mycenastrum fragile* Lév.

Other accepted species:

G. fumosa (Zeller) P. Ponce de León

G. hesperia (Morgan) P. Ponce de León

G. subcretacea (Zeller) P. Ponce de León



Note a Basidiomata. b Basidiospores. c Eucapillitium. d Exoperidium hyphae. Scale bar: a = 1 cm, b = 5 µm, c = 10 µm, d = 20 µm.

Source Redrawn from a = Rebriev and Assyov (2012), b−d = Cortez et al. (2012). For original basidiomata, refer to Rebriev and Assyov (2012).

Figure 5.25 *Gastropila fragilis*

5.3.1.28 *Morganella* Zeller

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.26

Classification: *Lycoperdaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Morganella was founded by S.M. Zeller in 1948, with its type species *M. mexicana* (Zeller, 1948). The type species was based on specimens collected from wet areas among moss and leaves in Guaymas, Sonora, Mexico (Zeller 1948). Initially, Zeller (1948) placed this genus under *Mesophelliaceae* Jülich. In 1967, Kreisel and Dring amended the classification and classified it within *Lycoperdaceae* (Kreisel & Dring,

1967; Alfredo et al., 2017). The peridium of *Morganella* consists of two layers, while *Mesophelliaceae* has three layers (Morales & Kimbrough, 1981). Members of *Morganella* are found worldwide, mainly in tropical and subtropical regions (Rebriev & Bulakh, 2015; He et al., 2019). They are primarily lignicolous and are rarely found in soil rich in organic matter (Kreisel & Dring, 1967; Suárez & Wright, 1996; Rebriev & Bulakh, 2015).

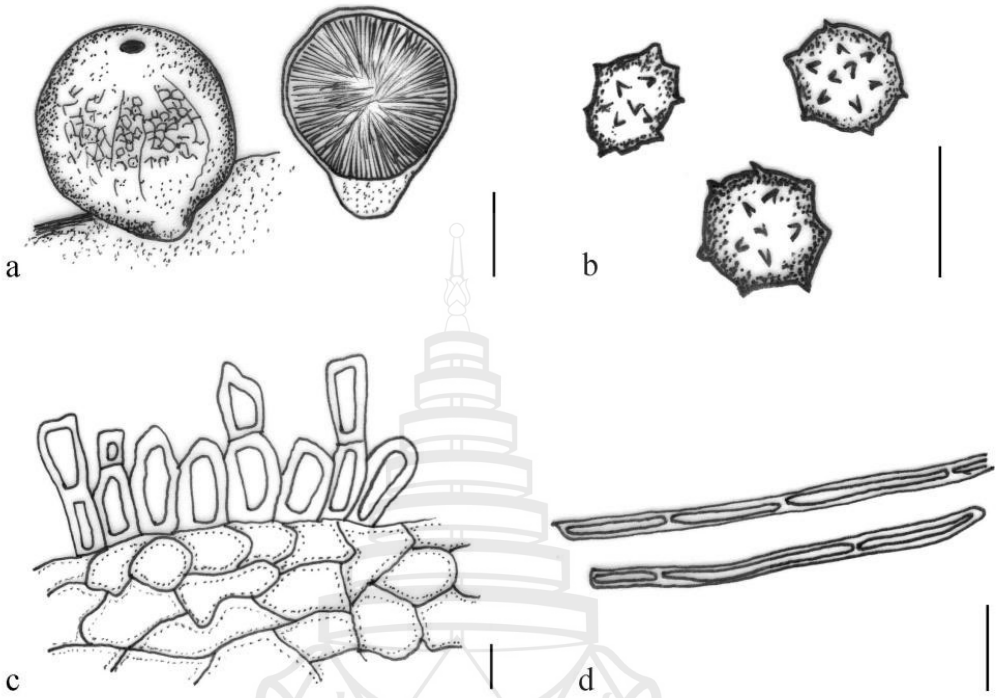
Species of *Morganella* are characterised by their epigeous, depressed, globose to pyriform basidiomata, which consist of a double peridium (exoperidium and endoperidium) (Zeller, 1948; Kreisel & Dring, 1967; Suarez & Wright, 1996; Rebriev & Bulakh, 2015). The exoperidium is velutinous, furfuraceous, granular-verrucose, or spinulose, and may be flesh-coloured or deep red-brown to purplish black (Morales & Kimbrough, 1981; Rebriev & Bulakh, 2015). The endoperidium bears an apical opening with an irregularly torn mouth (Rebriev & Bulakh, 2015). The gleba lacks true capillitium but contains abundant paracapillitium (Kreisel & Dring, 1967; Suárez & Wright, 1996; Rebriev & Bulakh, 2015). Basidiospores are globose to broadly ovoid and may be asperulate to echinulate (Zeller, 1948; Kreisel & Dring, 1967; Suárez & Wright, 1996; Rebriev & Bulakh, 2015).

Recently, Li et al. (2024a) described a new species, *Morganella tricolor*, along with two new combinations, *M. oblongata* and *M. mengsongensis*, based on morphological characteristics and phylogenetic analysis (ITS and LSU). *Morganella* differs from other genera in *Lycoperdaceae* by lacking capillitial threads (Morales & Kimbrough, 1981). Additionally, in *Morganella*, the glebal membranes remain persistent in the mature gleba, while in other genera of the family, these membranes are disrupted and become unrecognisable (Morales & Kimbrough, 1981). Index Fungorum (2025) lists 26 records of *Morganella,* but Species Fungorum (2025) recognises only 13 species worldwide.

Synonymy: *Lycoperdon* subgen. *Morganella* (Zeller) Jeppson & E. Larss.

Type species: *Morganella mexicana* Zeller

Other accepted species: (Species Fungorum – search *Morganella*)



Note a Basidiomata. b Basidiospores. c Exoperidium. d Paracapilitium. Scale bar: a = 2 mm, b = 3 µm, c–d = 10 µm.

Source Redrawn from Alfredo et al. (2012).

Figure 5.26 *Morganella rimosa*

Lyophyllaceae Jülich, *Biblthca Mycol.* 85: 378

Lyophyllaceae was established by W. Jülich (1982), with *Lyophyllum* P. Karst. as the type genus (Jülich, 1982). Species of *Lyophyllaceae* are characterised by the presence of macro-type siderophilous granulation in basidia (Jülich, 1982; Hofstetter et al., 2014). Hofstetter et al. (2002) undertook the first phylogenetic analyses within *Lyophyllaceae*. Hyde et al. (2024a) listed 34 genera in this family. Members of *Lyophyllaceae* are distributed worldwide and exhibit a high degree of ecological diversity, ranging from saprophytic to parasitic or mutualistic lifestyles (Hofstetter et al., 2014; Bellanger et al., 2015). Some species in *Lyophyllaceae* are well-known edible

mushrooms and are cultivated widely, such as *Lyophyllum shimeji* (Kawam.) Hongo and *Hypsizygus* Singer species (Bellanger et al., 2015).

5.3.1.29 *Gerhardtia* Bon

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.27

Classification: *Lyophyllaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Gerhardtia was established by M. Bon, based on *Lyophyllum* subgenus *Lyophyllopsis*, with *G. incarnatobrunnea* described as a type species (Bon, 1994; Endo et al., 2022). However, *G. incarnatobrunnea* was synonymised with *G. borealis* (Fr.) Contu & A. Ortega, making the latter the new type species (Bon, 1994; Vizzini et al., 2015; Endo et al., 2022). In the family *Lyophyllaceae*, *Gerhardtia* is uniquely characterised by the absence of clamp connections in its hyphae (Vizzini et al., 2015, 2017). Its species are saprotrophic and have a wide geographic distribution, occurring in Europe, New Zealand, North America, South America, China, Japan, and India (Izhar et al., 2021; Endo et al., 2022). Index Fungorum (2025) lists 19 records of *Gerhardtia*, whereas Species Fungorum (2025) recognises only 16 species worldwide.

Gerhardtia is characterised by basidiomata that vary in size (from small to large) and morphology (collybioid, tricholomatoid, or marasmioid), with pileus colours ranging from white to pale pink, greyish, lemon yellow, pale yellow, and yellowish to reddish brown (Qi et al., 2023). Initially, the genus was defined by the presence of verrucose basidiospores, basidia with siderophilous granules, a pileipellis structure (hymeniderm or trichoderm), and the absence of clamp connections (Bon, 1994; Vizzini et al., 2015; Thapa et al., 2024b). The discovery of *G. pseudosaponacea* J.A. Cooper and P. Leonard led to an update in basidiospore descriptions, which could be either smooth or verrucose (Cooper, 2014; Thapa et al., 2024b). Subsequently, the genus concept was further revised, with basidiospores described as irregular or undulate to nodulose rather than strictly verrucose (Vizzini et al., 2017; Thapa et al., 2024b).

Phylogenetically, *Gerhardtia* is a sister genus to *Calocybella* Vizzini, Consiglio & Setti; however, the latter shows context reddening upon bruising, turning

violaceous-red in alkaline solutions, and the presence of clamp connections (Vizzini et al., 2015).

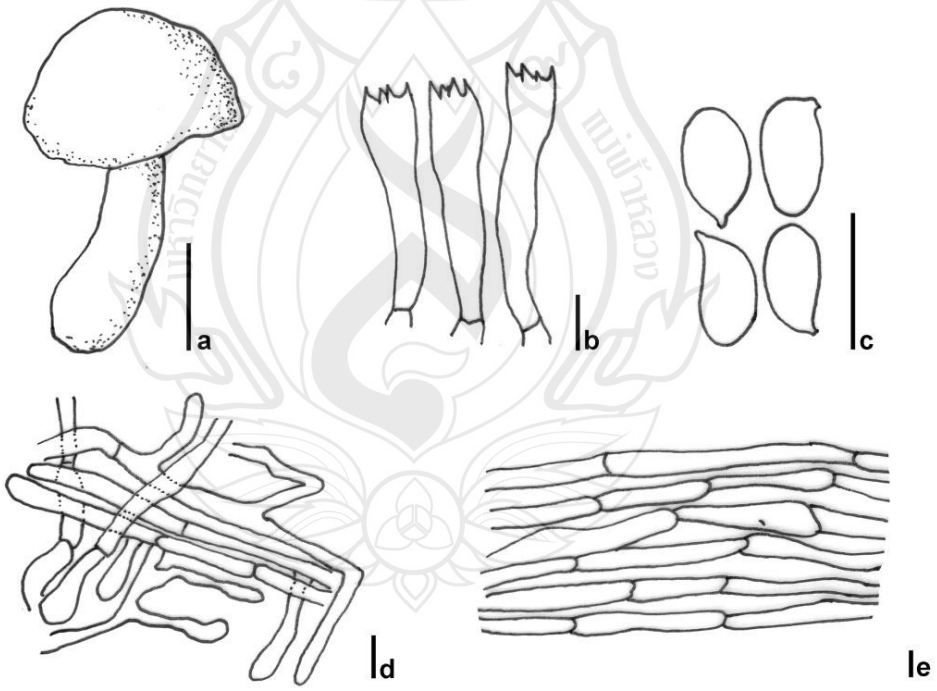
Endo et al. (2022) described a new species, *G. venosolamellata* N. Endo et al., based on morphological characteristics, phylogenetic analyses (ITS and LSU), and live culture characteristics. Mycelia of *G. venosolamellata* in culture produced arthroconidia through schizolytic and rhexolytic secession on malt extract agar (MEA) and potato dextrose agar (PDA), with occasional chlamydospores covered with crystals observed on MEA and malt extract-yeast extract-glucose agar (MYG) (Endo et al., 2022).

Synonymy: *Lyophyllum* subgen. *Lyophyllopsis* Ew. Gerhardt

Type species: *Gerhardtia borealis* (Fr.) Contu & A. Ortega

Basionym: *Agaricus borealis* Fr.

Other accepted species: (Species Fungorum – search *Gerhardtia*)



Note a Basidiomata. b Basidia. c Basidiospores. d Pileus hyphae. e Stipe hyphae. Scale bar: a = 2 cm, b−e = 5 µm.

Source Redrawn from Izhar et al. (2021).

Figure 5.27 *Gerhardtia foliicola* (LAH 36419)

5.3.1.30 *Ossicaulis* Redhead & Ginns

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.28

Classification: *Lyophyllaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Ossicaulis was established by S.A. Redhead and J. Ginns in 1985, with its type species, *O. lignatilis* (Redhead & Ginns, 1985; Qi et al., 2023). They are lignicolous, growing on decaying wood from Angiospermae, as well as on the decaying and live tree trunks of *Rhododendron* (Redhead & Ginns, 1985; Yang et al., 2017; Qi et al., 2023; Wei et al., 2023). Species of *Ossicaulis* cause brown-rot and are found mainly in the north temperate region, and a few in China and Australia (Redhead & Ginns, 1985; Qi et al., 2023).

The basidiomata of *Ossicaulis* are adnate, adnexed, or at most sub-decurrent lamellae, a regular trama, and a central to eccentric stipe (Holec & Kolařík, 2013). Basidiospores are small and ellipsoid (Holec & Kolařík, 2013). Basidia contain siderophilous granules of the oligo type (Redhead & Ginns, 1985; Holec & Kolařík, 2013). Cheilocystidia are narrowly clavate to coralloid when present (Redhead & Ginns, 1985; Holec & Kolařík, 2013). Hyphae in the epicutis are coralloid and contain clamp connections (Redhead & Ginns, 1985; Holec & Kolařík, 2013). Notably, Clémençon (2005a) examined the rhizomorph anatomy of *O. lignatilis* and found that it strongly resembles haustoria, with broad, distinctive thromboplerous hyphae and their association with intrahyphal hyphae.

Wei et al. (2023a) described a new species, *O. sichuanensis*, based on specimens collected in China, using morphological characteristics and phylogenetic analyses (ITS and LSU). Qi et al. (2023) described another new species, *O. borealis*. Index Fungorum (2025) lists eight records, while Species Fungorum (2025) has recognised six species worldwide.

Type species: *Ossicaulis lignatilis* (Pers.) Redhead & Ginns

Basionym: *Agaricus lignatilis* Pers.

Other accepted species:

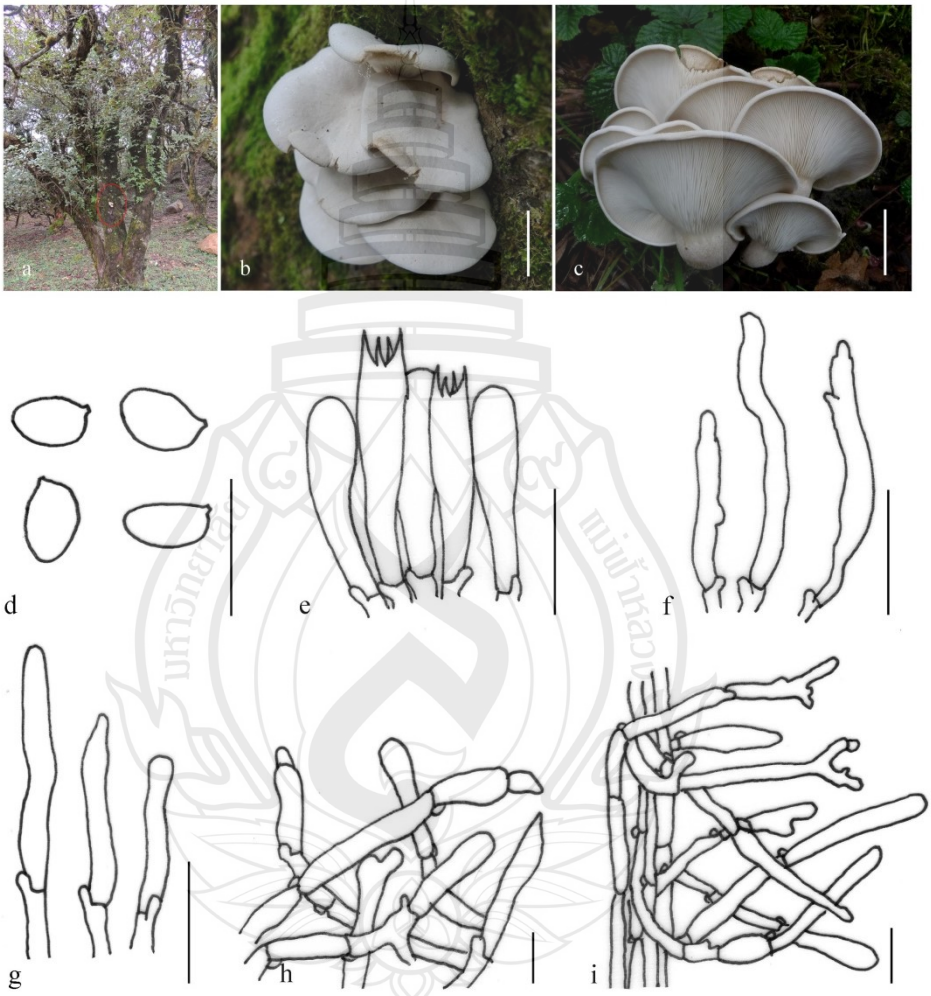
O. borealis X.D. Yu & H.B. Guo

O. salomii Siquier & Bellanger

O. semiocculta (Cleland) J.A. Cooper

O. sichuanensis S.W. Wei, Q. Wang & Yu Li

O. yunnanensis L.P. Tang, N.K. Zeng & S.D. Yang



Note a–c Basidiomata living on the tree trunk of *Rhododendron* sp. d Basidiospores. e Basidia and basidioles. f Cheilocystidia. g Pleurocystidia. h Pileipellis. i Stipitipellis. Scale bar: b, c = 2 cm, d = 5 µm, e–i = 10 µm.

Source Redrawn from Yang et al. (2017b).

Figure 5.28 *Ossicaulis yunnanensis* (HKAS 100527, holotype)

5.3.1.31 *Termitomyces* R. Heim

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 1.29

Classification: *Lyophyllaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Termitomyces was established by R. Heim in 1942 to accommodate 'termitophilous agarics' (Heim, 1942). *Termitomyces* species form a symbiotic association with fungus-growing termites in the subfamily *Macrotermitinae* and grow within a fungal comb constructed from termite faecal material (Ye et al., 2019; Usman & Khalid, 2020). The termites create a suitable environment for the *Termitomyces*, while the fungus serves as a food source for the termites, demonstrating obligate interdependence and coevolution between them (Aanen et al., 2007; Koné et al., 2018). *Termitomyces* has a cosmopolitan distribution, mainly in Africa, Asia, and the Pacific islands (Morris, 1986; Koné et al., 2018). Index Fungorum (2025) lists 113 records of *Termitomyces*, while Hyde et al. (2024) recognised approximately 50 species worldwide. The genus is distinct from other agaric genera by its long stem (Morris, 1986).

Termitomyces are characterised by basidiomata, which feature a pronounced umbo called perforatorium and a pseudorhiza that connects to the fungal comb (Usman & Khalid, 2020). Pileus is initially conic to convex, then plane with maturity (Jannual et al., 2020). Lamellae are free, white to creamy, and usually crowded (Morris, 1986). The stipe is central, cylindrical to subcylindrical, and has a longitudinally striated surface (Jannual et al., 2020). An annulus is absent (Jannual et al., 2020). The pseudorhiza is elongated and tapers toward the base (Jannual et al., 2020). Microscopically, basidiospores are ovoid to ellipsoid, smooth, thin-walled, inamyloid, cyanophilous, and exhibit a light pink deposit (Kaur et al., 2022). Basidia are clavate to subcylindrical, four-spored, inamyloid, and contain siderophilous granulation (Clémençon, 1984; Jannual et al., 2020). Cheilocystidia and pleurocystidia are abundant, clavate to pyriform, smooth, thin-walled, and inamyloid (Jannual et al., 2020). Hymenophoral trama may be either regular or bilateral (Kaur et al., 2022). Hyphae lack clamp connections.

The classification of *Termitomyces* in *Lyophyllaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina*, and *Basidiomycota* is in agreement in Index Fungorum, MycoBank, GenBank, UNITE, and the latest Outline of Fungi and fungus-like organisms (Hyde et al., 2024a).

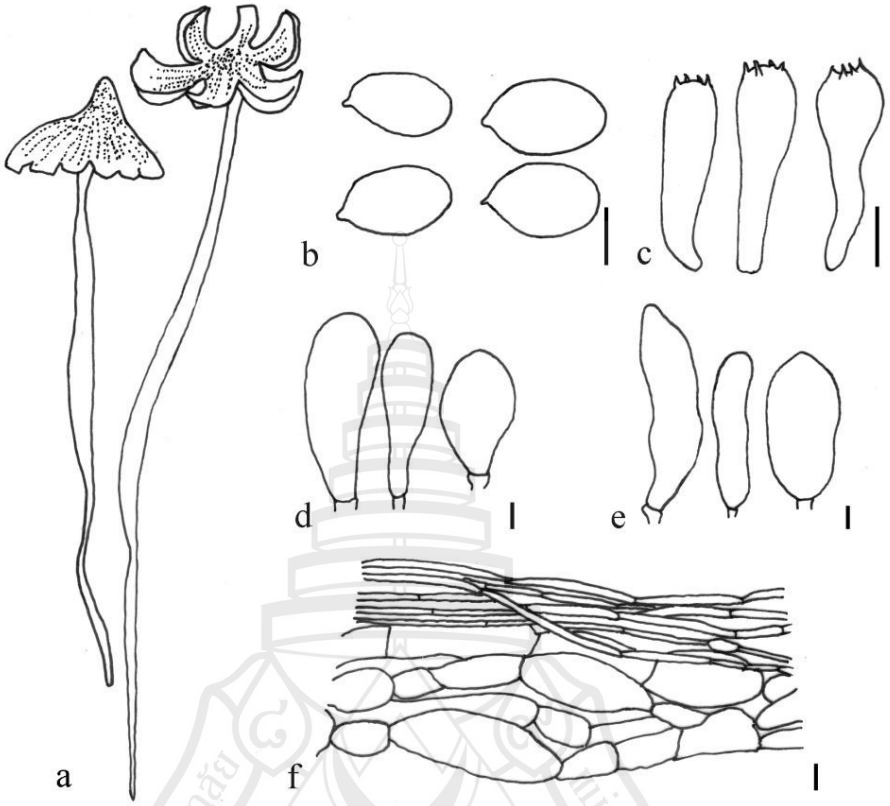
Ediriweera et al. (2023) described a new species, *T. srilankensis* Ediriweera, Voto, Karun. & Kularathne, utilising morphological characteristics and phylogenetic analyses (ITS). *Termitomyces* species have socio-economic and ecological values. They are widely consumed as a medicinal and nutritious delicacy in different regions, including equatorial Africa and Southeast and South Asia (Turnbull & Watling, 1999; Aryal & Budathoki, 2016). Proteomic analysis of an edible termite mushroom, *T. heimii* Natarajan, has revealed correlations between protein expression and developmental stages (Rahmad et al., 2014). Additionally, *Termitomyces* species are known sources of active compounds, including nectrianolins and termitomycesphins G and H (Qu et al., 2012; Kreuzenbeck et al., 2023). *Termitomyces striatus* has demonstrated antimicrobial properties and serves as a source of antimicrobial and antifungal compounds (Mahamat et al., 2018; Sitati et al., 2021).

Synonymy: *Podabrella* Singer, *Rajapa* Singer, *Sinotermitomyces* M. Zang

Type species: *Termitomyces striatus* (Beeli) R. Heim

Basionym: *Schulzeria striata* Beeli

Other accepted species: (Species Fungorum – search *Termitomyces*)



Note a Basidiomata. b Basidiospores. c Basidia. d Cheilocystidia. e Pleurocystidia. f Pileipellis. Scale bar: b = 5 μm, c–f = 10 μm.

Source Redrawn from Ye et al. (2019). For original basidiomata, refer to Ye et al. (2019).

Figure 5.29 *Termitomyces fragilis* (HKAS 88912, holotype)

Macrocystidiaceae Kühner, *Bull. mens. Soc. linn. Lyon* 48(3): 172

Macrocystidiaceae is a monogeneric family established by R. Kühner (1979) with *Macrocystidia* Joss. as the type genus (Kühner, 1979a; He et al., 2019). *Macrocystidiaceae* is the only family in the suborder *Macrocystidiineae* H. Qu, Z.W. Ge & Zhu L. Yang (Qu et al., 2025). *Macrocystidiaceae* is characterised by gymnocarpic mycenoid to collybioid basidiomata, with almost free lamellae, regular to subregular hymenophoral trama, lageniform to fusiform, thin-walled cystidia, and ellipsoid, thick-walled, cyanophilous, inamyloid, and mononucleate basidiospores (Kühner, 1979a;

Læssøe & Petersen, 2019; Vizzini et al., 2024). Members of *Macrocystidiaceae* are saprophytic and distributed worldwide (He et al., 2019).

5.3.1.32 *Macrocystidia* Joss.

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.30

Classification: *Macrocystidiaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota*, Fungi

Macrocystidia was established by M. Josserand in 1934, with *M. cucumis* as the type species (Josserand, 1934). The type species was initially described as *Agaricus cucumis*, based on specimens collected from soil associated with *Fagus* and *Pinus* (Persoon, 1796). Kühner (1979a) introduced the family *Macrocystidiaceae* to accommodate *Macrocystidia*, and its family-level status has been supported by Vizzini et al. (2024). However, its taxonomic placement at the family level has remained controversial (Moncalvo et al., 2002). Species of *Macrocystidia* are saprobic and are distributed worldwide (He et al., 2019).

Macrocystidia are characterised by collybioid to mycenoid basidiomata with a glabrous, hygrophanous pileus (Singer, 1964a). The stipe is central, rigid, slender, and glabrous, and lacking pseudorrhiza (Singer, 1964a). The epicutis consist of repent, filamentous hyphae with numerous large dermatocystidia (Singer, 1964a). Basidiospores are smooth, inamyloid, slightly thick-walled, and produce an ocher-reddish (or pinkish) spore deposit (Singer, 1964a). Gloeocystidia are abundant (Singer, 1964a; Izhar et al., 2022), and the hymenial trama is regular and inamyloid (Singer, 1964a).

Index Fungorum (2025) lists 16 records of *Macrocystidia,* but Species Fungorum (2025) recognises only seven species worldwide. Liu et al. (2025a) introduced a new species, *Macrocystidia hebeiensis*, based on morphological characteristics and phylogenetic analyses (ITS, LSU, SSU, *rpb1*, *rpb2*, *tub*, and *tef-1α*) of specimens collected in China. Phylogenetic evidence also indicated that *Macrocystidia* is closely related to *Pseudoclitopilus* Vizzini & Contu (Liu et al., 2025a).

Synonyms: *Galeromycena* Velen., *Macrocystis* R. Heim

Type species: *Macrocystidia cucumis* (Pers.) Joss.

Basionym: *Agaricus cucumis* Pers.

Other accepted species:

M. africana Singer

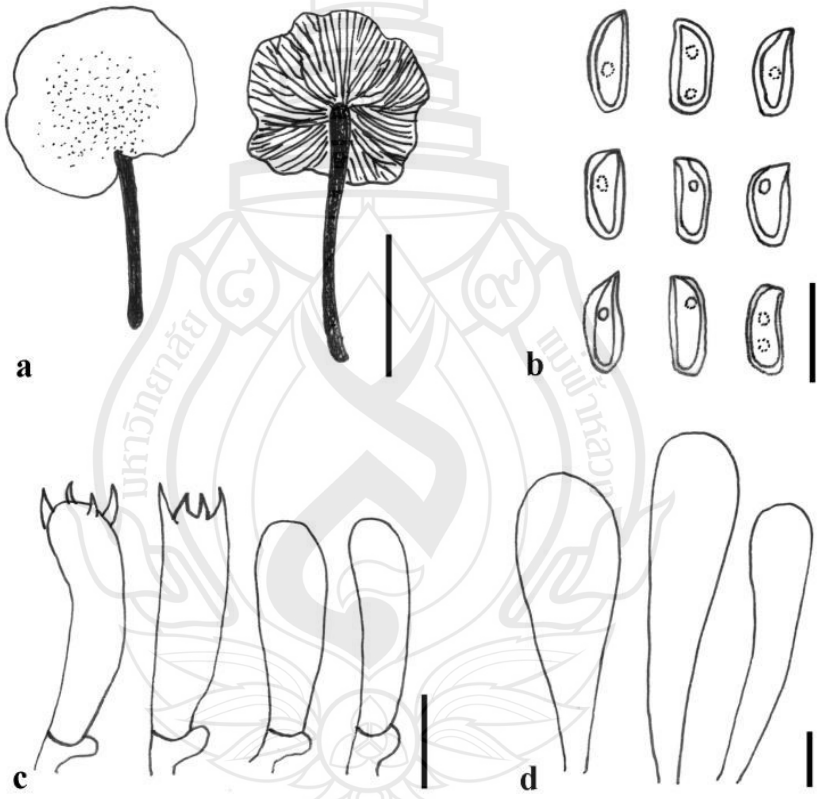
M. hebeiensis Shun Liu & Biao Zhu

M. incarnata Singer

M. indica Saini, Atri & Singer

M. occidentalis Singer

M. reducta E. Horak & Capellano



Note a Basidiomata. b Basidiospores. c Basidia and basidioles. d Cheilocystidia. Scale bar: a = 3 cm, b–d = 10 µm.

Source Redrawn from Liu et al. (2025a). For original basidiomata, refer to Liu et al. (2025a).

Figure 5.30 *Macrocystidia hebeiensis* (Liu 67, holotype)

Marasmiaceae Roze ex Kühner, *Bull. mens. Soc. linn. Lyon* 49: 76

Marasmiaceae was established by R. Kühner (1980), with *Marasmius* Fr. as the type genus (Kühner, 1980). *Marasmiaceae* is the type family of suborder *Marasmiineae* Aime, Dentinger & Gaya (Dentinger et al., 2016; Oliveira et al., 2024). He et al. (2024) reported 13 genera in *Marasmiaceae*: *Amyloflagellula* Singer, *Aphyllotus* Singer, *Brunneocorticium* Sheng H. Wu, *Campanella* Henn., *Cellypha* Donk, *Chaetocalathus* Singer, *Crinipellis* Pat., *Hymenogloea* Pat., *Marasmius*, *Moniliophthora* H.C. Evans, Stalpers, Samson & Benny, *Neocampanella* Nakasone, Hibbett & Goranova, *Paramarasmius* Antonín & Kolařík, and *Tetrapyrgos* E. Horak. *Marasmiaceae* is characterised by mostly small and thin, marcescent, or large, cyphelloid, marasmioid, campanelloid, or gymnopoid basidiomata with membranous, glabrous, velvet to pilose, dry, and white to strongly pigmented pileus (Oliveira et al., 2024). Hymenophore is whitish, smooth, or lamellate, with regular lamellae, fewer interveined to reticulate lamellae (Oliveira et al., 2024). Stipe can be none, short or well-developed, central to lateral, hollow, deeply pigmented-melanised, often chitinous, glabrous or pilose (Oliveira et al., 2024). Members of this family are distributed worldwide, and most are saprotrophic, while some are phytopathogenic (Oliveira et al., 2024).

5.3.1.33 *Crinipellis* Pat

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.31

Classification: *Marasmiaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Crinipellis Pat. are marasmioid or collybioid mushroom-forming fungi. The genus was established by Patouillard in 1889 with the type species *C. scabella* (Alb. and Schwein.) Murill (Singer, 1942a; de Arruda et al., 2005; Li et al., 2023). *Crinipellis* has a worldwide distribution with rich species diversity (Kerekes & Desjardin, 2009; Li et al., 2023). Index Fungorum (2024) lists 198 records of *Crinipellis*, while Wijayawardene et al. (2022) accepted only 65 species.

According to Singer (1986), *Crinipellis* was classified into five sections: *Crinipellis*, *Excentricinae*, *Grisentinae*, *Iopodinae*, and *Metuloidophorae* (Sharafudheen

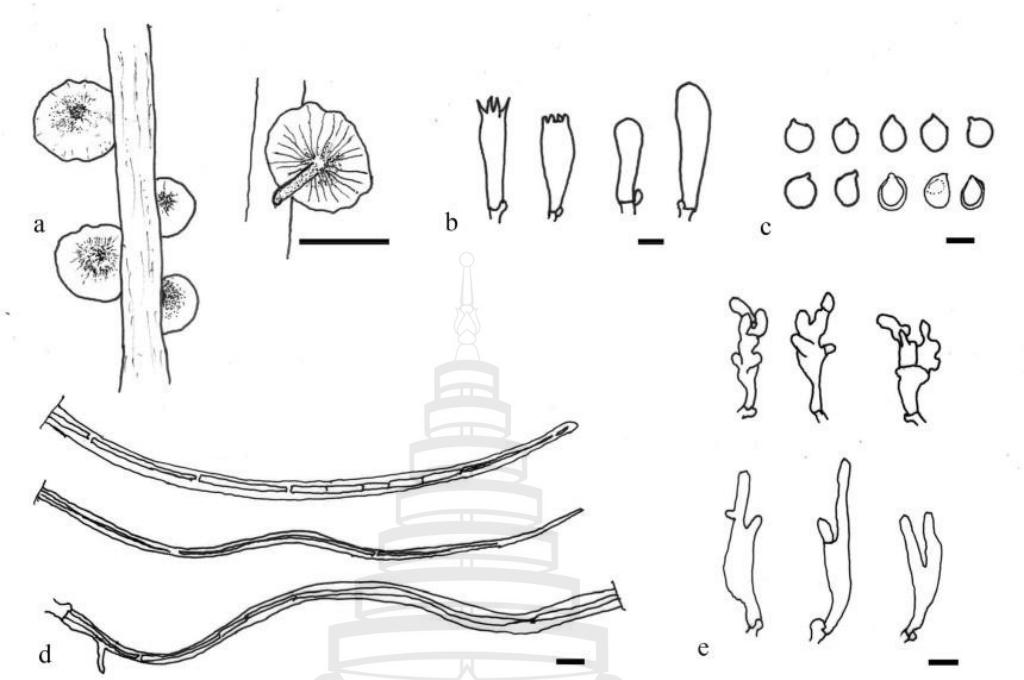
et al., 2023). Most species of *Crinipellis* are saprotropic with wood and litter, among which some have useful beneficial applications (Sharafudheen et al., 2023). Molecular studies reported *Crinipellis* as a sister clade with *Chaetocalathus* Singer, *Moniliophthora* H.C. Evans, Stalpers, Samson and Benny, and *Marasmius* Fr. *sensu stricto* (Aime & Phillip-Mora, 2005; Kerekes & Desjardin, 2009). *Crinipellis* basidiomata are characterised by a strigose, woolly to pilose, membranous to coriaceous pileus, which is formed by a trichoderm consisting of long hair-like, thick-walled, dextrinoid hyphae irregularly arising from a hypotrichium (Kerekes & Desjardin, 2009; de Oliveira & Hopkins, 2019). Stipe is covered with thick-walled, dextrinoid, hair-like terminal cells (Xia et al., 2015; Li et al., 2023). Lamellae are white to cream and free to adnate (Kerekes & Desjardin, 2009; de Oliveira & Hopkins, 2019). Latest studies used morphology and molecular phylogeny (ITS) for the identification of species of *Crinipellis* (Xia et al., 2015; Sharafudheen et al., 2023).

Some *Crinipellis* have potential antimicrobial activities. *Crinipellis rhizomaticola* showed fungicidal activity against *Magnaporthe oryzea* and *Colletotrichum coccodes* (Han et al., 2018). A crinipellin, an antibiotic extracted from *Crinipellis stipitaria,* can be used to inhibit gram-positive bacteria (*Bacillus brevis)* (Kupka et al., 1979). However, species of *C. siparuanae*, *C. pseudostipitaria*, and *C. scabella* are known to be parasitic (Singer, 1942a; Kerekes & Desjardin, 2009; Li et al., 2023).

Type species: *Crinipellis scabella* (Alb. & Schwein.) Murrill

Basionym: *Agaricus scabellus* Alb. & Schwein.

Other accepted species: (Species Fungorum – search *Crinipellis*)



Note a Basidiomata. b Basidia and basidioles. c Basidiospores. d Pileus hairs. e Cheilocystidia. Scale bar: a = 5 mm, b−e = 10 μm.

Source Redrawn from Li et al. (2023).

Figure 5.31 *Crinipellis deutziae*

Mycenaceae Overeem, *Icon. Fung. Malay.*: 14

Mycenaceae was established by Overeem (1926), with *Mycena* (Pers.) Roussel as the type genus. He et al. (2024) reported 11 genera in this family: *Cruentomycena* R.H. Petersen, Kovalenko & O.V. Morozova, *Cynema* Maas Geest. & E. Horak, *Favolaschia* (Pat.) Pat., *Flabellimycena* Redhead, *Heimiomyces* Singer, *Hemimycena* Singer, *Mycena*, *Panellus* P. Karst., *Resinomycena* Redhead & Singer, *Roridomyces* Rexer, and *Tectella* Earle. *Mycenaceae* is characterised by lamellate basidiomata, with pale and amyloid basidiospores and dextrinoid tissues (Moncalvo et al., 2002; Wei & Kirschner, 2019). Species of *Mycenaceae* are distributed worldwide and are saprotrophic on dead leaf litter and wood debris (Wei & Kirschner, 2019). Notably, this

family also consists of bioluminescent species, including *Filoboletus*, *Mycena*, *Panellus*, *Resinomycena*, and *Roridomyces* (Cortés-Pérez et al., 2019).

5.3.1.34 *Flabellimycena* Redhead

Index Fungorum, Facesoffungi, MycoBank, Fig. 5.32

Classification: *Mycenaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

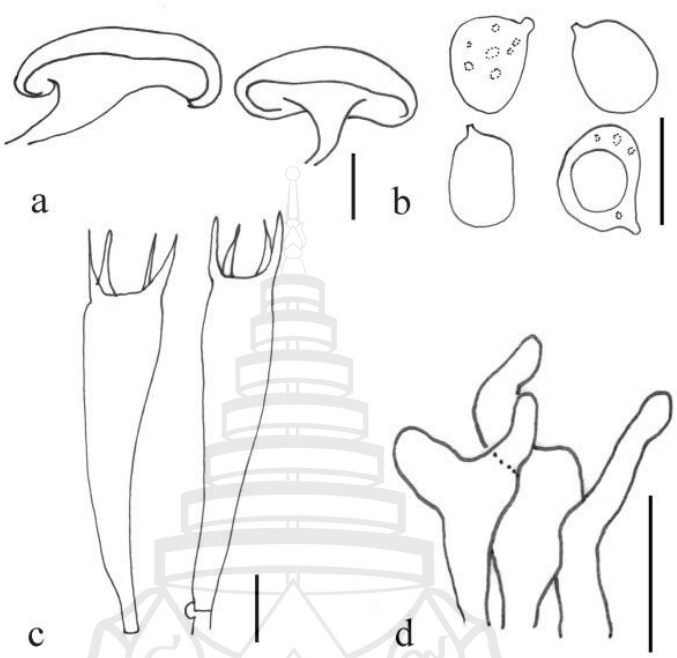
Flabellimycena, a monotypic genus, was established by S.A. Redhead in 1984, with its type species *F. flava* (Redhead, 1984a). This species was originally described based on specimens collected from rotten wood in Colombia, South America, and was initially classified as *Pleuromycenula flava* Singer (Redhead, 1984a). This genus is saprophytic and found in Colombia and Puerto Rico (Redhead, 1984a). Notably, *Flabellimycena* is listed in the "List of protected generic names of fungi" under the International Code of Nomenclature for algae, fungi, and plants (Kirk et al., 2013).

Flabellimycena is characterised by small, glabrous, yellow, and slightly ciliated basidiomata (Redhead, 1984a). Microscopically, its basidiospores are smooth, hyaline, and non-amyloid (Redhead, 1984a). Cheilocystidia are minute, irregular, and sometimes branched (Redhead, 1984a). The hyphae of pileipellis are non-amyloid, inflated, and clamped (Redhead, 1984a). The basal mycelium is waxy, composed of thick-walled, sub-gelatinised, smooth, clamped hyphae (Redhead, 1984a). The hyphal system is monomitic (Redhead, 1987).

Species delineation of *Flabellimycena* is based solely on macro- and micro-morphological characteristics due to the lack of molecular sequences (Miettinen & Hernawati, 2010; He et al., 2019). Morphologically, *Flabellimycena* is related to *Rimbachia* Pat. and *Helotium* Tode. However, *Rimbachia* is distinguished by the absence of yellow pigment, cheilocystidia, thick-walled basal hyphae, and its habitat on a woody stem (Redhead, 1984a). *Helotium* differs from *Flabellimycena* by its lack of yellow pigment (Redhead, 1984a). Molecular evidence is needed to differentiate *Flabellimycena* from these closely related genera.

Type species: *Flabellimycena flava* (Singer) Redhead

Basionym: *Pleuromycenula flava* Singer



Note a Basidiomata. b Basidiospores. c Basidia. d Cheilocystidia. Scale bar: a = 1 mm, b–d = 10 μm.

Source Redrawn from: a–c = iNaturalist (2025), d = Redhead (1984a). For original basidiomata, refer to Redhead (1984a) and GBIF (2025).

Figure 5.32 *Flabellimycena flava*

5.3.1.35 *Resinomycena* Redhead & Singer

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.33

Classification: *Mycenaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Resinomycena was established by S.A. Redhead and R. Singer in 1981, with its type species *R. rhododendri* (Redhead & Singer, 1981). The type species was originally described as *Agaricus rhododendri* Peck, based on specimens collected from dead wood of *Rhododendron maximum* in New York, USA (Peck, 1875). *Resinomycena* was split from the genus *Mycena* (Pers.) Roussel, based on abundant oleocystidia in the

pileus and stipe (Redhead & Singer, 1981; Antonín & Noordeloos, 2004). The genus is saprobic, found in leaf litter, twigs, and wood debris (Redhead & Singer, 1981; Bau et al., 2021). Members of *Resinomycena* are found in North America, Europe, Japan, Canada, Brazil, and China (Redhead & Singer, 1981; Redhead, 1984b; Desjardin et al., 2016; He et al., 2019).

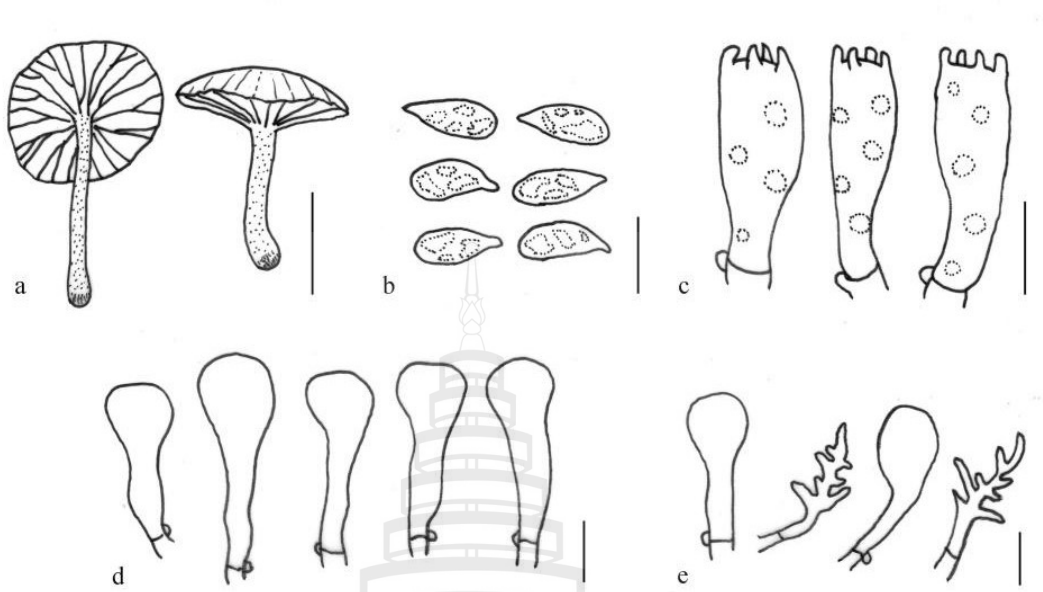
Species of *Resinomycena* are characterised by omphaliod or mycenoid, resinous basidiomata, covered with oliecystidia intermixed with dendroid, non-diverticulate hyphae, white or dull (Redhead & Singer, 1981). The lamellae are adnate to slightly decurrent, subdistant to crowded with resinous edges formed by numerous oleocystidia (Redhead & Singer, 1981). The stipe is equal, cartilaginous, and resinous, covered with resinous edges formed by oleocystidia and dendrohyphidia-like cells (Redhead & Singer, 1981). Basidiospores are smooth, hyaline, amyloid, and acyanophilic (Redhead & Singer, 1981). Basidia are narrowly cylindrical, 4-spored, and clamped (Redhead & Singer, 1981). Pileipellis has numerous dendrohyphidia-like terminal cells (Desjardin et al., 2016). Tramal tissues are weakly to strongly dextrinoid, and hyphae are intermixed (Redhead & Singer, 1981). Hymenophoral trama is regular (Redhead & Singer, 1981).

Bau et al. (2021) described two new species, *R. capitata* and *R. ellipsoidea*, based on morphology and phylogenetic analysis (ITS, LSU, *rpb2*, and *tef-1α*). *Resinomycena* is distinct from its closely related genera *Baeospora* Singer, *Hydropus* Kühner ex Singer, and *Mycena* (Pers.) Roussel by the abundance of resinous oleocystidia intermixed with dendrohyphidia (Redhead & Singer, 1981). Index Fungorum (2025) lists 17 records for *Resinomycena;* however, Species Fungorum (2025) recognises only 13 species worldwide.

Type species: *Resinomycena rhododendri* (Peck) Redhead & Singer

Basionym: *Agaricus rhododendri* Peck

Other accepted species: (Species Fungorum – search *Resinomycena*)



Note a Basidiomata. b Basidiospores. c Basidia. d Cheilocystidia. e Caulocystidia. Scale bar: a = 5 mm, b = 5 µm, c−e = 10 µm.

Source Redrawn from Bau et al. (2021).

Figure 5.33 *Resinomycena capitata*

5.3.1.36 *Xeromphalina* Kühner & Maire

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.34

Classification: *Mycenaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

The genus *Xeromphalina* was established by Kühner and Maire in 1934 to accommodate a small omphalioid mushroom, with *X. campanella* as the type species (Kühner & Maire, 1934). This genus was initially classified in the tribe *Marasmiaceae* Roze ex Kühner (Kühner, 1980). Later, it was transferred to the family *Tricholomataceae* R. Heim ex Pouzar (Singer, 1986; Moncalvo et al., 2002; Matheny et al., 2006). Subsequently, this genus has been reclassified under the family *Mycenaceae* Overeem (Antonín & Bitak, 2013; He et al., 2019; Vizzini et al., 2024). In 1968, *Xeromphalina* was divided into three sections: *Xeromphalina* (Singer) O.K. Miller, *Fulvipes* O.K.

Miller, and *Heimiomyces* (Singer) A.H. Smith (Miller, 1968). However, Redhead adopted Singer's classification, which recognises two subgenera: *Xeromphalina* subg. *Xeromphalina* Singer and subg. *Heimiomyces* (Singer, 1962; Redhead, 1988). Species of *Xeromphalina* are saprobic, typically occurring on fallen, decayed, and moss-covered logs and stumps (Bera et al., 2024), and are distributed worldwide, including in Africa, Asia, Europe, North America, and South America (Bera et al., 2024). The taxonomic classification of *Xeromphalina* is under *Mycenaceae* in Index Fungorum and GenBank; however, MycoBank and Hyde et al. (2024a) have placed it under *Xeromphalinaceae* Vizzini, Consiglio & P. Alvarado.

Xeromphalina is characterised by basidiomata with a convex pileus often bearing a central depression (Miller, 1968; Bera et al., 2024). The pileus surface is glabrous or pruinose, moist or dry, and ranges in colour from orangish to yellowish-brown or ochre yellow (Miller, 1968; Bera et al., 2024). Lamella is adnate or decurrent, intervenose, and subdistant to close (Miller, 1968; Bera et al., 2024). The stipe is slender, cylindrical, with a glabrous, pruinose, tomentose, or hispid surface (Miller, 1968; Bera et al., 2024). Basidiospores are elliptical to allantoid and amyloid (Miller, 1968; Bera et al., 2024). Hymenial cystidia are fusiform, subventricose, or irregularly branched (Miller, 1968; Bera et al., 2024). Pileocystidia are thin to thick-walled, fusoid or irregularly shaped, and hyaline to pigmented (Miller, 1968; Bera et al., 2024).

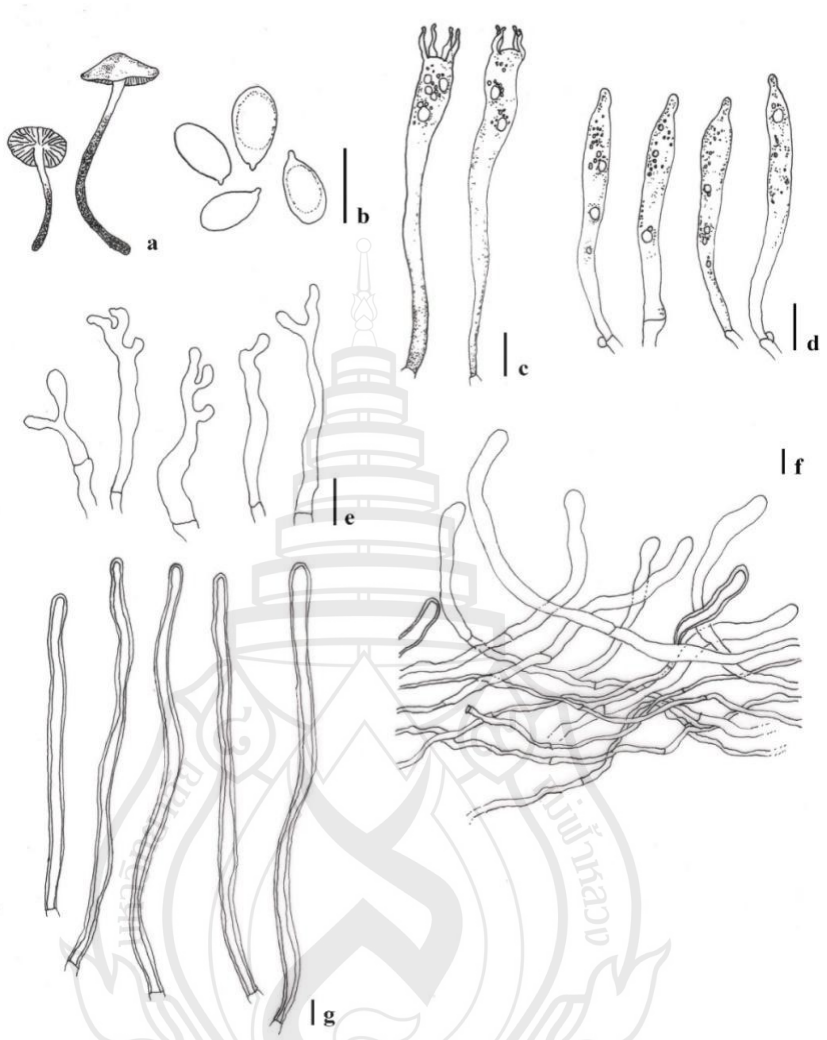
Bera et al. (2024) described a new species, *X. pseudotenuipes* I. Bera & S. Khyaju, based on morphological characteristics and phylogenetic analyses (ITS, LSU, and *rpb2*). Index Fungorum (2025) lists 51 records of *Xeromphalina*; however, only 37 species are recognised worldwide (Bera et al., 2024).

Synonymy: *Heimiomyces* Singer, *Omphalopsis* Earle, *Phlebomarasmius* R. Heim, *Valentinia* Velen.

Type species: *Xeromphalina campanella* (Batsch) Kühner & Maire

Basionym: *Agaricus campanella* Batsch

Other accepted species: (Species Fungorum – search *Xeromphalina*)



Note a Basidiomata. b Basidiospore. c Basidia. d Basidioles. e Cheilocystidia. f Transverse section through pileipellis. g Caulocystidia. Scale bars: b–g = 10 µm.

Source For original basidiomata, refer to Bera et al. (2024).

Figure 5.34 *Xeromphalina pseudotenuipes* (IB 23-002, holotype)

Mythicomycetaceae Vizzini, Consiglio & M. Marchetti, *Fungal Syst. Evol.* 3: 46

Mythicomycetaceae was established by A. Vizzini, G. Consiglio & M. Marchetti in 2019 under suborder *Agaricineae* Fr., with *Mythicomyces* Redhead & A.H. Sm. as the

type genus (Vizzini et al., 2019). He et al. (2024) reported two genera in this family, *Mythicomyces* and *Stagnicola* Redhead & A.H. Sm. *Mythicomycetaceae* is characterised by a mycenoid to phaeocollybioid basidiomata, with the absence of veils, a cartilaginous-horny, often tapering stipe, smooth or minutely punctate-verruculose basidiospores without a germ pore, and a greyish brown, pale hazel brown spore print (Vizzini et al., 2019). Cheilocystidia can be either metuloids or as thin-walled elements, while pleurocystidia, when present, are metuloids (Vizzini et al., 2019). Pileipellis are thin ixocutis without cystidioid elements but always clamped (Vizzini et al., 2019). Members of *Mythicomycetaceae* are distributed in the Northern Hemisphere, in boreal, subalpine, and montane coniferous forests, and are saprophytic on wood debris (Vizzini et al., 2019).

5.3.1.37 *Stagnicola* Redhead & A.H. Sm.

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.35

Classification: *Mythicomycetaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Stagnicola is a monotypic genus established by S.A. Redhead and A.H. Smith in 1986, with its type species *S. perplexa* (Redhead & Smith, 1986; He et al., 2019). The type species was originally classified as *Phaeocollybia perplexa*, based on specimens collected from rotten wood of Coniferae in England (Orton, 1977). *Stagnicola* is saprotrophic and distributed across Europe and North America (Vizzini et al., 2019). This genus is typically found on decaying plant debris in damp, moist environments, including coniferous forests and acid soils (Vizzini et al., 2019).

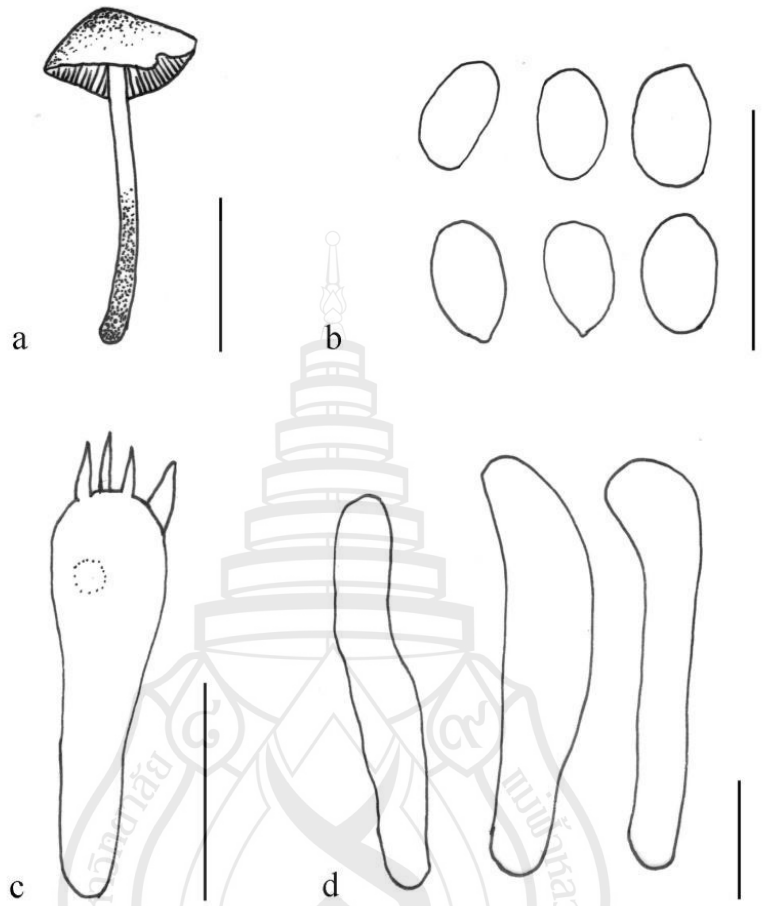
Stagnicola is characterised by mycenoid or collybioid to phaeocollybia-like basidiomata (Vizzini et al., 2019). The pileus is conical to convex, umbonate, hygrophanous, smooth, lubricous-viscid to greasy, striate, tawny, fulvous to sienna, with an orange-yellowish at the margin (Vizzini et al., 2019). *Lamellae* are adnexed-ventricose and crowded, with olivaceous tints and a concolourous edge (Vizzini et al., 2019). The stipe is central, smooth, horny, cartilaginous, shiny, purplish red, darkening to brown or blackish toward the base, with basal mycelial tomentum (Vizzini et al., 2019).

Basidiospores are ellipsoid to amygdaliform-reniform, smooth, hyaline, non-dextrinoid, inamyloid, cyanophilous, lacking a germ pore, and with a deep olive buff to pale hazel brown spore print (Vizzini et al., 2019). Basidia are typically 4-spored, occasionally 1-2-spored. Cheilocystidia are thin-walled, cylindrical to fusiform, while pleurocystidia are absent (Vizzini et al., 2019). The hymenophoral trama consists of regular, parallel hyphae (Vizzini et al., 2019). The pileipellis is a thin ixocutis of encrusted hyphae with yellow-brown pigment (Vizzini et al., 2019). Both caulocystidia and clamp connections are present (Vizzini et al., 2019).

Vizzini et al. (2019) used morphological and phylogenetic analysis (ITS, LSU, SSU, and *rpb2*) to distinguish this species from other closely related genera. *Stagnicola* shares similarities with *Simocybe* P. Karst., but the latter differs in having olivaceous tinges on the pileus surface, more pigmented and distinctly ovoid-reniform basidiospores, and a trichodermic-hymenidermic pileipellis with well-developed pileocystidia (Horak & Ronikier, 2011; Vizzini et al., 2019). *Stagnicola* also differs from its close genus *Mythicomyces* by lacking verrucose basidiospores, thick-walled hymenial cystidia, and purple hues in its spore deposit (Vizzini et al., 2019).

Type species: *Stagnicola perplexa* (P.D. Orton) Redhead & A.H. Sm.

Basionym: *Phaeocollybia perplexa* P.D. Orton



Note a Basidiomata. b Basidiospores. c Basidia. d Cheilocystidia. Scale bar: a = 1 cm, b−d = 10 μm.

Source Redrawn from Vizzini et al. (2019).

Figure 5.35 *Stagnicola perplexa*

Niaceae Jülich, *Biblthca Mycol.* 85: 381

Niaceae was established by W. Jülich (1982), with *Nia* R.T. Moore & Meyers as the type genus (Jülich, 1982). Hyde et al. (2024a) reported 14 genera in the family *Niaceae*: *Akenomyces* G. Arnaud ex D. Hornby, *Calathella* D.A. Reid, *Dendrothele* Höhn. & Litsch., *Digitatispora* Doguet, *Eoscyphella* A.G.S. Silva-Filho, Stevani & Menolli, *Flagelloscypha* Donk, *Halocyphina* Kohlm. & E. Kohlm., *Lachnella* Fr.,

Merismodes Earle, *Nia*, *Peyronelina* P.J. Fisher, J. Webster & D.F. Kane, *Phaeodepas* D.A. Reid, *Pseudolasiobolus* Agerer, and *Woldmaria* W.B. Cooke.

5.3.1.38 *Halocyphina* Kohlm. & E. Kohlm.

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.36

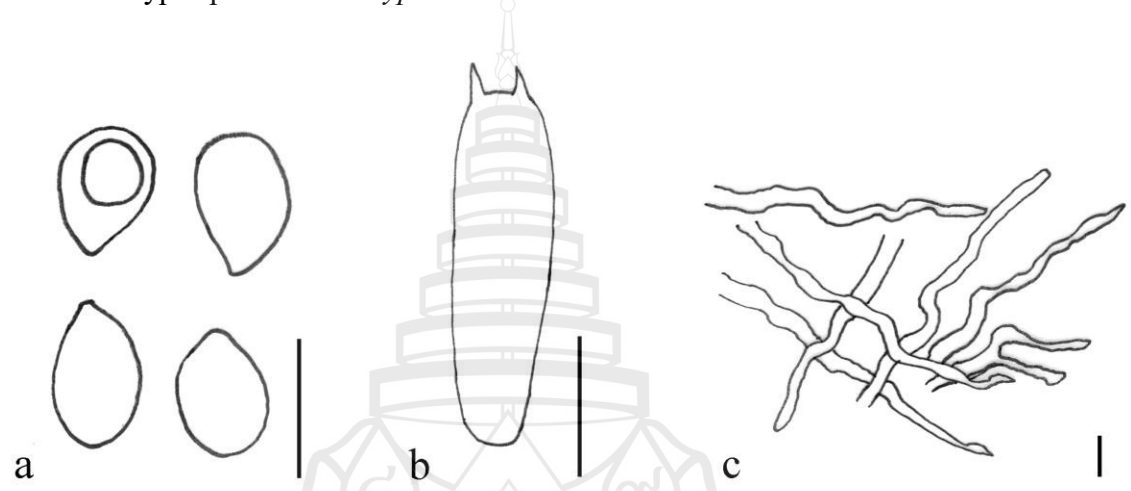
Classification: *Niaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Halocyphina is a monotypic genus established by J. Kohlmeyer & E. Kohlmeyer in 1965, with its type species *H. villosa* (Kohlmeyer, 1965). This species was originally described from specimens collected on rotten driftwood in the sea in Florida, USA (Kohlmeyer, 1965). Later, Ginns and Malloch (1977) re-described this genus. *Halocyphina* occurs as a saprobe in coastal marine environments, particularly on the roots and wood of mangroves (Hyde, 1989). It is distributed in Andaman and Nicobar Islands, Brunei, India, Indonesia, Malaysia, Seychelles, Thailand, and the USA (Alias & Jones, 2000; Venkateswara et al., 2001; Prasannarai & Sridhar, 2003; Fryar et al., 2004). The taxonomic classification of *Halocyphina* is placed under *Niaceae* in Index Fungorum and GenBank; however, MycoBank and Hyde et al. (2024a) have placed it under *Cyphellopsidaceae* Jülich.

Halocyphina is characterised by cyphelloid basidiomata, which are initially globose with a short stipe and later develop into a funnel-shaped form with a saucer-like hymenium that is pale yellow or pale orange-yellow (Ginns & Malloch, 1977). The external surface of the basidiomata is covered with numerous scattered hairs that are wavy, hyaline, refractive, and not incrusted (Ginns & Malloch, 1977). The context comprises closely packed hyphae oriented more or less parallel to the hymenium (Ginns & Malloch, 1977). Microscopically, the basidiospores are subglobose, hyaline, smooth, indextrinoid, and inamyloid (Ginns & Malloch, 1977). Basidia are short, broad, clavate or cylindrical, with a narrow base and 2–4 sterigmata (Ginns & Malloch, 1977). The hyphae are hyaline, thin-walled, occasionally branched, and exhibit rare clamp connections (Ginns & Malloch, 1977).

Halocyphina shares similarities with *Henningsomyces* Kuntze and *Rectipilus* Agerer, but is distinguished from both by its marine habitat and the presence of a covered hymenium at maturity (Ginns & Malloch, 1977). Additionally, it differs from the latter genera by having hyaline and unincrusted hairs (Ginns & Malloch, 1977).

Type species: *Halocyphina villosa* Kohlm. & E. Kohlm.



Note a Basidiospores. b Basidium. c Exterior hairs on basidiomata. Scale bar: a–c = 10 μm.

Source Redrawn from Ginns and Malloch (1977). For original basidiomata, refer to Ginns and Malloch (1977).

Figure 5.36 *Halocyphina villosa*

5.3.1.39 *Merismodes* Earle

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.37

Classification: *Niaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Merismodes was established by F.S. Earle (1909) with *M. fasciculata* as the type species, described initially as *Cantharellus fasciculatus* from bark in New York, USA (Earle, 1909). Members of *Merismodes* are saprobic and widely distributed (Silva-Filho et al., 2023; He et al., 2019). Index Fungorum (2025) lists 20 records for *Merismodes*, whereas Species Fungorum (2025) recognises 12 species worldwide. The

taxonomic classification of *Merismodes* is placed under *Niaceae* in Index Fungorum and MycoBank; however, Hyde et al. (2024a) have placed it under *Cyphellopsidaceae Jülich.*

Members of *Merismodes* are characterised by minuscule basidiomata, gregarious, and growing in clusters (Adamčík, 2001). The receptacles are cyphelloid, cupulate or tubular, pendant or sessile, with a smooth hymenium and a covering of yellow-brown to brown hairs (Adamčík, 2001; Silva-Filho et al., 2023). The subiculum is either developed or absent (Silva-Filho et al., 2023). The external hyphae are thick-walled, straight, unbranched, yellow to brown pigmented, terminal ends incrusted or smooth, obtuse to inflated, and inamyloid (Adamčík, 2001; Silva-Filho et al., 2023). The trama can be gelatinous or non-gelatinous (Silva-Filho et al., 2023). Basidiospores are ellipsoid, subglobose, cylindrical, allantoid, or subfusiform, smooth, hyaline, thin-walled, and inamyloid (Silva-Filho et al., 2023). Basidia are cylindrical to clavate, typically 4-spored, but occasionally 2-spored, and cystidia are absent or rarely present (Silva-Filho et al., 2023). Clamp connection present or absent (Silva-Filho et al., 2023).

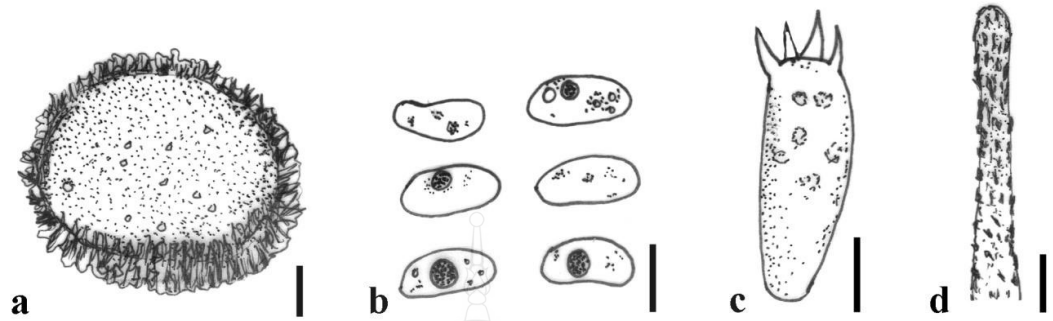
Taxonomic placement of *Merismodes* has been revised several times. Initially, Donk (1951) classified it in *Cyphellaceae* Burnett, later transferred to *Cyphellopsidaceae* Jülich (Jülich, 1982), then to *Crepidotaceae* (S. Imai) Singer (Moser, 1983), and most recently to *Niaceae* Jülich (Silva-Filho et al., 2023). Molecular phylogenetic analyses (ITS and LSU) confirmed *Merismodes* as a monophyletic lineage. Silva-Filho et al. (2023) reported three new combinations: *M. monacha* (Speg.) Silva-Filho, Mombert & Menolli, *M. filipendula* (Læssøe) Silva-Filho & Menolli, and *M. subsphaerospora* (Mombert) Silva-Filho, Mombert & Menolli.

Synonymy: *Cyphellopsis* Donk, *Maireina* W.B. Cooke, *Phaeocyphellopsis* W.B. Cooke, *Pseudodasyscypha* Velen.

Type species: *Merismodes fasciculata* (Schwein.) Donk

Basionym: *Cantharellus fasciculatus* Schwein.

Other accepted species: (refer to Species Fungorum – *Merismodes*)



Note a Basidiomata. b Basidiospores. c Basidia. d External hyphae. Scale bar: a = 0.5 mm, b–d = 10 µm.

Source Redrawn from Silva-Filho et al. (2023). For original basidiomata, refer to Silva-Filho et al. (2023).

Figure 5.37 *Merismodes monacha* (ALV30536)

5.3.1.40 *Woldmaria* W.B. Cooke

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.38

Classification: *Niaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Woldmaria is a monotypic genus established by W.B. Cooke in 1961 in honour of the Swedish mycologist S. Woldmar (Cooke, 1961; Piątek & Bujakiewicz, 2004). Initially, the genus was classified under *Cyphellopsidaceae* Jülich (Cooke, 1961) but later reclassified under *Niacea* Jülich (Jülich, 1981). The type species, *W. crocea*, was initially described as *Solenia crocea* P. Karst., based on a specimen collected on a dead frond (rhachis) of *Struthiopteris germanica* in Finland (Cooke, 1961). *Woldmaria crocea* was synonymised with *W. filicina* (Knudsen & Hansen, 1996). This genus is saprobic and host-specific on dead parts of ferns, primarily in *Matteucia struthiopteris* (Dam & Dam-Elings, 1991; Piątek & Bujakiewicz, 2004). It is distributed across Europe and North America, including Austria, Canada, Denmark, Finland, Germany, Norway, Poland, Romania, Sweden, the Czech Republic, and the USA (Knudsen & Hansen, 1996; Piątek & Bujakiewicz, 2004; Bresinsky, 2018). The taxonomic classification of *Woldmaria* is

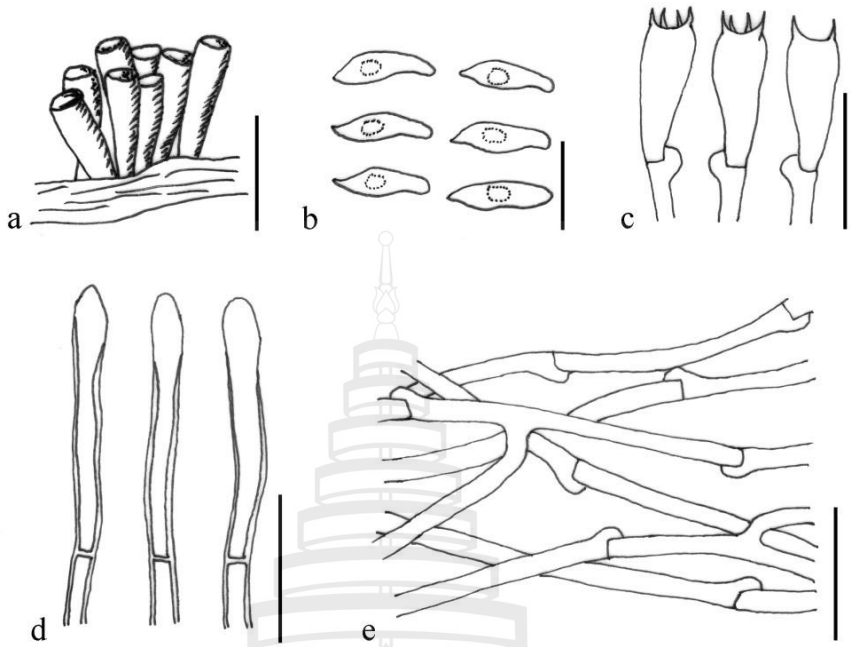
placed under *Niaceae* in Index Fungorum and GenBank; however, MycoBank and Hyde et al. (2024a) have placed it under *Cyphellopsidaceae* Jülich.

Woldmaria is characterised by its annual, minute, and densely gregarious basidiomata, cylindrically elongated, sessile, and inrolled margins (Piątek & Bujakiewicz, 2004), brown, smooth, and covered with yellow-brown hairs on the surface, while the hymenial surface is brown (Piątek & Bujakiewicz, 2004). The marginal hairs are thick-walled, cylindrical, acuminate, smooth, and septate with a yellow-brown base and hyaline tip (Piątek & Bujakiewicz, 2004). Microscopically, basidiospores are fusiform, apiculate, smooth, and hyaline, containing a central oil drop (Piątek & Bujakiewicz, 2004). Basidia are clavate, four-spored, and clamped at the base (Piątek & Bujakiewicz, 2004). The hyphal system is monomitic, consisting of thin-walled, branched, and clamped hyphae (Piątek & Bujakiewicz, 2004).

Bodensteiner et al. (2004) utilised morphological characteristics and phylogenetic analysis (ITS) to delineate *Woldmaria* from other genera. Recently, Silva-Filho et al. (2023) found that *Woldmaria* forms a sister clade with *Eoscyphella* Silva-Filho, Stevani & Menolli based on molecular analysis (LSU). *Woldmaria* is also morphologically similar to *Eoscyphella*; however, the former is distinct from the latter by the absence of conspicuous long hairs in the receptacle, its subglobose to broadly ellipsoid basidiospores, regularly bi-spored basidia, and unclamped hyphae (Silva-Filho et al., 2023).

Type species: *Woldmaria filicina* (Peck) Knudsen

Basionym: *Solenia filicina* Peck



Note a Basidiomata. b Basidiospores. c Basidia. d Marginal hairs. e Hyphae. Scale bar: a = 2 mm, b = 10 µm, c–e = 30 µm.

Source Redrawn from Piątek and Bujakiewicz (2004). For original basidiomata, refer to GBIF (2025).

Figure 5.38 *Woldmaria filicina* (KRAM F-51212)

Omphalotaceae Bresinsky, in Kämmerer, Besl & Bresinsky, *Pl. Syst. Evol.* 150(1-2): 113

Omphalotaceae was established by A. Kämmerer, H. Besl & A. Bresinsky in 1985, with *Omphalotus* Fayod as the type genus (Kämmerer et al., 1985). *Omphalotaceae* is characterised by morphologically diverse marasmioid and gymnopoid agaric basidiomata (Oliveira et al., 2019). He et al. (2024) reported 16 genera in family *Omphalotaceae*: *Anthracophyllum* Ces., *Caripia* Kuntze, *Collybiopsis* (J. Schröt.) Earle, *Connopus* R.H. Petersen, *Gymnopanella* Sand.-Leiva, J.V. McDonald & Thorn, *Gymnopus* (Pers.) Gray, *Hymenoporus* Tkalčec, Mešić & Chun Y. Deng, *Lentinula* Earle, *Mycetinis* Earle, *Neonothopanus* R.H. Petersen & Krisai, *Omphalotus*, *Paragymnopus* J.S. Oliveira, *Paramycetinis* R.H. Petersen, *Pseudomarasmius* R.H. Petersen & K.W.

Hughes, *Pusillomyces* J.S. Oliveira, and *Rhodocollybia* Singer. Members of this family are distributed worldwide and are saprotrophic or parasitic (Oliveira et al., 2019).

5.3.1.41 *Lentinula* Earle

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.39

Classification: *Omphalotaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Lentinula was introduced by Earle in 1909 (Earle, 1909), initially typified by *Lentinus cubensis* Berk. & M.A. Curtis, which later synonymised with *Lentinula boryana* (Berk. & M.A. Curtis) Pegler (Pegler, 1975; Menolli et al., 2022). Initially, *Lentinula* was considered a synonym of *Lentinus* Fr., but morphological differences in hyphal structure and type of wood rot types eventually established *Lentinula* as a distinct genus (Pegler, 1983a; Redhead & Ginns, 1985; Capelari et al., 2010). Phylogenetic analyses further supported this distinction. Species of this genus are wood-decaying white rot fungi found widely across Asia-Australasia, the Americas, and Madagascar (Chen et al., 2016a; Menolli et al., 2022). *Lentinula edodes* (Berk.) Pegler, commonly known as *shiitake* 'oak mushroom' in Japan or *xiang-gu* 'fragrant mushroom' in China, is one of the most cultivated edible mushrooms globally (Chen et al., 2016a; Menolli et al., 2022).

The basidiomata of *Lentinula* are typically convex to applanate, fleshy, smooth, and glabrous when young, sometimes become squamose or fissured with maturity, and have entire or minutely serrulate edges (Pegler, 1983a). Lamellae are adnate to adnexo-sinuate, initially free from the stipe, whitish at first, but discolouring to brownish or vinaceous as they mature, and are crowded (Pegler, 1983a). Stipe can be central or eccentric, cylindrical or compressed, and solid (Pegler, 1983a). Veils are cortinoid, fugacious, and typically remain on the pileus margin (Pegler, 1983a). The hyphal system is monomitic, characterised by inflated, sclerified generative hyphae, and exhibits constricted septa at clamp connections (Pegler, 1983a). Basidiospores are small, ovo-ellipsoid to ellipso-cylindric, hyaline, inamyloid, indextrinoid, thin-walled, and produce a white spore deposit (Pegler, 1983a). Pleurocystidia are absent (Pegler, 1983a).

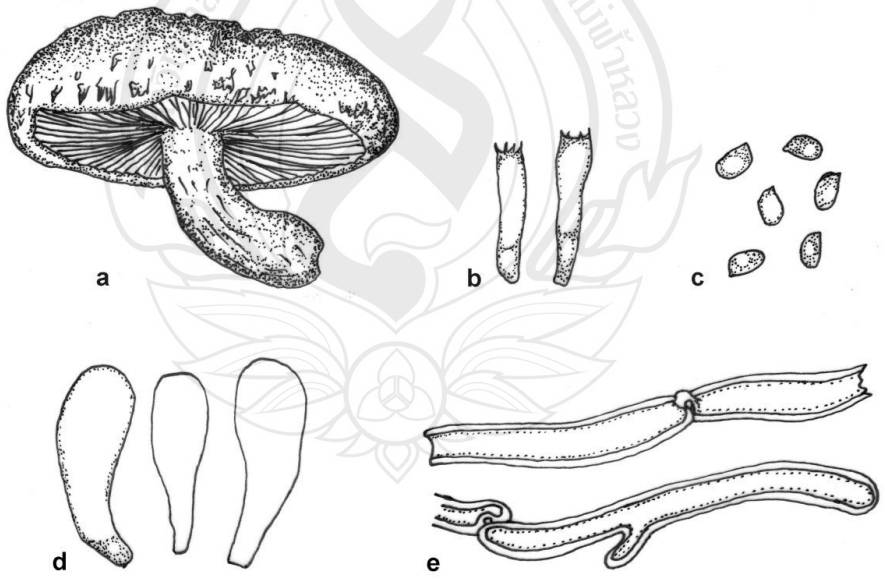
Hibbett and Vigalys (1993) conducted the first phylogenetic study on *Lentinula,* demonstrating its closer relationship to *Collybia* (Fr.) Staude than to *Lentinus*. Capelari et al. (2010) used both morphological and phylogenetic analysis (LSU) to identify *L. raphanica* (Murrill) J.L. Mata & R.H. Petersen. More recently, multi-gene phylogenetic analyses (ITS, LSU, and *tef1-α*), morphological characters, and mating compatibility have been used to delineate species within *Lentinula* (Menolli et al., 2022). Index Fungorum (2025) reports 17 records of *Lentinula,* but only 11 species are recognised worldwide (Menolli et al., 2022; Oliveira et al., 2022). Advances in technology have also enabled the complete mitochondrial genome of this species to be determined using next-generation sequencing (Chen et al., 2016a; Yang et al., 2017c).

Synonymy: *Shitaker* Lloyd

Type species: *Lentinula boryana* (Berk. & Mont.) Pegler

Basionym: *Lentinus cubensis* Berk. & M.A. Curtis

Other accepted species: (Species Fungorum – search *Lentinula*)



Note a Basidiomata (×1). b Basidia (×1000). c Basidiospores (×1000). d Cheilocystidia (×1000). e Context hyphae (×500).

Source Redrawn from Pegler (1983a).

Figure 5.39 *Lentinula edodes*

Physalacriaceae Corner, *Beih. Nova Hedwigia* 33: 10

Physalacriaceae was established by E.J.H. Corner in 1970, with *Physalacria* Peck as the type genus (Corner, 1970). He et al. (2024) reported 32 genera recognised in this family worldwide. *Physalacriaceae* accommodates a wide range of basidiomata types: agaricoid, cantharelloid, clavarioid, secotioid, and corticoid basidiomata and is characterised by narrowly clavate basidia, thin-walled, smooth, ellipsoidal, cylindrical, fusiform, or lacrimiform basidiospores, and a monomitic hyphal system (Henkel et al., 2010; Moreau et al., 2015; Park et al., 2017). Molecular phylogenetic analyses confirmed monophyly in *Physalacriaceae* (Moncalvo et al., 2002; Matheny et al., 2006). Members of *Physalacriaceae* are distributed worldwide and are mainly saprobic, although some species are parasitic (Park et al., 2017). Some members of this family are valuable edible mushrooms (*Flammulina velutipes* (Curtis) Singer), while some are forest pathogens (*Armillaria* (Fr.) Staude) (Park et al., 2017).

5.3.1.42 *Anastrophella* E. Horak & Desjardin

Index Fungorum, Facesoffungi, MycoBank, Fig. 5.40

Classification: *Physalacriaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota*, Fungi

Anastrophella was established by E. Horak & Desjardin in 1994, with *A. subpeltata* as the type species (Horak & Desjardin, 1994). Species of *Anastrophella* are regarded as terrestrial and saprobic fungi (Horak & Desjardin, 1994). The etymological meaning of "*Anastrepho*" is turned upside down or inverted, referring to the alignment of the pileus to the stipe (Horak & Desjardin, 1994). The monotypic taxon *Physalacria* section *Pileolina* Singer was established by Singer for *Physalacria subpeltata* Redhead, E. Horak & Desjardin, and was later recombined as *A. subpeltata* (Singer, 1976; Horak & Desjardin, 1994). Morphologically, *Anastrophella* is characterised by nutant and minute basidiomata, with inverted-cupulate pilei and smooth basidiospores, a relatively long, central pseudo-stipe, and a hymeniform pileipellis composed of smooth, vesiculose cells and pilocystidia (Horak & Desjardin, 1994). Basidiospores are ellipsoid or subfusiform, light in colour, hyaline, and inamyloid (Horak & Desjardin, 1994).

Anastrophella is closely related to *Gloiocephala* Massee and *Physalacria* Peck (Horak & Desjardin, 1994). Additionally, the basidiomata of *Hispidocalyptella* E. Horak & Desjardin are morphologically similar to those of *Anastrophella* species (Horak & Desjardin, 1994). However, *Anastrophella* can be distinguished by its hymeniform pileipellis composed of clavate or vesiculose cells and pilocystidia (Horak & Desjardin, 1994). The identification of *Anastrophella* species relies solely on macro- and micro-morphological characteristics, as no molecular evidence has been reported (He et al., 2019).

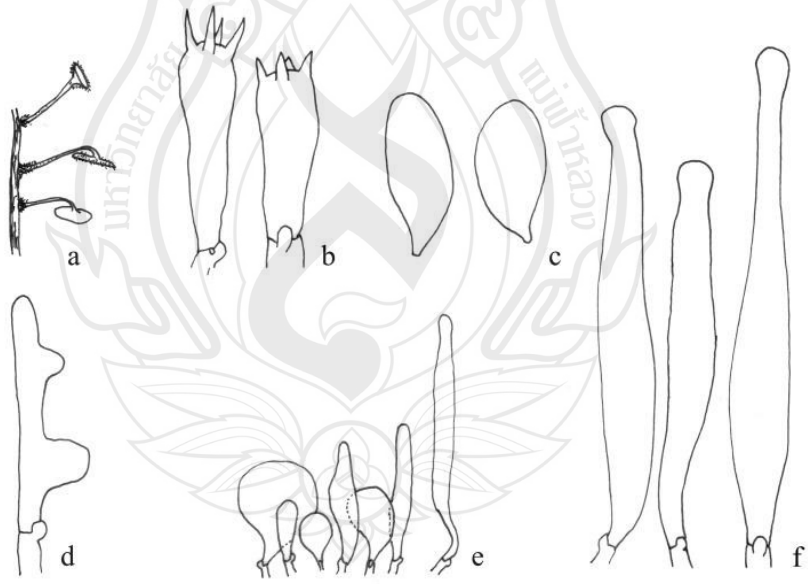
Type species: *Anastrophella subpeltata* (Redhead) E. Horak & Desjardin

Basionym: *Physalacria subpeltata* Redhead

Other accepted species:

P. macrospora E. Horak & Desjardin

P. podocarpicola Issh. Tanaka



Note a Basidiomata (×3). b Basidia (×1000). c Basidiospores (×2000). d Terminal cell of cortical hyphae of stipe (×1000). e Pileipellis with pilocystidia (×500). f Hymenial cystidia (×1000).

Source Redrawn from Horak and Desjardin (1994).

Figure 5.40 *Anastrophella macrospora* (PDD, holotype)

5.3.1.43 *Epicnaphus* Singer

Index Fungorum, Facesoffungi, MycoBank, Fig. 5.41

Classification: *Physalacriaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Epicnaphus was established by Rolf Singer to accommodate *E. phalaropes* as its type species (Singer, 1960). The type specimen was collected from a fallen, dead branch of a dicotyledonous tree in the Bolivian rainforest (Singer, 1960). Subsequently, *E. longispora* was introduced by Raithelhuber in 1973 (Patouillard & Gaillard, 1888). *Epicnaphus* species are primarily found in South America, including Argentina (He et al., 2019).

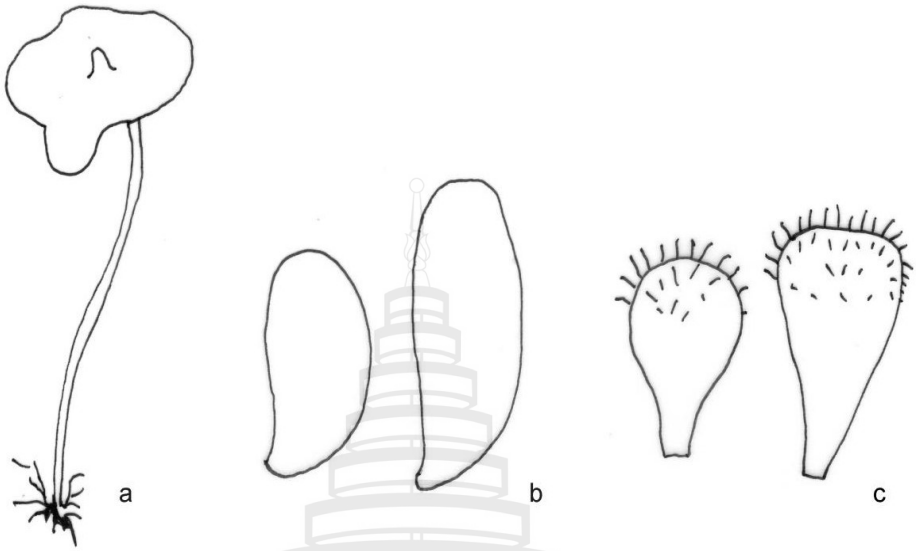
Epicnaphus species exhibit distinct mycenoid-stereoid basidiomata with a centrally stipitate structure, a smooth hymenial surface, and basal mycelium (Singer, 1960). Both the pileus and the stipe are pigmented, and the epicutis of the pileus has a hymeniform to subhumeniform structure composed of clavate or clavate-subvesiculose elements (Singer, 1960). The upper portion features thin, diverging rotalis-type setulae (Singer, 1960). Basidiospores are ellipsoid, medium-sized, and inamyloid, while dermatocystidia and hymenial cystidia are absent (Singer, 1960). The hyphae are non-gelatinised and pseudoamyloid (Singer, 1960).

The identification of *Epicnaphus* species was based on macro- and micro-morphological characteristics due to a lack of molecular data (He et al., 2019). Index Fungorum (2025) lists three records of *Epicnaphus*; however, He et al. (2019) and Hyde et al. (2024a) recognise only two species. The genus is thought to be closely related to *Marasmius* section *Sicci* Singer. It differs by its smooth hymenial surface and the presence of rotalis-type setulae among epicuticular elements (Singer, 1960). Additionally, the stipe of *Epicnaphus* species is either institious, rhizomorphic, or directly attached to the substratum, further distinguishing them from other species in the section (Singer, 1960).

Type species: *E. phalaropus* Singer

Other accepted species:

E. longispora Raithelh.



Note a Basidiomata (×4). b Basidiospores (×2000). c Epicuticular broom cells (×1000).
Source Redrawn from Singer (1960).

Figure 5.41 *Epicnaphus phalaropus*

5.3.1.44 *Flammulina* P. Karst.

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.42

Classification: *Physalacriaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

The genus *Fammulina* was established in 1891 by Petter Adolf Karsten. *Flammulina,* which includes edible mushrooms, is cosmopolitan in distribution and typically found in deciduous forests (Ge et al., 2008). *Flammulina velutipes* (Curtis) Singer, commonly known as "*Enokitake*", is recognised for its nutritional and medicinal properties and is one of the most widely cultivated mushrooms worldwide (Ge et al., 2008). Initially, *Flammulina* was considered a monotypic genus until *F. ononidis* Arnolds was separated from *F. velutipes* (Arnolds, 1977; Ge et al., 2008). Subsequently, the use of different techniques, such as mating studies, restriction fragment length polymorphism (RFLP) patterns, and phylogenetic studies (ITS, *tef1-α*, *rpb2*, and HD1) led to the

identification of different species (Bas, 1983; Hughes et al., 1999; Petersen et al., 1999; Methven et al., 2000; Ge et al., 2008; Ge et al., 2015; Wang et al., 2018). *Flammulina* species are characterised by a smooth, sticky pileus that is viscid when wet, yellowish lamellae that are adnate to adnexed, inamyloid basidiospores, and a suprapellis consisting of a hymeniform or palisadic layer over a gelatinised hypodermium interspersed with pilocystidia (Ge et al., 2015).

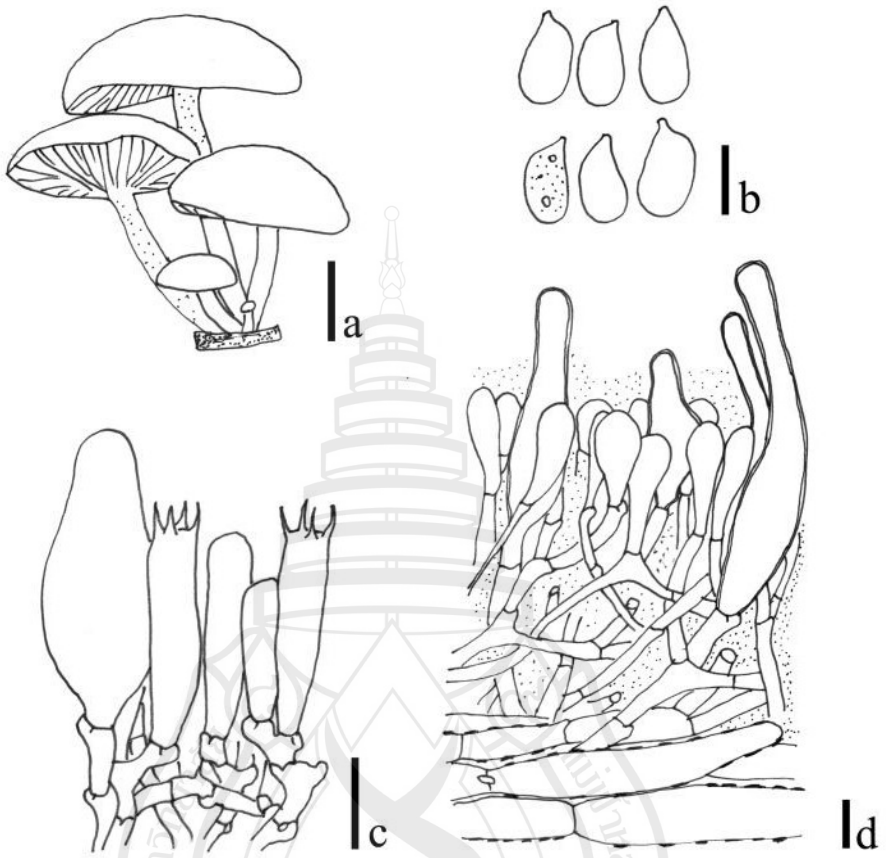
Index Fungorum (2025) reports 36 records of *Flammulina*; however, Hyde et al. (2024) recognised approximately 15 species worldwide. Regarding medicinal properties, a new group of antimicrobial compounds, enokipodins A, B, C, and D, has been produced from the mycelium culture of *F. velutipes* (Ishikawa et al., 2005). Furthermore, *F. velutipes* is renowned for its anti-cancer properties (Wang et al., 2018).

Synonymy: *Collybidium* Earle, *Myxocollybia* Singer, *Myxocollybia* Singer

Type species: *Flammulina velutipes* (Curtis) Singer

Basionym: *Agaricus velutipes* Curtis

Other accepted species: (Species Fungorum – search *Flammulina*)



Note a Basidiomata. b Basidiospores. c Subhymenium and hymenium with pleurocystidia and basidia. d Radial section of pileipellis. Scale bar: a = 1 cm, b = 5 μm, c–d = 10 μm.

Source Redrawn from Ge et al. (2008).

Figure 5.42 *Flammulina yunnanensis* (HKAS41344, holotype)

5.3.1.45 *Manuripia* Singer

Index Fungorum, Facesoffungi, MycoBank, Fig. 5.43

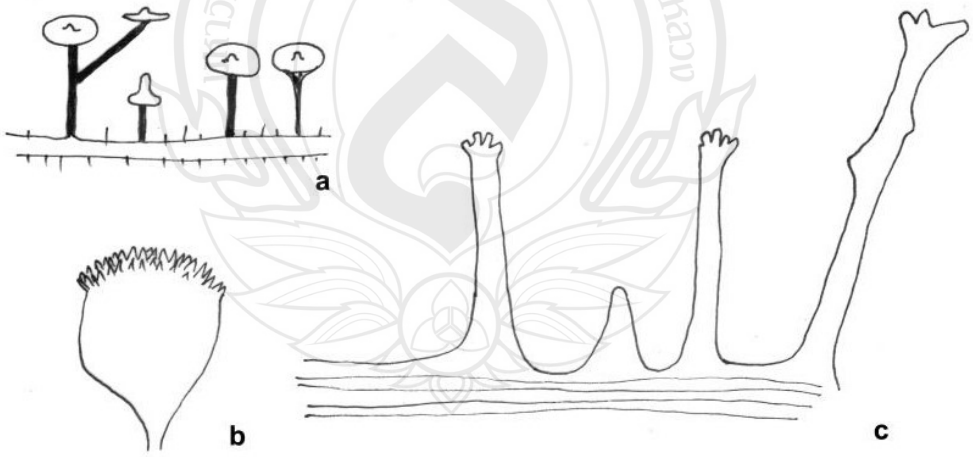
Classification: *Physalacriaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Manuripia is a monotypic genus established by Rolf Singer, with *M. bifida* as the type species (Singer, 1960). The specimen was collected from a dead fallen woody

stick of a dicotyledonous plant in the rainforest in Bolivia (Singer, 1960). *Manuripia* is characterised by centrally stipitate and pileate basidiomata, a hymenial surface that is smooth or with few low veins, and pigmentation on the pileus and stipe (Singer, 1960). The epicutis of pileus consists of balloon-shaped elements with short divergent setulae (Singer, 1960). Hymenial cystidia are absent in *Manuripia* (Singer, 1960). Basidiospores are ellipsoid and inamyloid (Singer, 1960). Hyphae are inamyloid (Singer, 1960). Stipe is sometimes branched and arises from rhizomorphs (Singer, 1960).

Manuripia roughly corresponds to section Hygrometrici of *Marasmius* Fr., but it differs in having rhizomorphigenous stipes that may be branched and in the absence of lamellae (Singer, 1960). *Manuripia* differs from section *Marasmius* in the absence of collarium, as well as the combination of smooth, flat pileus and inamyloid hyphae (Singer, 1960). Additionally, *Manuripia* differs from both these sections in the crust-like aggregation of the setulae of the epicuticular broom cells (Singer, 1960). No molecular evidence is available for *Manuripia* (He et al., 2019).

Type species: *Manuripia bifida* Singer



Note a Basidiomata, ×4. b Element of epicutis, ×1000. c Rhizomorph, ×1000.
Source Redrawn from Singer (1960).

Figure 5.43 *Manuripia bifida*

5.3.1.46 *Physalacria* Peck

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.44

Classification: *Physalacriaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota*, Fungi

Physalacria, the type genus of the family *Physalacriaceae* Corner, was established by C.H. Peck (1882) with *Physalacria inflata* as the type species (Peck, 1882; Kirk et al., 2008). The type species was described as *Mitrula infalta* from specimens collected on bark in South Carolina, USA (Peck, 1882). The genus was initially placed in *Clavariaceae* Chevall. (Clements & Shear, 1931; Baker, 1941; Corner, 1950) or *Thelephoraceae* Chevall. (McGuire, 1939), and later, the genus was reclassified as *Physalacriaceae* (Berthier, 1985). Members of *Physalacria* are saprotrophic on several tree species, including *Cryptomeria*, *Podocarpus*, and bamboos (Qin & Yang, 2016). *Physalacria* are distributed worldwide, including Africa, Asia, Europe, North America, South America, and Oceania (Qin & Yang, 2016; He et al., 2019; Liu et al., 2025b). Index Fungorum (2025) lists 49 records of *Physalacria*, while Hyde et al. (2024a) recognised approximately 35 species worldwide.

Members of *Physalacria* are characterised by small (shorter than 1 cm), stipitate-cespitose, geotropic basidiomata, with globose to subconical, hollow, fertile heads borne on a central sterile stipe (Inderbitzin & Desjardin, 1999; Qin & Yang, 2016). The hymenium is smooth on the surface of the heads (Qin & Yang, 2016). Basidiospores are smooth and inamyloid, and clamp connections are abundant (Baker, 1941; Corner, 1950; Berthier, 1985; Liu et al., 2025b).

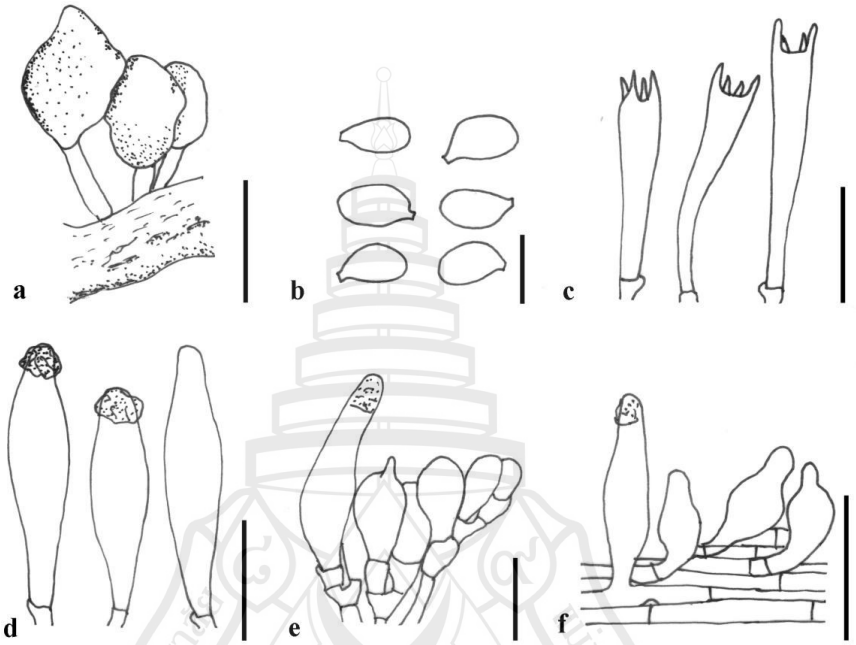
Li and Bau (2024) described a new species from China, *P. jilinensis* T. Bau & S.Y. Li, using ITS and LSU genes, along with the morphological characteristics. Liu et al. (2025b) published another new species, *P. tianzhongshanensis* A. Tohtirjap, L.R. Zhang & F. Wu. Phylogenetic analysis indicated that *Physalacria* is closely related to the corticioid genus *Cylindrobasidium* Jülich (Dentinger & McLaughlin, 2006; Qin & Yang, 2016).

Synonymy: *Baumanniella* Henn., *Eoagaricus* L. Krieg., *Hormomitaria* Corner

Type species: *Physalacria inflata* (Fr.) Peck

Basionym: *Mitrula inflata* Fr.

Other accepted species: (Species Fungorum – search *Physalacria*)



Note a Basidiomata. b Basidiospores. c Basidia. d Hymenial cystidia. e Sterile part of the hymenium. f Stipitipellis and caulocystidia. Scale bar: a = 2 mm, b = 5 μm, c = 10 μm, d–e = 20 μm, f = 30 μm.

Source Redrawn from Li and Bau (2024). For original basidiomata, refer to Li and Bau (2024).

Figure 5.44 *Physalacria jilinensis*

5.3.1.47 *Strobilurus* Singer

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.45

Classification: *Physalacriaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Strobilurus was established by R. Singer in 1962, and its type species is *S. conigenoides* (Singer, 1962b). This species was originally described from specimens collected from decaying fruit of *Magnolia* in New Jersey, USA (Singer, 1962b). Species

of *Strobilurus* are saprotrophic and exhibit substrate specificity, growing on buried cones or wood of various *Pinaceae* and angiosperm trees, as well as on seed pods or fruits, including those of *Magnolia* and *Liquidambar* (Wells & Kempton, 1971; Redhead, 1980; Wani et al., 2021; Singh et al., 2023). These fungi are distributed across subtropical and temperate regions in Asia, Europe, and North America (Qin et al., 2018; He et al., 2019).

Strobilurus is characterised by collybioid basidiomata with adnexed to almost free lamellae (Wani et al., 2021). The stipe bears a long tapering rooting base or pseudorhiza and lacks a veil (Wani et al., 2021). Basidiospores are smooth, thin-walled, non-amyloid, and white in deposit (Wani et al., 2021). Both hymenial cystidia and dermatocystidia are present in the cortical layers of the pileus and stipe (Wani et al., 2021). Additionally, the hyphal system lacks clamp connections (Wani et al., 2021; Singh et al., 2023).

In phylogenetic analyses, *Strobilurus* formed a sister group with *Xerula* Maire or *Marasmius epiphyllus* (Pers.) Fr. (Vizzini et al., 2013; Hao et al., 2014; Qin et al., 2014). Qin et al. (2018) conducted genus-specific morphological and phylogenetic analyses of *Strobilurus* species, using ITS, LSU, *rpb2*, *tef-1α*, and *tub1* markers. These analyses also examined geographical distribution, associated host trees, basidiospore sizes, and the shape of pleurocysticia (Qin et al., 2014). According to Index Fungorum (2025), there are 27 species of *Strobilurus,* while Wani et al. (2021) recognised only 13 species worldwide.

The classification of *Strobilurus* in *Physalacriaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina*, and *Basidiomycota* is in agreement in Index Fungorum, MycoBank, GenBank, UNITE, and the latest Outline of fungi and fungus-like organisms (Hyde et al., 2024a).

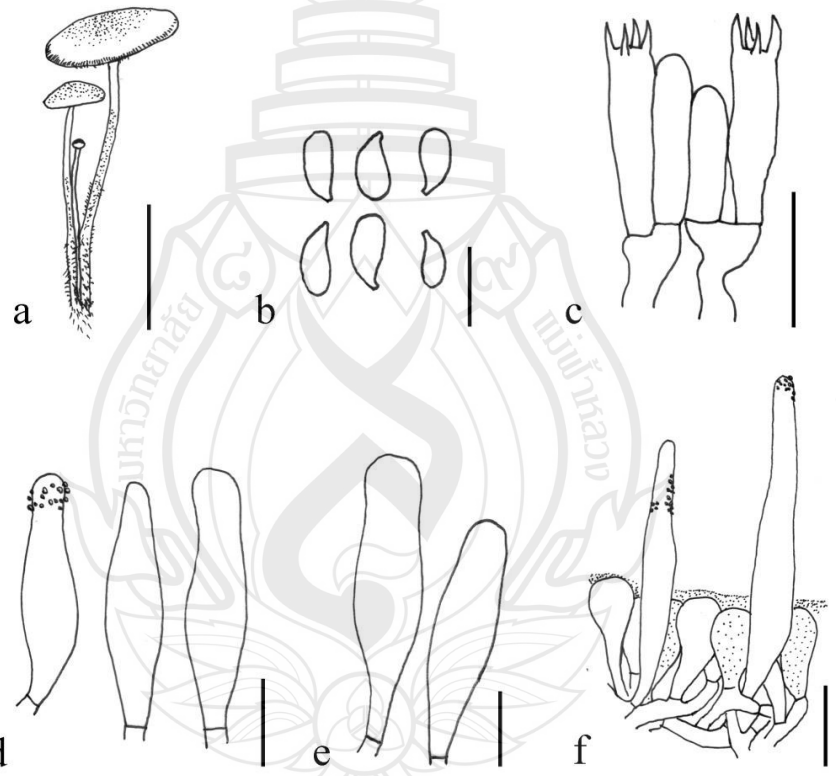
Species of *Strobilurus* have a wide range of applications, including the production of secondary metabolites and agricultural fungicides. For instance, *Strobilurus ohshimae*, a wild edible mushroom from Japan, has been a source of sesquiterpenoids known as strobilols A–D (Hiramatsu et al., 2007). Species such as *S. tenacellus* exhibit strong antifungal activity and are extensively utilised in producing broad-spectrum

strobilurin fungicides (quinone oxidase inhibitors) (Anke et al., 1977; Bartlett et al., 2002; Balba, 2007; Serra et al., 2023). For instance, strobilurins A and B show high resistance to yeasts and filamentous fungi (Anke et al., 1977). Additionally, a new sesquiterpenoid, strobiluric acid, has been isolated from *S. stephanocystis* (Hiramatsu et al., 2007).

Type species: *Strobilurus conigenoides* (Ellis) Singer

Basionym: *Agaricus conigenoides* Ellis

Other accepted species: (Species Fungorum – search *Strobilurus*)



Note a Basidiomata. b Basidiospores. c Basidia and basidioles. d Pleurocystidia. e Cheilocystidia. f Pileipellis and pileocystidia. Scale bar: a = 3 cm, b = 5 µm, c–e = 10 µm, f = 20 µm.

Source Redrawn from Qin et al. (2018). For original basidiomata, refer to Qin et al. (2018).

Figure 5.45 *Strobilurus orientalis* (HKAS 54522, holotype)

Pleurotaceae Kühner, *Bull. mens. Soc. linn. Lyon* 49: 184

Pleurotaceae was established by R. Kühner (1980) with *Pleurotus* (Fr.) P. Kumm. as the type genus (Kühner, 1980). He et al. (2024) reported six genera in this family: *Agaricochaete* Eichelb., *Hohenbuehelia* Schulzer, *Lignomyces* R.H. Petersen & Zmitr., *Pleurotus*, *Radulomycetopsis* Dhingra, Priyanka & J. Kaur, and *Resupinatus* Nees ex Gray. Members of *Pleurotaceae* are distributed worldwide and are saprotrophic (He et al., 2019). Some species, including *Pleurotus ostreatus* (Jacq.) P. Kumm., are highly edible and have potential nutraceutical and biotechnological applications (Niego et al., 2021).

5.3.1.48 *Agaricochaete* Eichelb.

Index Fungorum, Facesoffungi, MycoBank, Fig. 5.46

Classification: *Pleurotaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Agaricochaete was established by F. Eichelbaum in 1906 to accommodate two new species, *A. mirabilis* and *A. hericium*, which were collected from the East Usambara Mountains in Tanzania (Eichelbaum, 1906; Natarajan & Raman, 1980). *Agaricochaete* is a rare fungus (Pegler, 1977; Natarajan & Raman, 1980). Pegler (1977) described *A. keniensis* as a new species from Kenya, and in 1980, Natarajan & Raman described *A. indica* from India (Pegler, 1977; Natarajan & Raman, 1980).

Species of *Agaricochaete* are characterised by clitocyboid basidiomata with a depressed to infundibuliform and subhygrophanous pileus (Pegler, 1977). The lamellae are decurrent, moderately spaced, with lamellulae, and the edge of the lamellae is heteromorphic (Pegler, 1977). The stipe is well-developed, tubular and hollow, central, concolourous to the pileus, and has no veil (Pegler, 1977). Basidiospores are hyaline, cylindrical, thin-walled, and smooth, while basidia are narrowly clavate and produce four basidiospores (Pegler, 1977). The hyphal system is monomitic with clamp connections but non-gelatinised (Pegler, 1977). Cheilocystidia are present, and pleurocystidia are thick-walled, pointed, and encrusted metuloids (Pegler, 1977).

Identification of *Agaricochaete* species is based entirely on macro- and micro-morphological characteristics due to a lack of molecular evidence (He et al., 2019). *Agaricochaete* species are similar to *Hymenochaete* Lév. and *Hydnochaete* Bres. in terms of hymenium morphology; however, *Agaricochaete* is distinct in having thick lamellae (Eichelbaum, 1906).

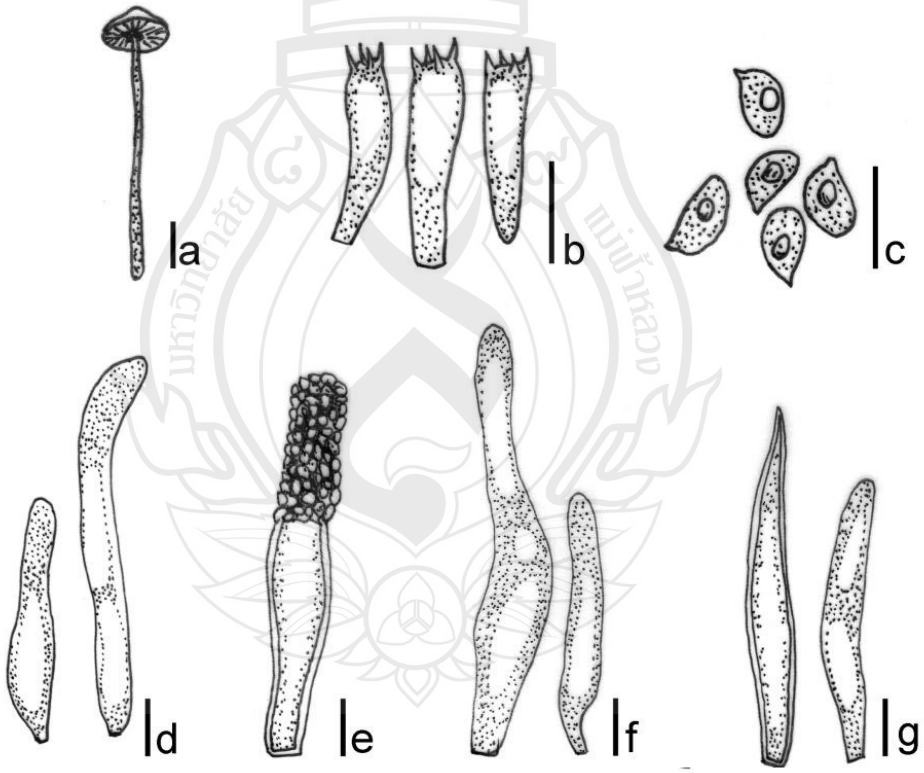
Type species: *Agaricochaete mirabilis* Eichelb.

Other accepted species:

A. hericium Eichelb.

A. indica Natarajan & Raman

A. keniensis Pegler



Note a. Basidiomata. b Basidia. c Basidiospores. d Cheilocystidia. e Pleurocystidia. f Caulocystidia. g Pileocystidia. Scale bar: a = 1 cm, b–g = 10 µm.

Source Redrawn from Natarajan and Raman (1980).

Figure 5.46 *Agaricochaete indica*

Psathyrellaceae Vilgalys, Moncalvo & Redhead, in Redhead, Vilgalys, Moncalvo, Johnson & Hopple, *Taxon* 50(1): 226

Psathyrellaceae was established by S.A. Redhead, R. Vilgalys, J.M. Moncalvo, J. Johnson & J.S. Jr Hopple (2001) with *Psathyrella* (Fr.) Quél. as the type genus (Redhead et al., 2001). He et al. (2024) reported 20 genera in this family. *Psathyrellaceae* is characterised by small to large, smooth to innately fibrillose, white to dark reddish-brown basidiomata, with dark basidiospores (Nagy et al., 2013; Örstadius et al., 2015). Many species in *Psathyrellaceae*, commonly known as inky caps, are fragile and deliquescent, exhibiting the ability to digest themselves through autodigestive chitinases and turning into a blackish inky fluid (Kües, 2000; Nagy et al., 2013; Örstadius et al., 2015). Members of *Psathyrellaceae* are distributed worldwide and are saprotrophic, commonly growing mainly on wood and plant residue (Örstadius et al., 2015).

5.3.1.49 *Cystoagaricus* Singer

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.47

Classification: *Psathyrellaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Cystoagaricus was established by Rolf Singer, with *C. strobilomyces* as the type species. Initially, this species was classified as *Nolanea strobilomyces* Murril (Singer, 1947). The type specimen was collected from decayed wood in Alachua County, USA (Singer, 1947). Species of *Cystoagaricus* are distributed across subtropical regions of America and Europe, including the USA, Argentina, Germany, Ecuador, and France (He et al., 2019). Index Fungorum (2025) reports 14 records of *Cystoagaricus*, while Muñoz et al. (2022) recognised only 11 species worldwide.

Cystoagaricus is characterised by small to medium-sized, non-deliquescent basidiomata, often found on wood (lignicolous) (Örstadius et al., 2015; Muñoz et al., 2022). Pileus exhibits a wide range of colours, including grey, brown, orangish, dark brown, or occasionally olivaceous. Its surface may be fibrillose, squamulose, spiny, or squarrose, with or without striations (Örstadius et al., 2015; Muñoz et al., 2022), and a

veil (Örstadius et al., 2015; Muñoz et al., 2022). Lamellae are often crowded, adnate to adnexed, and initially greyish, becoming dark brown with age (Örstadius et al., 2015; Muñoz et al., 2022). Stipe is fibrillose, often displaying velar remnants on its lower portion (Örstadius et al., 2015; Muñoz et al., 2022). Context is whitish and may darken with age (Örstadius et al., 2015; Muñoz et al., 2022).

Basidiospores are small to medium-sized, irregular, and typically troncoconic, subtroncoconic, subrectangular, or mitriform forms (Örstadius et al., 2015; Muñoz et al., 2022). Cheilocystidia and pleurocystidia are present, often utriform or clavate in shape (Örstadius et al., 2015; Muñoz et al., 2022).

Örstadius et al. (2015) illustrated morphological characteristics and phylogenetic analyses (ITS, LSU, *β-tub*, and *tef-1α*) to delineate species within *Cystoagaricus. Cystoagaricus* shares similarities with the genus *Nolanea,* particularly in having angular basidiospores. However, the two genera differ in shape and colour of their basidiospores, as well as the size and shape of their basidia. The basidia of *Nolanea* are typically larger and narrower compared to those of *Cystoagaricus* (Singer, 1947).

Type species: *C. strobilomyces* (Murrill) Singer

Basionym: *Nolanea strobilomyces* Murrill

Other accepted species:

C. hirtosqamulosus (Peck) Örstadius & E. Larss.

C. jujuyensis Singer

C. lepidotoides (A.H. Sm.) G. Muñoz, L.A. Parra & J.C. Zamora

C. olivaceogriseus (A.H. Sm.) Örstadius & E. Larss.

C. populinus (Britzelm.) G. Muñoz, L.A. Parra & J.C. Zamora

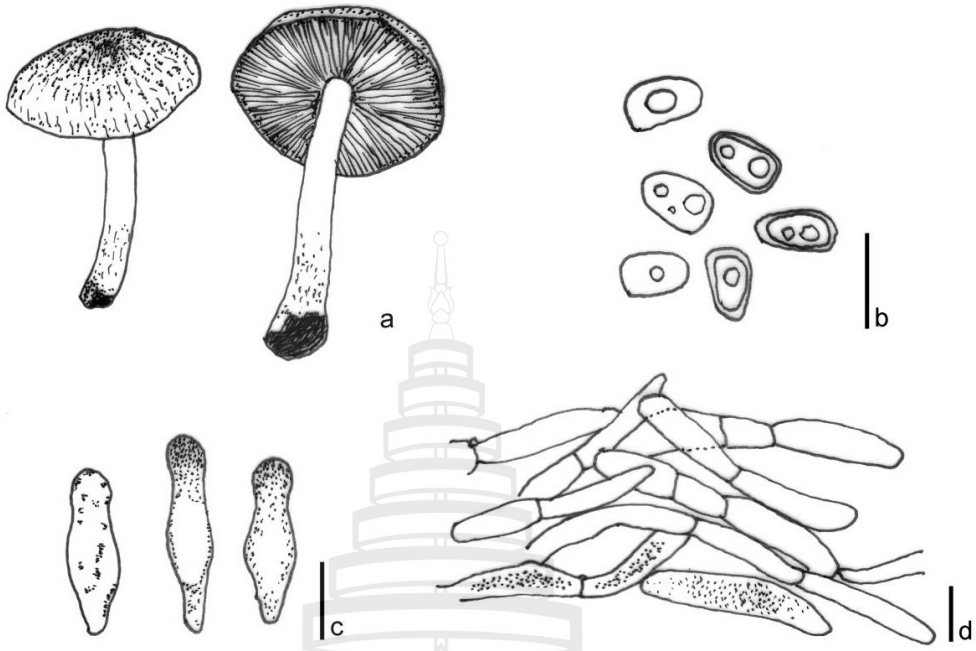
C. propinquus (A.H. Sm.) Voto

C. squarrosiceps (Singer) Örstadius & E. Larss.

C. subamarus (A.H. Sm.) Voto

C. silvestris (Gillet) Örstadius & E. Larss.

C. weberi (Murrill) Voto



Note a Basidiomata. b Basidiospores. c Pleurocystidia. d Universal veil. Scale bar: a = 10 μm, b−d = 20 μm.

Source Redrawn from Muñoz et al. (2022).

Figure 5.47 *Cystoagaricus lepidotoides* (GM2552)

5.3.1.50 *Gasteroagaricoides* D.A. Reid

Index Fungorum, Facesoffungi, MycoBank, Fig. 5.48

Classification: *Psathyrellaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Gasteroagaricoides, a monotypic genus, was established by E.A. Reid in 1986, with its type species *G. ralstoniae* (Reid, 1986). This species was originally described based on specimens collected from debris between rotting logs in Norfolk Island, Australia (Reid, 1986). Notably, *Flabellimycena* is listed in the “List of protected generic names of fungi” under the International Code of Nomenclature for algae, fungi, and plants (Kirk et al., 2013).

Gasteroagaricoides is characterised by its agaricioid basidiomata, with a convex, granular-verrucous cap and strongly curved margin (Reid, 1986). The pileus

surface is covered with thin-walled, globose, ovate, or fusiform warts (Reid, 1986). The hymenium consists of very thin lamellae with basidia interspersed with large globose cells (brachycystidia, pseudoparaphyses) but lacks cystidia (Reid, 1986). Basidiospores are symmetrical, elongate-elliptic, smooth, hyaline or sub-hyaline, with distinct walls but lack a germ pore (Reid, 1986). The hyphae have slightly thickened walls and bear clamp connections (Reid, 1986).

Species delineation of *Gasteroagaricoides* is based solely on macro- and micro-morphological characteristics, as no molecular sequences are available (Reid, 1986; He et al., 2019). *Gasteroagaricoides* is morphologically similar to *Jugisporipsathyra* J.Q. Yan, Y.G. Fan & S.N. Wang (Wang et al., 2022). However, the latter is distinct from *Gasteroagaricoides* by having a smooth and reticulate-ridged pileus (Wang et al., 2022). The genus is placed in *Psathyrellaceae* Vilgalys, Moncalvo & Redhead, though molecular evidence is needed to differentiate it from closely related genera (Wang et al., 2022).

Type species: *Gasteroagaricoides ralstoniae* D.A. Reid

Note a Thin-walled element comprising the pileal warts (×666). b Basidiospores (×666). c Basidiospores attached to a basidium (×666).

Source Redrawn from Reid (1986).

Figure 5.48 *Gasteroagaricoides ralstoniae*

5.3.1.51 *Macrometrula* Donk & Singer

Index Fungorum, Facesoffungi, MycoBank, Fig. 5.49

Classification: *Psathyrellaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

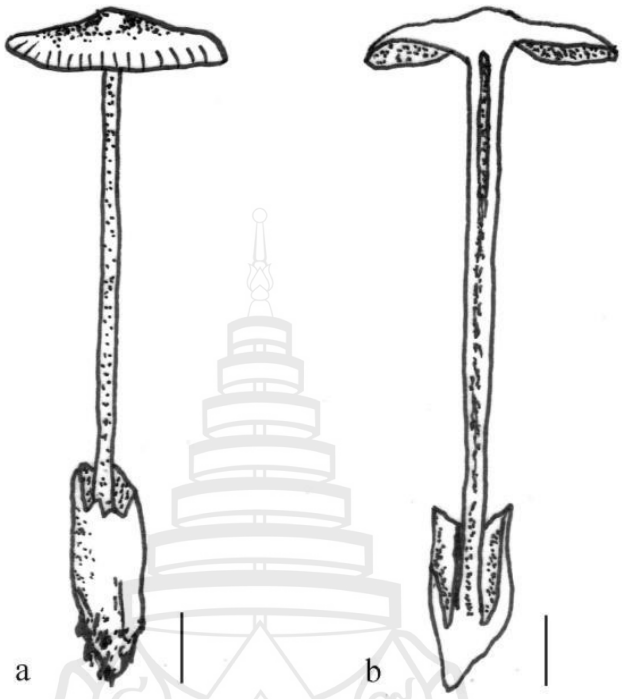
Macrometrula, a monotypic genus, was introduced by M.A. Donk and R. Singer in 1948, and its type species is *M. rubriceps* (Singer, 1948). The type species was initially classified as *Agaricus rubriceps*, based on a specimen collected from soil in the Aroid house at Kew Gardens, England (Singer, 1948). The genus is rare, as no additional specimens have been discovered since its initial description (Shaw, 1961).

Macrometrula is characterised by fleshy, campanulate to expanded, umbonate, and smooth basidiomata (Cooke, 1887). The margin is faintly striate, and the gills are free, lanceolate, crowded, and purplish brown (Cooke, 1887). The stipe is erect, fistulose, paler than the pileus, and bears mycelial roots (Cooke, 1887). The volva is saccate, whitish and torn at the margin (Cooke, 1887). Basidiospores are pale brownish, subregular, and inamyloid and feature a wide, flattened germinative pore (Singer, 1948; Shaw, 1961). The basidia are four-spored (Singer, 1948). The cystidia are ventricose upwards and attenuated or subcapitate at the apex (Singer, 1948).

Macrometrula is reported only through macro- and micro-morphological characteristics, and molecular sequences are lacking (He et al., 2019). *Macrometrula* is morphologically closely related to *Psathyrella* (Fr.) Quél. in their anatomy; however, the former is distinguished by its large, cup-shaped saccate volva (Singer, 1948).

Type species: *Macrometrula rubriceps* (Cooke & Massee) Donk & Singer

Basionym: *Agaricus rubriceps* Cooke & Massee



Note a Basidiomata. b Vertical Section of basidiomata. Scale bar: a–b = 1 cm.

Source Redrawn from Kew Botanic Garden, catalogue number: K-M000165895. For original basidiomata, refer to Kew Botanic Garden.

Figure 5.49 *Macrometrula rubriceps*

Pterulaceae Corner, *Beih. Nova Hedwigia* 33: 10

Pterulaceae was established by E.J.H. Corner (1970) with *Pterula* Fr. as the type genus (Corner, 1970). He et al. (2024) reported nine genera in this family: *Allantula* Corner, *Chaetotyphula* Corner, *Coronicium* J. Erikss. & Ryvarden, *Lepidomyces* Jülich, *Merulicium* J. Erikss. & Ryvarden, *Myrmecopterula* Leal-Dutra, Dentinger & G.W. Griff., *Phaeopterula* (Henn.) Sacc. & D. Sacc., *Pterula*, and *Pterulicium* Corner. *Pterulaceae* is characterised by coralloid or filiform basidiomata with a dimitic hyphal system (Corner, 1970; Leal-Dutra et al., 2018). Members of *Pterulaceae* are distributed worldwide and are mainly saprophytic, growing on wood or leaf litter; some species are pathogenic to plants, causing culm rot disease (Leal-Dutra et al., 2020).

5.3.1.52 *Allantula* Corner

Index Fungorum, Facesoffungi, MycoBank, Fig. 5.50

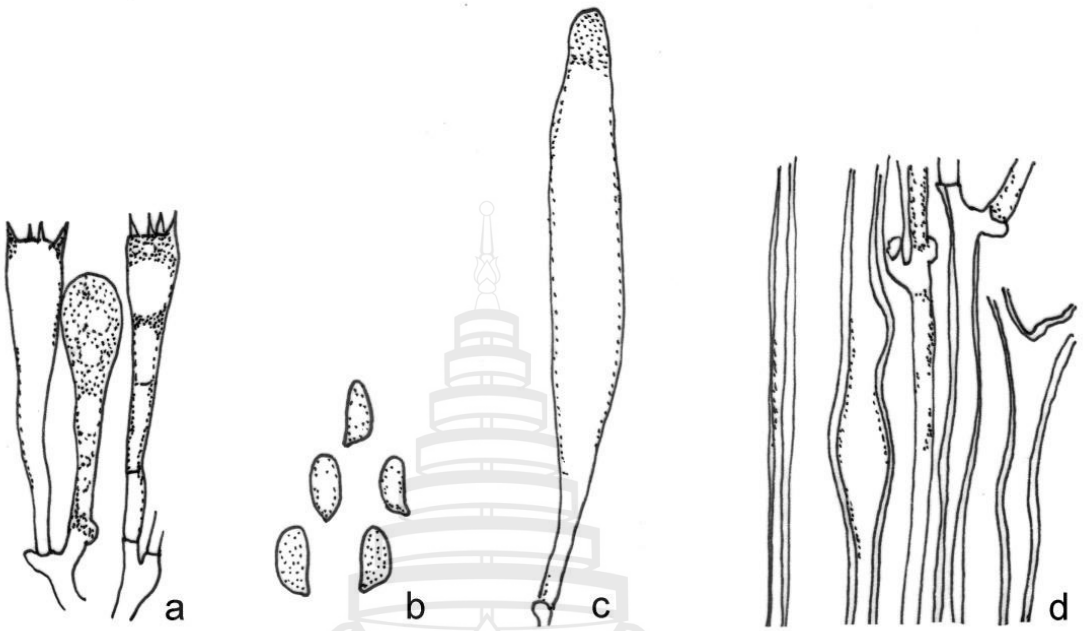
Classification: *Pterulaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

The monotypic genus *Allantula* was established by E.J.H. Corner in 1952, with *A. diffusa* as its type species (Corner, 1952a). The specimen was collected on dead branches in Brazil (Corner, 1952a). The genus is rare, as no subsequent record has been reported (Corner, 1952a; Leal-Dutra et al., 2018, 2020).

The basidiomata of *Allantula* emerge from slender rhizomorphs, which appear as small, sausage-like, decumbent swellings that are generally curved and occasionally bifid or anastomosed, with a waxy-fleshy (Corner, 1952a; Dutra et al., 2018). The rhizomorph grows along the undersurface of dead wood or bark, developing numerous adventitious branches primarily in an acropetal arrangement (Corner, 1952a). Lateral outgrowths of generative hyphae from the rhizomorph form basidia or cystidia (Corner, 1952a). The sympodial growth of subhymenial hyphae leads to thickening of the hymenium layer (Corner, 1952a).

Microscopically, the basidiospores are white, smooth, or aguttate (Corner, 1952a). The basidia are four-spored (Corner, 1952a). The hyphal system is dimitic, featuring clamped generative hyphae (Corner, 1952a); skeletal hyphae are found only in the rhizomorphs and have hyaline, thick walls that may branch or exist as intercalary segments of the generative hyphae (Corner, 1952a). Cystidia are thin-walled and are embedded within the hymenium (Corner, 1952a). Species of *Allantula* are identified solely based on the macro- and micro-morphological characteristics due to a lack of molecular evidence (Leal-Dutra et al., 2018, 2020).

Type species: *Allantula diffusa* Corner



Note a Basidia (×1000). b Basidiospores (×1000). c Cystidia (×1000). d Hypha (×1000).
Source Redrawn from Corner (1952a).

Figure 5.50 *Allantula diffusa*

5.3.1.53 *Chaetotyphula* Corner

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.51

Classification: *Pterulaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Chaetotyphula was established in 1950 by E.J.H. Corner to accommodate two species, *C. actiniceps* and *C. hyaline*, which were collected from Java and Malaysia, respectively (Corner, 1950). Species of *Chaetotyphula* are saprophytic (Corner, 1950). The genus is globally distributed, including Argentina, Brazil, Colombia, Costa Rica, Ecuador, Panama, Puerto Rico, Singapore, and Thailand (Dentinger & McLaughlin, 2006; He et al., 2019; Boonpratuang et al., 2023). Dentinger & McLaughlin (2006) used morphological characteristics and phylogenetic analyses (LSU) for species delineation

within *Chaetotyphula*. Index Fungorum (2025) reports nine records of *Chaetotyphula,* while He et al. (2019) recognised only seven species.

Species of *Chaetotyphula* are characterised by small basidiomata with the hymenium covering the entire head (Corner, 1950, 1970; Poinar & Brown, 2003). The basidiospores are broadly ellipsoid to subglobose (Corner, 1950, 1970; Poinar & Brown, 2003). Basidia are typically 2-spored, occasionally 1-spored (Corner, 1950, 1970; Poinar & Brown, 2003). Both leptocystidia and caulocystidia are elongated and thick-walled (Corner, 1950, 1970; Poinar & Brown, 2003). The hyphal system is monomitic, characterised by thin-walled generative hyphae (Corner, 1950, 1970; Poinar & Brown, 2003).

Chaetotyphula, along with *Pistillaria* Fr. and *Typhula* (Pers.) Fr. is classified within typhyloid fungi of the *Agaricales* (Corner, 1967). However, *Chaetotyphula* is distinguished from *Typhyla* in the absence of sclerotia, the lack of non-thickening hyphae, and the presence of thick-walled cystidia (Boonpratuang et al., 2023). *Chaetotyphula* and *Pistillaria* are taxonomically closer due to the absence of sclerotium in their basidiomata (Boonpratuang et al., 2023). However, *Pistillaria* lacks cystidia (Corner, 1950, 1953; Boonpratuang et al., 2023). Additionally, *Chaetotyphula* is morphologically similar to *Actiniceps* Berk. & Broome in terms of small size, lack of pigmentation, the presence of hymenial and/or caulocystidia, hyaline appearance, and smooth-walled, globose to ellipsoid basidiospores (Dentinger & McLaughlin, 2006; Boonpratuang et al., 2023).

Type species: *Chaetotyphula hyalina* (Jungh.) Corner

Basionym: *Typhula hyaline* Jungh.

Other accepted species:

C. actiniceps (Petch) Corner

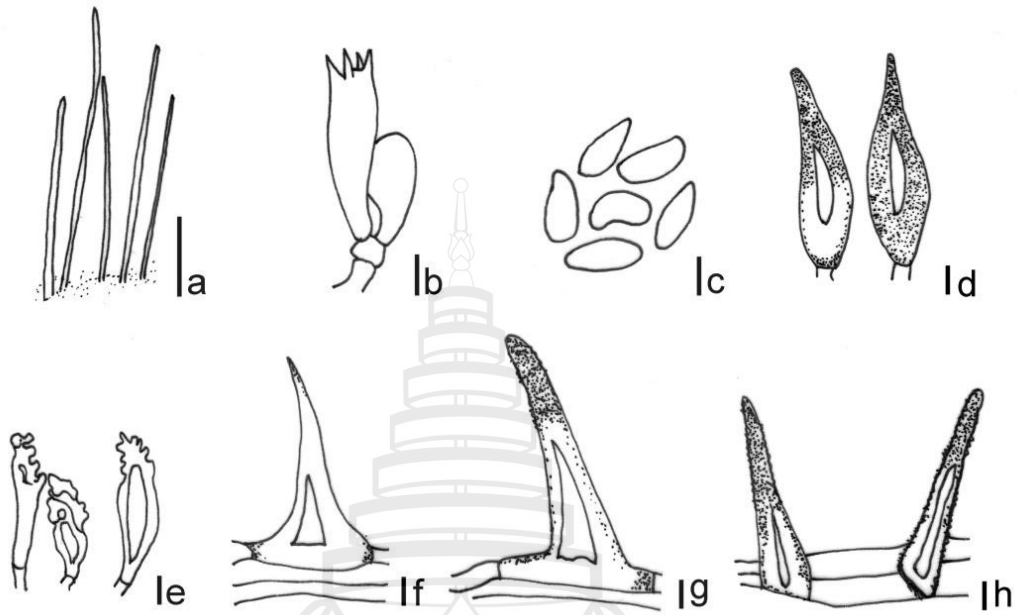
C. amylochaete Singer

C. columbiana Singer

C. gelatinosa Corner

C. montana Singer

C. tetraspora Corner



Note a Basidiomata. b Basidia. c Basidiospores. d Head-metuloid cystidia. e Thick- and thin-walled head diverticulate. f Cystidia without metuloid. g Triangular cystidia with metuloid. h Traingular caulocystidia with metuloid at stipe. Scale bar: a = 5 mm, b–h = 10 μm.

Source Redrawn from Boonpratuang et al. (2023). a = BBH24935, b–h = BBH01684

Figure 5.51 *Chaetotyphula columbiana*

5.3.1.54 *Parapterulicium* Corner

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.52

Classification: *Pterulaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Parapterulicium, a genus of coralloid fungi, was established by E.J.H. Corner in 1952 (Corner, 1952a). The type species, *P. subarbusculum*, was described from a collection of dead twigs and leaves in Brazilian forests (Corner, 1952a). In the same publication, Corner also described another *P. octopodites* Corner. However, in 2018, this species was reclassified as *Baltazaria octopodites* (Corner) Leal-Dutra, Dentinger &

G.W. Griff. (Leal-Dutra et al., 2018). Corner (1957) also described *P. simplex*, based on specimens collected from Argentina. Index Fungorum (2025) lists three records, while Species Fungorum (2025) recognises only two species worldwide. *Parapterulicium* species are saprophytic in Argentina and Brazil (Corner, 1952a, 1957).

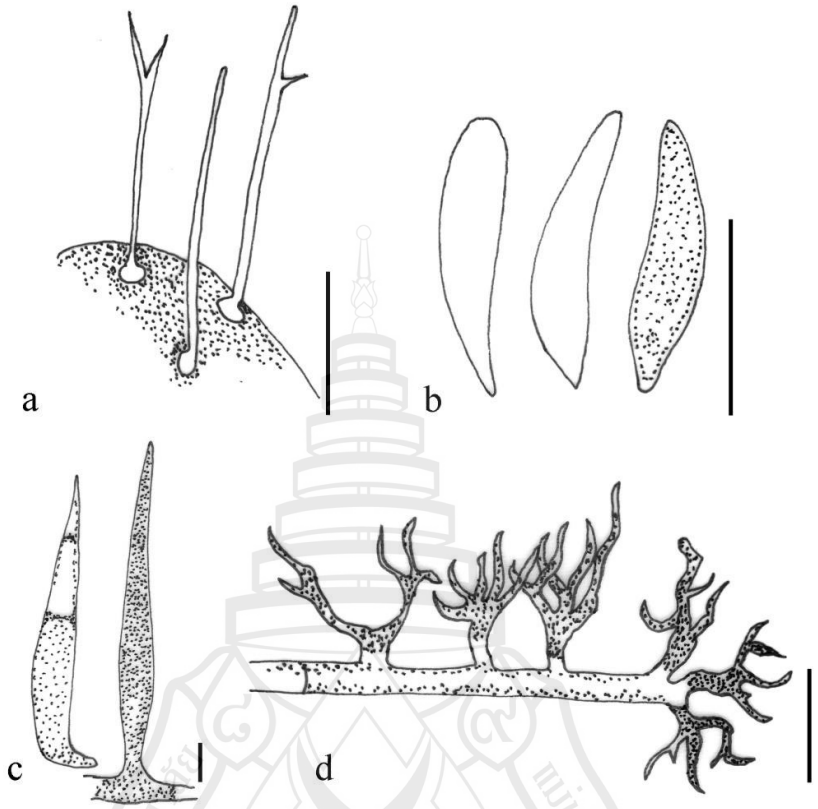
Parapterulicium is characterised by its basidiomata, which occur solitary or in small groups (Corner, 1952a). The stipe is glabrous or subfibrillose, sterile, becoming pale brownish, and is attached to substrates by a small floccose mycelial disc (Corner, 1952a). The branches are slender at the base and tapered into filiform points (Corner, 1952a). The resupinate corticoid patch of the basidiomata on hosts appears dry, floccoso-coriaceous, and light-coloured (Corner, 1952a). Gleocystidia are clavate to cylindrical, blunt, thin-walled, and extend through the thickened hymenium (Corner, 1952a). Discophyses are hyaline, slender, and abundant, with short, tapering arms emerging from the subhymenial generative hyphae (Corner, 1952a). The hyphal system is dimitic, consisting of clampless generative hyphae, while the ends of skeletal hyphae either dichophyses or appear papillate in the hymenium (Corner, 1952a).

Species delineation of *Parapterulicium* from other genera is based on morphological characteristics and phylogenetic analyses (ITS and LSU) (Leal-Dutra et al., 2018). Morphologically, *Parapterulicium* is closely related to *Pterula* Fr., particularly in its adventitious branching (Corner, 1952a). However, the latter is distinguished by its hard and horny basidiomata upon drying (Corner, 1952a). Additionally, *Parapterulicium* resembles *Pterulicium* Corner due to its corticioid state (Corner, 1952a). Nevertheless, both *Pterula* and *Pterulicium* differ from *Parapterulicium* by their lack of gloecystidia (Corner, 1952a).

Type species: *Parapterulicium subarbusculum* Corner

Other accepted species:

P. simplex Corner



Note a Basidiomata. b Basidiospores. c Gloeocystidia. d Dichophyses. Scale bar: a = 1 cm, b–d = 10 μm.

Source Redrawn from Leal-Dutra et al. (2018). For original basidiomata, refer to Leal-Dutra et al. (2018).

Figure 5.52 *Parapterulicium subarbusculum*

5.3.1.55 *Pterulicium* Corner

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.53

Classification: *Pterulaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota*, Fungi

The genus *Pterulicium* was established by Corner in 1950, with the type species *P. xylogenum* (Corner, 1952b). Most *Pterulicium* species inhibit soil or litter, whereas *P. xylogenum* is known to cause culm rot disease in bamboo (Harsh et al., 2005; Leal-Dutra et al., 2020).

The basidiomata of *Pterulicium* are typically pteruloid, rarely corticioid, appearing solitary or gregarious, and are simple or scarcely branched, with occasional significant unilateral branching (Leal-Dutra et al., 2020). The stipe can range in colour from creamy white to brown, with tips that are creamy white or pale brown on uniformly coloured basidiomata (Leal-Dutra et al., 2020). The hyphal system is dimitic, consisting of slightly thick-walled skeletal hyphae and thin-walled, often clamped generative hyphae (Leal-Dutra et al., 2020). Hymenial cystidia are usually present, while caulocystidia are only sometimes observed (Leal-Dutra et al., 2020). Basidia are terminal and vary in shape from clavate to suburniform (Leal-Dutra et al., 2020). Basidiospores can be globose, subglobose, pip-shaped, amygdaliform to subamygdaliform, or ellipsoid (Leal-Dutra et al., 2020).

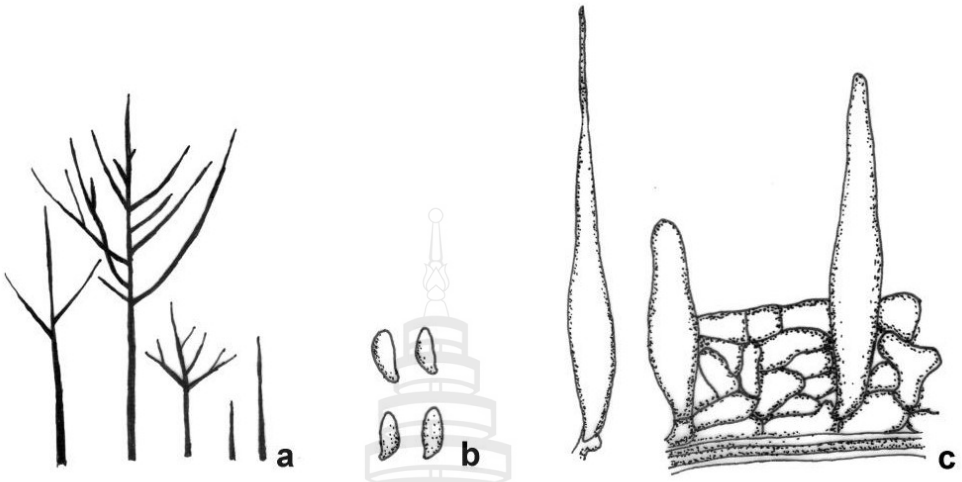
Pterulicium differs from the closely related genus *Phaeopterula* Henn. by having pigmentation only at the stipe base and mostly unbranched basidiomata. In contrast, *Phaeopterula* has a distinct brown main axis and symmetrical branching (Leal-Dutra et al., 2020). Leal-Dutra et al. (2020) used morphological and phylogenetic analyses of combined ITS, LSU, and *rpb2* to identify species within *Pterulicium,* which verified 31 species from *Pterula* Fr. and 15 from *Deflexula* Corner to *Pterulicium* (Olariaga et al., 2022). Mycobank (2025) has recognised 42 species within *Pterulicium.*

Synonymy: *Deflexula* Corner

Type species: *Pterulicium xylogenum* (Berk. & Broome) Corner

Basionym: *Clavaria xylogena* Berk. & Broome

Other accepted species: (Species Fungorum – search *Pterulicium*)



Note a Basidiomata (×2). b Basidiospores (×1000). c Caulocystidia (×1000).

Source Redrawn from Corner (1952b).

Figure 5.53 *Pterulicium fluminense* (holotype)

Strophariaceae Singer & A.H. Sm., *Mycologia* 38(5): 503

Strophariaceae was established by R. Singer & A.H. Smith (1946) with *Stropharia* (Fr.) Quél. as the type genus (Singer & Smith, 1946). He et al. (2024) reported 11 genera in this family: *Agrocybe* Fayod, *Brauniella* Rick ex Singer, *Deconica* (W.G. Sm.) P. Karst., *Hypholoma* (Fr.) P. Kumm., *Kuehneromyces* Singer & A.H. Sm., *Leratiomyces* Bresinsky & Manfr. Binder ex Bridge, Spooner, Beever & D.C. Park, *Melanotus* Pat., *Pholiota* (Fr.) P. Kumm., *Protostropharia* Redhead, Moncalvo & Vilgalys, *Pyrrhulomyces* E.J. Tian & Matheny, and *Stropharia*. *Strophariaceae* is characterised by agaric basidiomata, with cylindrical to narrowly clavate basidia, violaceous basidiospores with germ pores, and monomitic hyphal system (Cho et al., 2016). Members of *Strophariaceae* are distributed worldwide and are mainly saprophytic (soil, dung, grass root, plant litter), and some species are ectomycorrhizal (Cho et al., 2016; Lebel et al., 2022). Some species of this family are considered potentially medicinal mushrooms with anticancer properties (Song et al., 1998; Cho et al., 2016).

5.3.1.56 *Agrocybe* Fayod

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.54

Classification: *Strophariaceae, Agaricales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota*, Fungi

Agrocybe was established by V. Fayod in 1889 with *A. praecox* as the type species (Fayod, 1889). Members of *Agrocybe* are saprophytic, growing in forest grassland, on dung, or debris (Niveiro et al., 2020; Li et al., 2023b; Zhang et al., 2024b), and are widely distributed in temperate regions of Asia, Europe, and North America (Flynn & Miller, 1990; Li et al., 2023b). Index Fungorum (2025) lists 195 records of *Agrocybe,* while Hyde et al. (2024a) recognised approximately 110 species worldwide. Singer (1986) initially classified *Agrocybe* within the family *Bolbitiaceae* Singer, based on characteristics such as the pear-shaped to subspherical spherocytes of the pileipellis, the presence or absence of hymenial cystidia, and brown spore prints. Additionally, this genus was separated into two subgenera, *Agrocybe* subg. *Agrocybe* Fayod and subg. *Aporus* Singer (Singer, 1986). *Agrocybe* subg. *Agrocybe* was further divided into five sections (*Agrocybe*, *Pediades*, *Microsporae*, *Allocystides*, and *Evelatae*), while the latter comprised two sections (*Aporus* and *Velatea*) (Singer, 1986). Subsequent taxonomic revision transferred the section *Evelatae* to the subgenus. *Aporus* and the eliminated section *Allocystides* (Watling, 1982). However, recent molecular phylogenetic analyses support placement of *Agrocybe* under the family *Strophariaeae* Singer & A.H. Sm. (Walther & Weiß, 2006; Kirk et al., 2008; He et al., 2019). Notably, phylogenetic analyses based on ITS and LSU regions have revealed that *Agrocybe* is polyphyletic (Matheny et al., 2006; Kiyashko et al., 2022).

Members of *Agrocybe* are characterised by small to medium-sized basidiomata with a membranous ring (Niveiro et al., 2020; Li et al., 2023b). The pileus is semiglobate, fleshy, and either smooth or slightly wrinkled (Zhang et al., 2024b). The stipe is white, buff, or ochraceous in colour and bears a distinct ring (Zhang et al., 2024b). The context is white or pale-coloured and exhibits a mealy taste and smell (Zhang et al., 2024b). Basidiospores are ovoid, ellipsoid, or fusiform, smooth, thick-walled, yellow to light-brown, bear broad germ pores, and have a brown spore print

(Niveiro et al., 2020; Li et al., 2023b; Zhang et al., 2024b). The pileipellis is hymeniderm or ixohymeniderm (Niveiro et al., 2020; Li et al., 2023b).

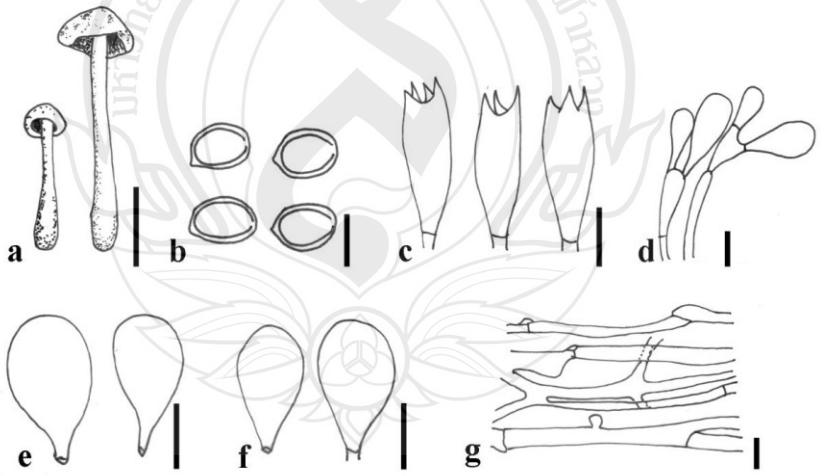
Li et al. (2023b) described a new species, *Agrocybe striatipes* R.L. Zhao & J. Xin Li from China, based on a combination of morphological characteristics and phylogenetic analyses (ITS and LSU). The type species, *A. praecox*, has been domesticated for food (Wu et al., 2020; Kartal et al., 2022). Several species of *Agrocybe* are reported to be rich in secondary metabolites with anticancer, anti-obesity, antitumour, anti-ageing, and hypoglycemic properties (Wu et al., 2020; Kartal et al., 2022; Zhang et al., 2024b). Members of this genus exhibit hydrolytic and lignolytic enzymatic activities and are useful in bioremediation (Kartal et al., 2022).

Synonymy: *Bulla* Battarra ex Earle, *Bulla* Battarra, *Cyclopus* (Quél.) Barbier, *Hylophila* subgen. *Cyclopus* Quél., *Pseudodeconica* Overeem, *Togaria* W.G. Sm.

Type species: *Agrocybe praecox* (Pers.) Fayod

Basionym: *Agaricus praecox* Pers.

Other accepted species: (Species Fungorum – search *Agrocybe*)



Note a Basidiomata. b Basidiospores. c Basidia. d Pileipellis hyphae. e Cheilocystidia. f Pleurocystidia. g Stipitipellis hyphae. Scale bar: a = 2 cm, b–g = 5 μm.

Source Redrawn from Li et al. (2023b). For original basidiomata, refer to Li et al. (2023b).

Figure 5.54 *Agrocybe striatipes* (HMAS486942, holotype)

Atheliales Jülich

Atheliaceae Jülich, *Biblthca Mycol.* 85: 355

Atheliaceae was established by W. Jülich (1982) with *Athelia* Pers. as the type genus (Jülich, 1982). He et al. (2024) reported 11 genera in this family: *Athelia*, *Athelicium* K.H. Larss. & Hjortstam, *Athelocystis* Hjortstam & Ryvarden, *Butlerelfia* Weresub & Illman, *Elaphocephala* Pouzar, *Hypochnella* J. Schröt., *Fibulomyces* Jülich, *Hypochniciellum* Hjortstam & Ryvarden, *Melzericium* Hauerslev, *Mycostigma* Jülich, and *Taeniospora* Marvanová. *Atheliaceae* is characterised by annual, resupinate, effused, loosely adnate, and pellicular basidiomata, with an undifferentiated margin, smooth hymenium, sub-globose to elliptic or fusoid, thin-walled, hyaline, and smooth basidiospores, monomitic hyphal system, and without cystidia (Sulistyo et al., 2021). Members of the family are distributed worldwide and are mainly saprotrophic, while a few species are parasitic on plants or lichens (Sulistyo et al., 2021).

5.3.1.57 *Butlerelfia* Weresub & Illman

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.55

Classification: *Atheliaceae, Atheliales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

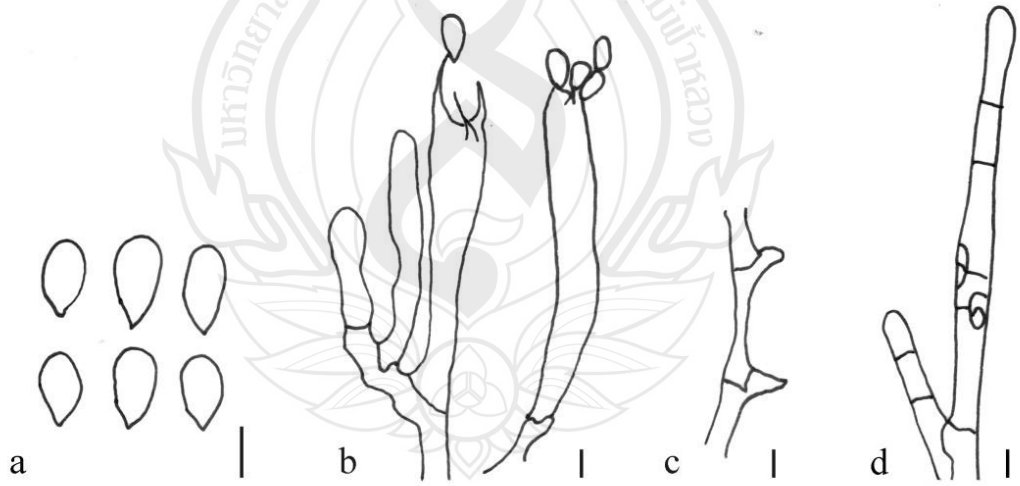
Butlerelfia, a monotypic genus, was established by L.K. Weresub and W.I. Illman in 1980, with its type species *B. eustacei* (Weresub & Illman, 1980). The species was named in honour of H.J. Eustace and L.F. Butler, who first described the species (Weresub & Illman, 1980). Initially, this species was classified as *Corticium centrifugum* sensu Butler, a name now considered inapplicable (Weresub & Illman, 1980). *Butlerelfia* species are distributed in North America and Europe (Wenneker et al., 2017; He et al., 2019).

Butlerelfia is characterised by broadly effused basidiomata that are smooth, white to creamy, and turn tan with maturity (Weresub & Illman, 1980). The context is prosenchymatous and somewhat ceraceaous, while the hymenium is homogeneous (Weresub & Illman, 1980). Basidiospores are ellipsoid to ovoid or somewhat oblong (Weresub & Illman, 1980). Basidia are long, evenly clavate, and possess four sterigmata

(Weresub & Illman, 1980). In culture, the mycelium of *B. eustacei* grows rapidly, initially white and floccose, then becoming farinose with fertile granules, and producing delicate athelioid membranes during fruiting (Weresub & Illman, 1980). Notably, hypha branching is typically interseptal rather than originating from the clamp cells (Weresub & Illman, 1980).

The type species, *Butlerelfia eustacei,* is known to cause "fish-eye rot disease" in apples and pears in cold storage, as well as "fig black necrosis" in fig orchards (Weresub & Illman, 1980; Sholberg & Haag, 1996; Negahban et al., 2025). Recently, Negahban et al. (2024) used morphological characteristics and phylogenetic analyses (ITS, LSU, and *rpb2*) to delineate this species from other closely related genera. Additionally, pathogenicity on detached shoots and one-year-old saplings of fig cultivars revealed that *B. eustacei* causes brown lesions and wood discolouration (Negahban et al., 2025).

Type species: *Butlerelfia eustacei* Weresub & Illman



Note a Basidiospores. b Basidia with attached basidiospores. c–d Branching from clamped cells. Scale bar: a–d = 10 µm.

Source Redrawn from Weresub and Illman (1980). For original basidiomata, refer to Weresub and Illman (1980).

Figure 5.55 *Butlerelfia eustacei*

5.3.1.58 *Lyoathelia* Hjortstam & Ryvarden

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.56

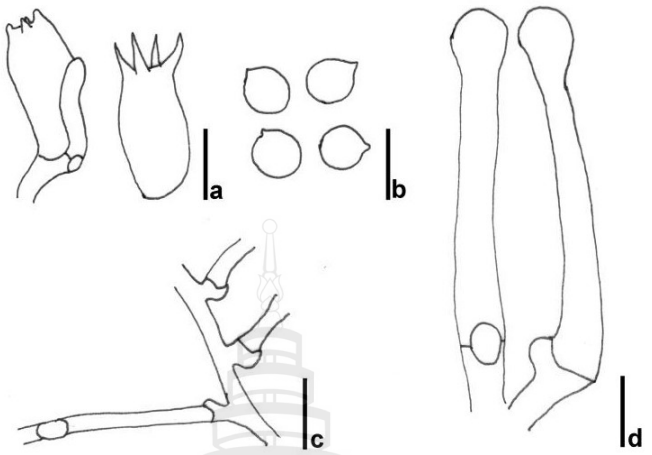
Classification: *Atheliaceae, Atheliales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota*, Fungi

Lyoathelia is a monotypic genus established by K. Hjortstam and L. Ryvarden with its type species *L. laxa* (Burt) Hjortstam & Ryvarden, first described from coniferous wood in Canada (Hjortstam & Ryvarden, 2004). *Lyoathelia laxa* is rare and has only been reported in Canada, Japan, Russia, Spain, and the USA (Burt, 1925; Jülich, 1972; Hjortstam & Ryvarden, 2004). The taxonomic classification of *Lyoathelia* is under Atheliaceae in Index Fungorum; however, MycoBank and Hyde et al. (2024a) have placed it under *Hymenochaetales* genera *incertae sedis*.

Lyoathelia basidiomata is resupinate, loosely adnate, effused, thin, membranous, fragile, light cream in colour, and has a well-developed subiculum (Burt, 1925; Hjortstam & Ryvarden, 2004). The hymenophore is smooth, whitish, fibrillose to fimbricate, and sometimes with mycelial cords (Burt, 1925; Hjortstam & Ryvarden, 2004). Basidiospores are almost globose, thin to moderately thick-walled, hyaline, smooth, inamyloid, indextrinoid, acyanophilic, and have a distinct apiculus (Burt, 1925; Hjorstam & Ryvarden, 2004). Basidia are doliform-pedunculate in shape, mostly with four sterigmata or rarely two, and a basal clamp connection (Burt, 1925; Jülich, 1972; Hjortstam & Ryvarden, 2004; Sulistyo et al., 2021). Cystidia are relatively rare, well-differentiated, capitate, and moderately encrusted (Jülich, 1972; Hjortstam & Ryvarden, 2004; Sulistyo et al., 2021). The hyphal system is monomitic, featuring thin-walled, narrow hyphae that are somewhat encrusted and clamped (Hjortstam & Ryvarden, 2004). Sulistyo et al. (2021) used morphological and phylogenetic analyses with combined ITS and LSU genes to further delineate *L. laxa*. It has been proposed that *L. laxa* should be classified within *Hymenochaetales* (Sulistyo et al., 2021).

Type species: *Lyoathelia laxa* (Burt) Hjortstam & Ryvarden

Basionym: *Peniophora laxa* Burt



Note a Basidia. b Basidiospores. c Hyphae. d Cystidia. Scale bar: a–d = 10 µm.

Source Redrawn from Jülich (1972). For original basidiomata, refer to Mycoportal (2024).

Figure 5.56 *Lyoathelia laxa* (holotype)

5.3.1.59 *Melzericium* Hauerslev

Index Fungorum, Facesoffungi, MycoBank, Fig. 5.57

Classification: *Atheliaceae, Atheliales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

The corticioid genus *Melzericium* was established by K. Hauerslev, with its type species *M. udicola,* described based on a specimen collected in Sweden (Jülich, 1976). *Melzericium* species are widespread (especially in Europe, North America, and Asia) and saprobic in nature (Ghobad-Nejhad et al., 2008). Morphologically, the basidiomata of *Melzericium* are resupinate, effused, membranous, adnate, and separable into small pieces (Jülich, 1976). The hymenial surface is cream-colored, smooth, and typically not cracked when dried, with a margin that is colourless or whitish, indeterminate, and thinning out (Jülich, 1976). The hyphal system is monomitic, featuring hyaline, thin-walled, smooth, and clamped hyphae (Jülich, 1976; Maekawa & Norden, 2002). Basidiospores are hyaline, thin-walled, amyloid, indextrinoid, cyanophilous, and smooth with a distinct apiculus (Jülich 1976). Basidia are stalked,

hyaline, smooth, thin-walled, clamped at the base, with four sterigmata, and flexuous-cylindrical when young, becoming clavate upon maturity (Jülich 1976). Cystidia are absent (Jülich, 1976; Maekawa & Norden, 2002).

Species identification within *Melzericium* is based solely on morphological characteristics, as no molecular evidence has been reported (He et al., 2019). The genus includes three accepted species: *M. bourdotii* is characterised by distinctly constricted spores in the middle, *M. udicola* by bean- or kidney-shaped spores, and *M. rimosum* by cylindrical to suballantoid spores, often with a suprahilar depression (Jülich, 1976; Ghobad-Nejhad et al., 2008; He et al., 2019).

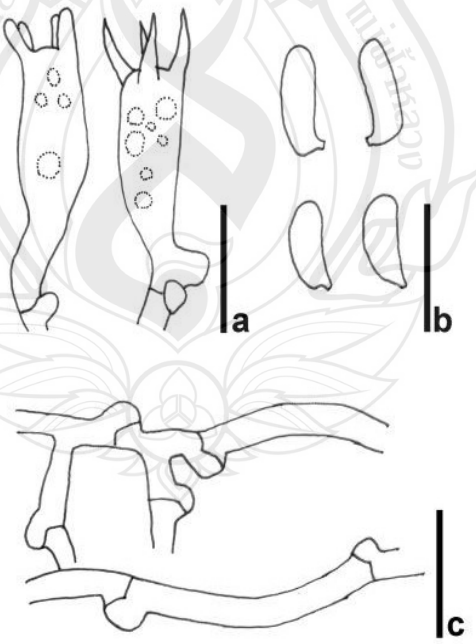
Type species: *Melzericium udicola* (Bourdot) Hauerslev

Basionym: *Corticium udicola* Bourdot

Other accepted species:

M. bourdotii Jülich

M. rimosum Bononi & Hjortstam



Note a. Basidia. b Basidiospores. c Subicular hyphae. Scale bar: a−c = 10 µm.

Source Redrawn from Maekawa and Norden (2002).

Figure 5.57 *Melzericium rimosum* (TMI25484)

Boletales E.-J. Gilbert 1931

Boletaceae Chevall., *Fl. gén. env. Paris* (Paris) 1: 248

Boletaceae is the largest and most diverse family in *Boletales* E.-J. Gilbert, established by F.F. Chevallier in 1826, with *Boletus* L. as its type genus (Chevallier, 1826a; Wang et al., 2023b). *Boletaceae* are distributed worldwide and are ectomycorrhizal mushroom-forming fungi (Tremble et al., 2024). *Boletaceae* is characterised by large, fleshy, and brilliantly coloured basidiomata, with tubulose, lamellate, or loculus hymenophore (Wang et al., 2023b). He et al. (2024) reported 112 genera in this family. Some species of this family are wild-collected edible mushrooms (Dentinger & Suz, 2014; Tremble et al., 2024).

5.3.1.60 *Buchwaldoboletus* Pilát

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.58

Classification: *Boletaceae, Boletales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Buchwaldoboletus was established by A. Pilát in 1969, with its type species *B. lignicola* (Pilát, 1969). This species was first described by Franz Joseph Kallenbach in 1929 as *Boletus lignicola*, based on specimens collected from soil near conifer trunks in Germany (Pilát, 1969). Species of *Buchwaldoboletus* are non-mycorrhizal, saprophytic, and lignicolous (Ortíz-Santana & Both, 2011). However, the type species *B. lignicola* is mycoparasitic on the wood decay fungus *Phaeolus schweinitzii* (Fr.) Pat. (Caiafa & Smith, 2022). Notably, *Buchwaldoboletus* species exhibit dual trophic modes as saprobes and mycoparasites (Caiafa & Smith, 2022). Although members of *Buchwaldoboletus* are distributed worldwide, *B. lignicola* is a rare species (Ortíz-Santana & Both, 2011; Blanco-Dios, 2013; Jo et al., 2019).

Buchwaldoboletus is characterised by a decurrent and aruate hymenophore, bluing, yellow flesh, and basal mycelium (Pilát, 1969). Basidiomata lack a clamp connection, although they are present in the hyphae of cultures (Pilát, 1969; Watling, 2008). Caiafa and Smith (2022) demonstrated that *Buchwaldoboletus* is polyphyletic. Watling et al. (2005) proposed two lineages within *Buchwaldoboletus,* namely, *Lignicola*

and *Sphaerocephalus*. Later, Ortíz-Santana and Both (2011) added a third lineage, *Hemichrysus*. *Lignicola* lineages are characterised by a tomentose pileus and stipe with shades of brown or reddish brown, dry, yellow context, and bluing, especially above the tubes (Ortíz-Santana & Both, 2011; Blanco-Dios, 2013). The *Sphaerocephalus* group features a yellow pileus and stipe, a silky tomentose pileus that is viscid when wet, context bluing, and habitat on pine sawdust, often in enclosed areas (Ortíz-Santana & Both, 2011; Blanco-Dios, 2013). *Hemichrysus* group has a bright yellow pileus and stipe, pulverulent appearance, a yellow pore surface that becomes subferrugineous, and a yellow stipe above, and reddish below (Ortíz-Santana & Both, 2011; Blanco-Dios, 2013).

Qin et al. (2024) used morphological and phylogenetic analyses (LSU, *tef-1α*, and *rpb2*) to delineate *Buchwaldoboletus* from other closely related genera. Phylogenetically, *Buchwaldoboletus* is closely related to *Chalciporus* Bataille and *Pseudophylloporus* N.K. Zeng, H.Z. Qin, W.F. Lin & L.G. Hu (Qin et al., 2024). However, *Chalciporus* has a pinkish-red to reddish-brown pileal surface, and its context does not turn bluish when injured (Qin et al., 2024). Additionally, *Pseudophylloporus* has a nearly smooth pileal surface and a lamellate hymenophore (Qin et al., 2024). Index Fungorum (2025) lists 15 records of *Buchwaldoboletus,* while Hyde et al. (2024a) recognised only 13 species worldwide.

Type species: *Buchwaldoboletus lignicola* (Kallenb.) Pilát

Basionym: *Boletus lignicola* Kallenb.

Other accepted species:

B. acaulis (Pegler) Both & B. Ortiz

B. brachyspermus (Pegler) Both & B. Ortiz

B. duckeanus (Singer) Both & B. Ortiz

B. kivuensis (Heinem. & Gooss.-Font.) Both & B. Ortiz

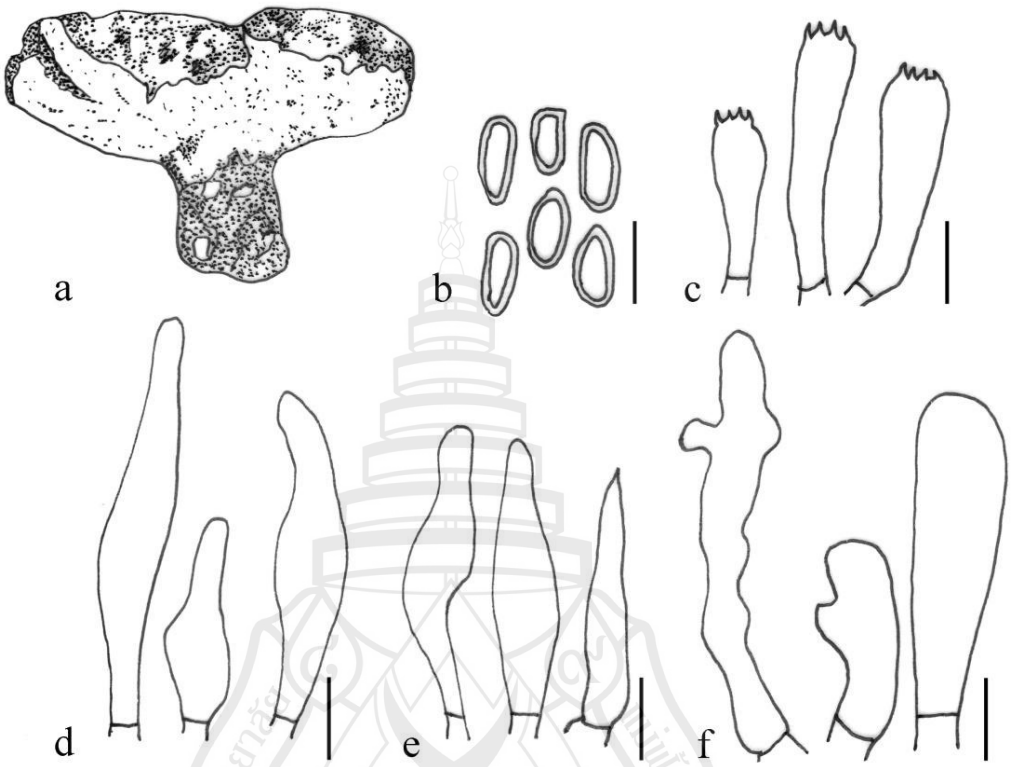
B. parvulus (Natarajan & Purush.) Both & B. Ortiz

B. pontevedrensis Blanco-Dios

B. pseudolignicola (Neda) Both & B. Ortiz

B. spectabilis Watling

B. xylophilus (Petch) Both & B. Ortiz



Note a Basidiomata. b Basidiospores. c Basidia. d Cystidia. e Caulocystidia. f End cells of peleipellis. Scale bar: b–f = 10 μm.

Source Redrawn from Blanco-Dios (2013). For original basidiomata, refer to Blanco-Dios (2013).

Figure 5.58 *Buchwaldoboletus pontevedrensis* (holotype)

5.3.1.61 *Chalciporus* Bataille

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.59

Classification: *Boletaceae, Boletales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Chalciporus was established by F. Bataille in 1908, with *C. piperatus* (Bataille, 1908) as its type species. Initially, this species was classified as *Boletus piperatus* Bull. based on specimens collected in France (Bulliard, 1790). The genus

diverged early in the evolutionary history of the *Boletaceae* (Nuhn et al., 2013; Xu et al., 2021). *Chalciporus* species form an ectomycorrhizal association with a wide range of hosts, including *Pinus*, *Fagus*, *Quercus*, *Betula*, *Nothofagus*, *Cistus*, and *Abies* (Singer, 1986; Degreef & Kesel, 2008; Ayala-Vásquez et al., 2023). Nuhn et al. (2013) reported that the type species also exhibits mycoparasitic behaviour, colonising *Amanita muscaria* (L.) Lam. (Dickie et al., 2010, 2016). Members of *Chalciporus* are distributed worldwide (Degreef & Kesel, 2008; Klofac & Krisai-Greihuber, 2021; Ayala-Vásquez et al., 2023).

Chalciporus is characterised by small to medium-sized basidiomata with a pinkish-red to reddish-brown pileus and a pileipellis composed of trichoderm (Ayala-Vásquez et al., 2023). The hymenophore is adnate to sub-decurrent, with colours ranging from reddish-brown to salmon, yellow, or chrome, which remains unchanged or slowly turns bluish to dull blue when cut (Ayala-Vásquez et al., 2023). The stipe is solid, with its base covered in yellow mycelium, and it lacks velar remnants on both the cap and stipe (Degreef & Kesel, 2008). Basidiospores are smooth-walled and either elongate or short ellipsoid (Degreef & Kesel, 2008; Xu et al., 2021). Cystidia are typically conspicuous, while hyphae lack clamp connections (Singer, 1986; Degreef & Kesel, 2008). The taste of *Chalciporus* is either mild or acrid peppery (Singer, 1986).

Phylogenetically, *Chalciporus* is most closely related to the monotypic genus *Buchwaldoboletus* Pilát (Nuhn et al., 2013). However, the latter differs in having a decurrent to arcuate hymenophore, bluing and yellow flesh (Singer, 1986). Additionally, members of *Buchwaldoboletus* lack clamp connections in basidiomata, though these are present in hyphae of cultures (Singer, 1986; Watling, 2008; Nuhn et al., 2013).

The classification of *Chalciporus* within *Boletaceae, Boletales, Agaricomycetidae, Agaricomycetes, Agaricomycotina*, and *Basidiomycota* is in agreement with Index Fungorum, MycoBank, GenBank, UNITE, and the latest Outline of fungi and fungus-like organisms (Hyde et al., 2024).

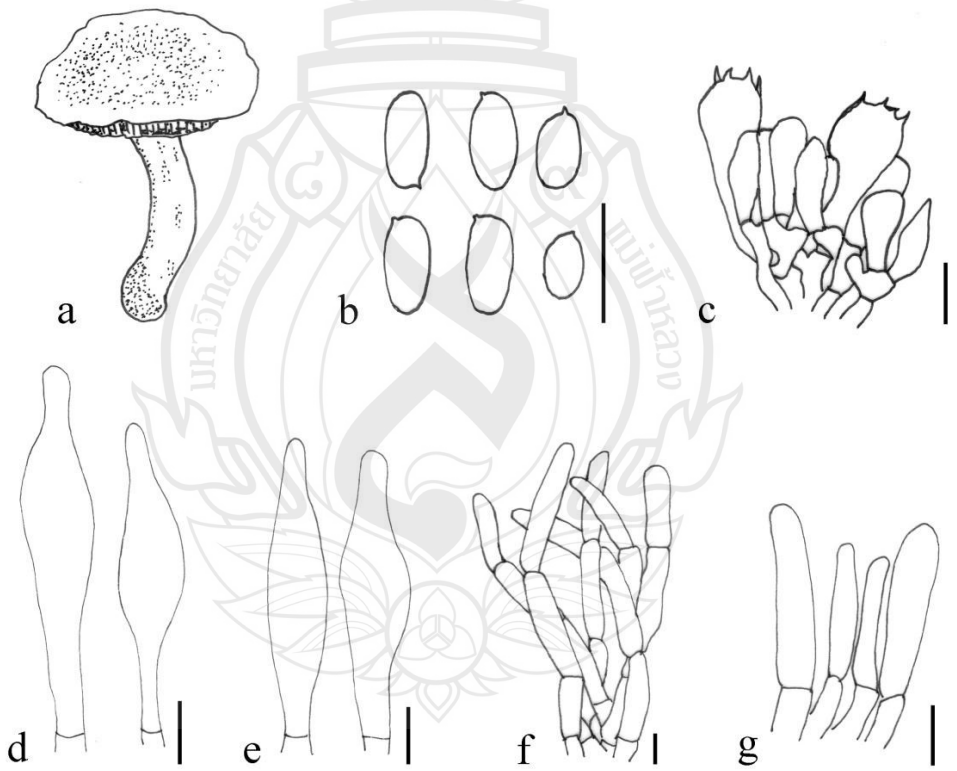
Ayala-Vásquez et al. (2023) described two new species, *C. perezsilvae* and *C. piedracanteadensis,* using morphological characteristics and phylogenetic analyses (ITS, LSU, *rpb2*, and *tef-1α*). Nanu and Kumar (2024) described a new species, *C.*

rubrostipitatus, based on morphological and molecular analyses (ITS, LSU, and *rpb2*). Index Fungorum (2025) lists 49 records, while Ayala-Vásquez et al. (2023) recognised only 31 species worldwide. Several metabolites have been characterised from species of *Chalciporus*, including sclerocitrin, variegaic acid, variegatorubin, chalcitrin, and *2H*-azepine derivative chalcoporone (Xu et al., 2021). The type species is believed to be edible and has been used for dyeing (Li & Song, 2002; Roberts & Evans, 2011).

Synonymy: *Chalciporus* subgen. *Rubinoboletus* (Pilát & Dermek) Klofac & Krisai, *Rubinoboletus* Pilát & Dermek

Type species: *Chalciporus piperatus* (Bull.) Bataille

Other accepted species: (Species Fungorum – search *Chalciporus*)



Note a Basidiomata. b Basidiospores. c Basidia and basidioles. d Cheilocystidia. e Pleurocystidia. f Pileipellis. g Stipitipellis. Scale bar: b–g = 10 µm.

Source Redrawn from Xu et al. (2021). For original basidiomata, refer to Xu et al. (2021).

Figure 5.59 *Chalciporus vulparius* (FHMU5560, holotype)

5.3.1.62 *Chamonixia* Rolland

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.60

Classification: *Boletaceae, Boletales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Chamonixia Rolland was established by Rolland in 1899, with *Chamonixia caespitosa* Rolland from France designated as the type species (Mleczko et al., 2009; Orihara et al., 2016). This fungus is one of the sequestrated descendants of epigeous boletes (Orihara et al., 2016). The species of *Chamonixia* are characterised by gasteroid, spongy, white, fibrillose basidiomata, which often turn blue when bruised (Rolland, 1899; Mleczko et al., 2009; Orihara et al., 2016). The hymenophore is loculate, with small, round to oval chambers that are initially pale, then brown, and lack a stipe (Rolland, 1899; Mleczko et al., 2009; Orihara et al., 2016). Basidia are mostly 4-spored and elliptic, brown, with 6–12 large, blunt, and longitudinal irregular ridges of basidiospores (Lebel et al., 2012; Orihara et al., 2016). The species of *Chamonixia* has four developmental steps identical to those of *Suillus* and *Boletinus*, and basidiomata are exocarpic, claustropileate, and amphicleistoblemate (Clémençon, 2005b; Mleczko et al., 2009).

Chamonixia is polyphyletic, with *Chamonixia* s. str. from Europe and North America, and the remaining species found in Australasia, Japan, and China were transferred into another genus, *Rossbeevera* T. Lebel & Orihara (Lebel et al., 2012; Orihara et al., 2016). Index Fungorum (2025) reports 10 records of *Chamonixia*, while Hyde et al. (2024a) accepted only 4 species. Lebel et al. (2012) conducted morphological and phylogenetic analyses (ITS and LSU) of species of *Chamonixia* and found affinities with *Leccinum* and *Leccinellum*. Orihara et al. (2016) used morphology and phylogenetic analysis (ITS) to distinguish species of *Chamonixia*. The type species, *Chamonixia caespitosa*, is often considered rare and listed as endangered in the USA and many European countries (Mleczko et al., 2009; Orihara et al., 2016).

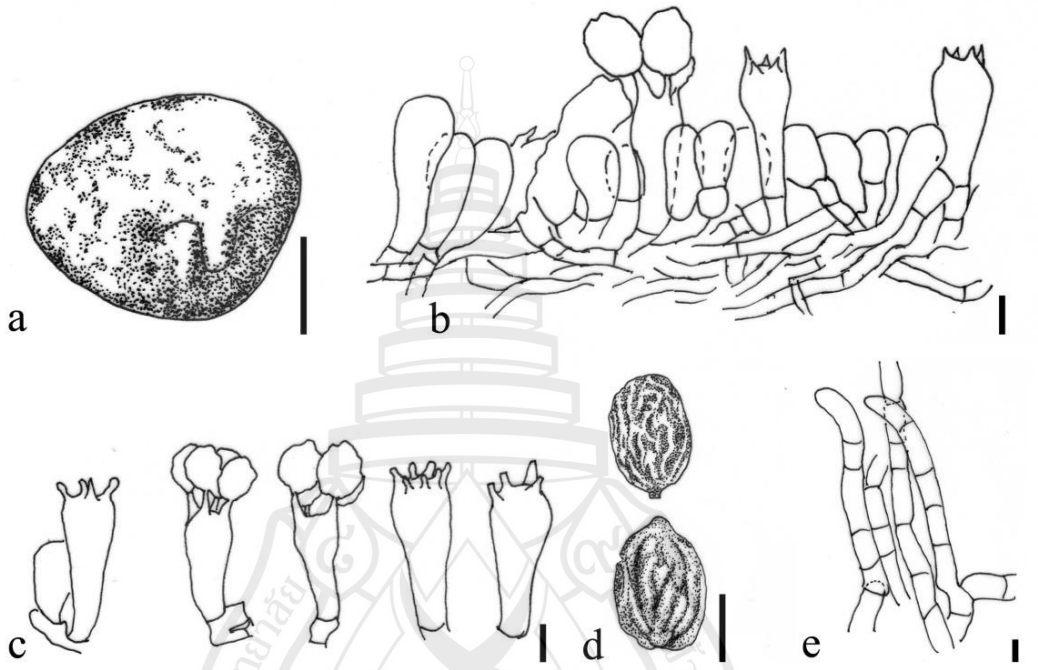
Type species: *Chamonixia caespitosa* Rolland

Other accepted species:

C. albida (Massee & Rodway) Y.S. Chang & Kantvilas

C. brevicolumna A.H. Sm. & Singer

C. caudata (Zeller & C.W. Dodge) A.H. Sm. & Singer



Note a Basidiomata. b Section through hymenium and subhymenium with basidia, and sterile elements. c Basidia. d Basidiospores. e Hyphae on the peridium surface. Scale bar: a = 1 cm, b–e = 10 μm.

Source Redrawn from Mleczko et al. (2009).

Figure 5.60 *Chamonixia caespitosa*

5.3.1.63 *Gastroboletus* Lohwag

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.61

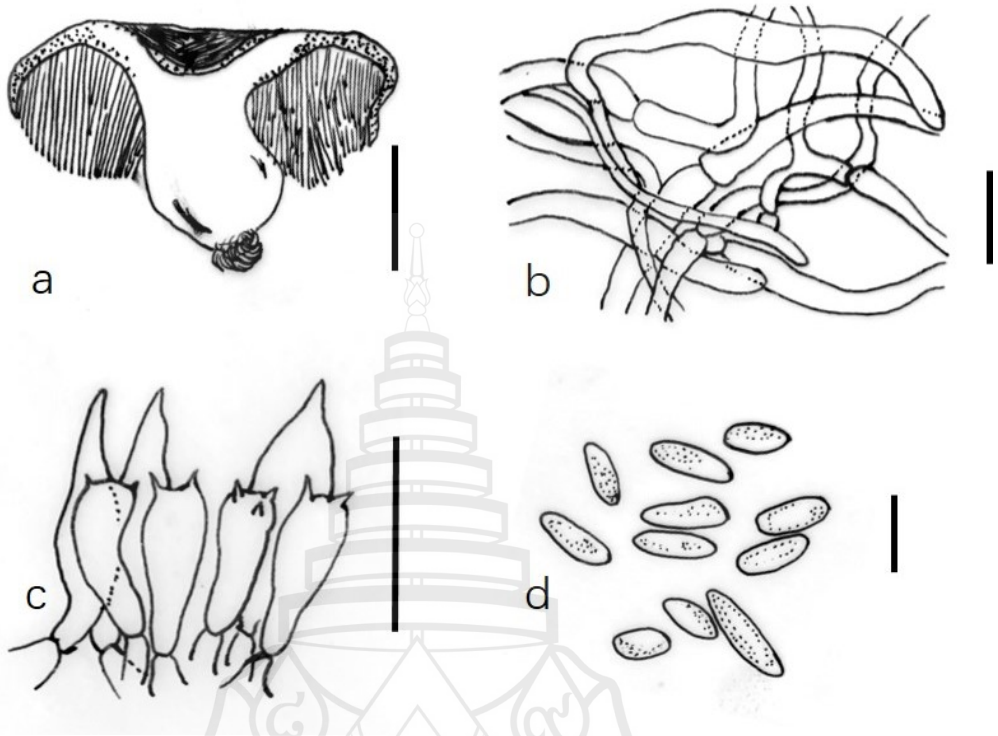
Classification: *Boletaceae, Boletales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

The genus *Gastroboletus* was established by Lohwag in 1926 based on specimens collected from the ground in China (Lohwag, 1926). In 1937, Lohwag further described the specimen and classified it as *Gastroboletus boedijnii*, which became the

type species of the genus (Lohwag, 1937). *Gastroboletus* is readily distinguished by its hymenophore, which, although distinctly tubulose, is developed to preclude deposition of spores. The 'tubes' are often not vertically oriented and may be covered by a well-developed, persistent peridial membrane or blocked by outgrowths of wall tissue. Spore deposits have never been observed from any of these fungi on either the adjacent substrate or on the inner surface of the peridial membrane (Lohwag, 1926, 1937; Smith & Singer, 1959). *Gastroboletus* has been reported from North and South America, Asia, South Africa, Western Europe, and eastern Australia (Lohwag, 1926; Zang, 1995; Smith & Singer, 1959; Singer & Smith, 1964; Thiers & Trappe, 1969; Horak, 1977; Thiers, 1979; Cázares & Trappe, 1991; Nouhra & Castellano, 1995; Trappe & Castellano, 2000; Nouhra et al., 2002). Species of *Gastroboletus* have significant ecological value, but there have been no reports of their medicinal or edible uses. Currently, 21 records of *Gastroboletus* are listed in Index Fungorum (2025), whereas Hyde et al. (2024a) recognised 13 species. Nouhra et al. (2002) provided a comprehensive key to all known species of *Gastroboletus*.

Type species :*Gastroboletus boedijnii* Lohwag

Other accepted species: (Species Fungorum – search *Gastroboletus*)



Note a. Basidiomata section. b. Peridium hyphae. c. Basidia and cystidia. d. Basidiospore. Scale bars: a = 1 cm, b = 10 μm, c = 20 μm, d. = 10 μm.

Source Redrawn from Smith and Singer (1959) and Nouhra et al. (2002).

Figure 5.61 *Gastroboletus turbinatus*

5.3.1.64 *Gymnogaster* J.W. Cribb

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.62

Classification: *Boletaceae, Boletales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

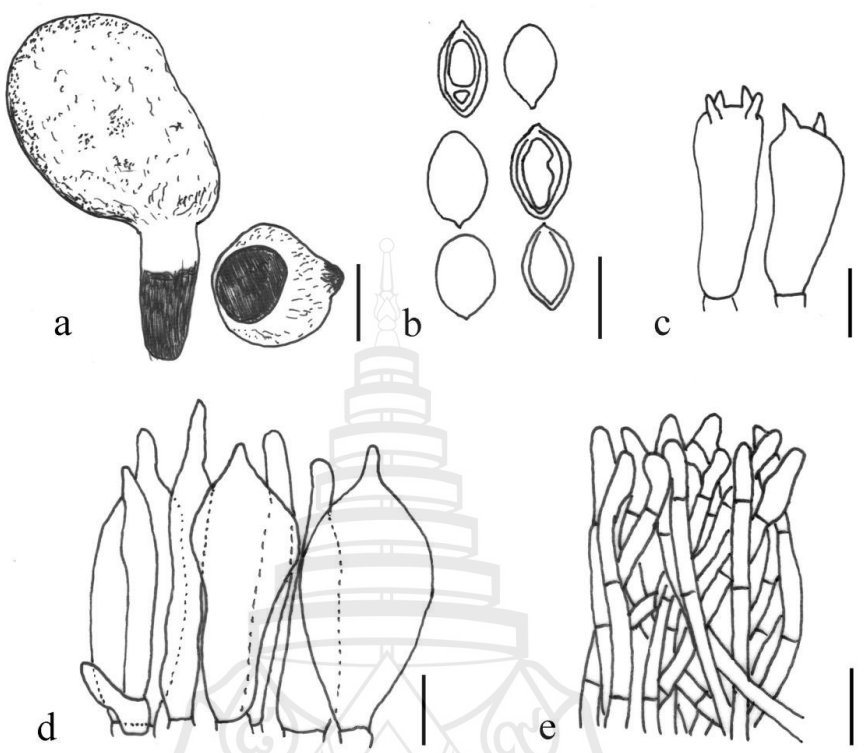
Gymnogaster, a monotypic genus, was established by J.W. Cribb in 1956 with its type species, *G. boletiodes* (Cribb, 1956). This species was described from specimens collected on wood in Queensland, Australia (Cribb, 1956). *Gymnogaster* is an emergent truffle-like fungus growing gregariously and forming mycorrhizal associations with *Eucalyptus*, *Lophostemon*, and *Corymbia* (Bougher & Barrett, 2020). This genus is endemic to Australia (Cribb, 1956; Halling et al., 2012; Bougher & Barrett, 2020). The

taxonomic placement of *G. boletiodes* was uncertain for a long time, with it being placed in either *Secotiaceae* Tul. & C. Tul. or *Agaricaceae* Chevall. (Cribb, 1956; Kirk et al., 2008). However, through phylogenetic analyses, Halling et al. (2012) demonstrated that *Gymnogaster* belongs to *Boletaceae* (Zhao et al., 2014; Smith et al., 2015).

Gymnogaster is characterised by its bright lemon-yellow basidiomata, ovoid, subglobose to elongate, or irregular shape (Cribb, 1956; Gelardi et al., 2017). The pileus features a small, apical, appressed disc that is depressed and occasionally absent (Gelardi et al., 2017). The hymenophore is permanently exposed, moderately fleshy, and composed of labyrinthine to irregularly folded chambers (Gelardi et al., 2017). The stipe is central, straight, and cylindrical, and extends into the hymenophore as a columella. It is bright yellow internally and externally, bruising blue and later turning dark brown (Cribb, 1956; Gelardi et al., 2017). The apex of the columella is deep russet, indicating a reduced peridium (Cribb, 1956). Basidiospores are symmetrical, ellipsoidal, citriform or ovate, with a prominent apiculus, inamyloid, and acyanophilic (Gelardi et al., 2017). Basidia are cylindrical-clavate to clavate and 4-spored (Cribb, 1956). The odour ranges from faint to occasionally pungent (Gelardi et al., 2017). Cheilocystidia are abundant, straight to flexuous, variably shaped, irregularly cylindrical, smooth, moderately thick-walled, and have rounded to subacute tips (Gelardi et al., 2017). Pleurocystidia are uncommon, and clamp connections are absent in all tissues (Gelardi et al., 2017).

Halling et al. (2012) utilised morphological characteristics and phylogenetic analyses (LSU and *tef-1α*) to delineate this genus from closely related genera. Morphologically, *Gymnogaster* resembles *Secotium* Kunze but is distinct from *Secotium* in the absence of a peridium (Cribb, 1956). Additionally, *G. boletoides* also resembles *Neoboletus thibetanus* (Shu R. Wang & Yu Li) Zhu L. Yang, B. Feng & G. Wu (Wu et al., 2016; Gelardi et al., 2017). However, the latter species lacks apical peridial remnants (Gelardi et al., 2017).

Type species: *Gymnogaster boletoides* J.W. Cribb



Note a Basidiomata. b Basidiospores. c Basidia. d Cheilocystidia and Pleurocystidia. e Pileipellis. Scale bar: a = 1 cm, b–d = 10 µm, e = 20 µm.

Source Redrawn from Gelardi et al. (2017). For original basidiomata, refer to Gelardi et al. (2017).

Figure 5.62 *Gymnogaster boletoides* (Halling 9455, BRI)

5.3.1.65 *Mackintoshia* Pacioni & Sharp

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.63

Classification: *Boletaceae, Boletales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Mackintoshia, a monotypic genus, was established by Giovanni Pacioni and Cathy Sharp in 2000 (Pacioni & Sharp, 2000). The type species, *M. persica*, was described based on a specimen collected from sandy soil and litter under *Burkea africana* in Zimbabwe (Pacioni & Sharp, 2000). *Mackintoshia*, a sequestrate fungus, forms symbiotic associations with ectomycorrhizal hosts in the family *Caesalpiniaceae* (Pacioni

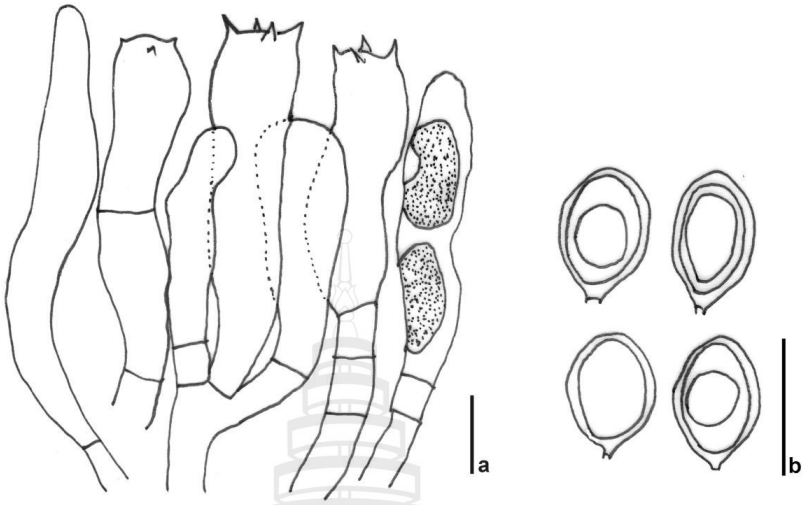
& Sharp, 2000; Sharp & Minter, 2014; Smith et al., 2015). It is a highly prized edible fungus, also known as "*Matifi*" and is consumed by both people and antelope in the Karanga region of Zimbabwe (Pacioni & Sharp, 2000).

Mackintoshia is characterised by hypogeous, subglobose or subpyriform basidiomata, in which the gleba is white to pale ochraceous and turning to olivaceous at maturity (Sharp & Minter, 2014). The basidiospores are smooth, dextrinoid, strongly cyanophilic, and relatively thick-walled (Sharp & Minter, 2014). Basidia are hyaline, strongly cyanophilic, clavate-utriculate to utriculate, typically 4-spored, sometimes 2-spored, and often arise from a short cylindrical basal cell or directly from a branched element (Sharp & Minter, 2014). Cystidia are clavate to cylindrical, thin-walled, and contain cyanophilic content, while tramal hyphae are broad, hyaline, and loosely interwoven (Sharp & Minter, 2014). Clamp connections are absent (Sharp & Minter, 2014). The fungus has a slight taste and a pleasant odour similar to that of ripe peaches (Sharp & Minter, 2014).

Mackintoshia shares basidiospore characteristics with *Galerina* Earle; however, its basidiospores are statismosporic and lack a noticeable reduction in wall thickness at the apex corresponding to a germ pore area (Pacioni & Sharp, 2000). Phylogenetically, *Mackintoshia* is closely related to *Mycoamaranthus* Castellano, Trappe & Malajczuk; however, the latter differs in having gleba without a columella, a basal pad, spiny mature basidiospores, and the absence of cystidia (Pacioni & Sharp, 2000).

In 2015, Smith et al. used morphological characteristics and phylogenetic analyses (ITS and LSU) to show that *Mackintoshia persica* and *Jimtrappea guyanensis* T.W. Henkel, M.E. Sm. & Aime belong to the same clade; however, their relationship has low bootstrap support and significant divergence (Smith et al., 2015).

Type species: *Mackintoshia persica* Pacioni & Sharp



Note a Section of the hymenium layer. b Basidiospores. Scale bar: a–b = 10 µm.

Source Redrawn from Pacioni and Sharp (2000).

Figure 5.63 *Mackintoshia persica*

5.3.1.66 *Paxillogaster* E. Horak

Index Fungorum, Facesoffungi, MycoBank

Classification: *Boletaceae, Boletales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Paxillogaster is a monotypic gasterioid genus established by E. Horak and M. Moser in 1966 (Horak & Moser, 1966). Its type species, *P. luteus*, was described from specimens collected on the ground under *Nothofagus dombeyi* in Rio Negro, South America (Horak & Moser, 1966). *Paxillogaster* forms ectomycorrhizal associations with plants and is found in South America, including Argentina (Pegler & Young, 1981; Nedelin, 2014).

Paxillogaster is characterised by its epigeal, stipitate basidiomata with a sub-lamellate gleba that is partially or permanently enclosed (Pegler & Young, 1981). Basidiospores are cylindric, asymmetric, and yellowish, with a suprahilar applanation, a broadly rounded apex, and a uniformly rugulose surface (Pegler & Young, 1981). The hyphae lack clamp connections (Pegler & Young, 1981).

Species delineation of *Paxillogaster* from other genera is based solely on macro- and micromorphology due to the lack of molecular sequences (He et al., 2019). *Paxillogaster* is closely related to *Xerocomaceae* Pegler & T.W.K. Young by its elongated, yellowish basidiospores and the absence of clamp connections (Pegler & Young, 1981).

Type species: *Paxillogaster luteus* E. Horak

5.3.1.67 *Phylloboletellus* Singer

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.64

Classification: *Boletaceae, Boletales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

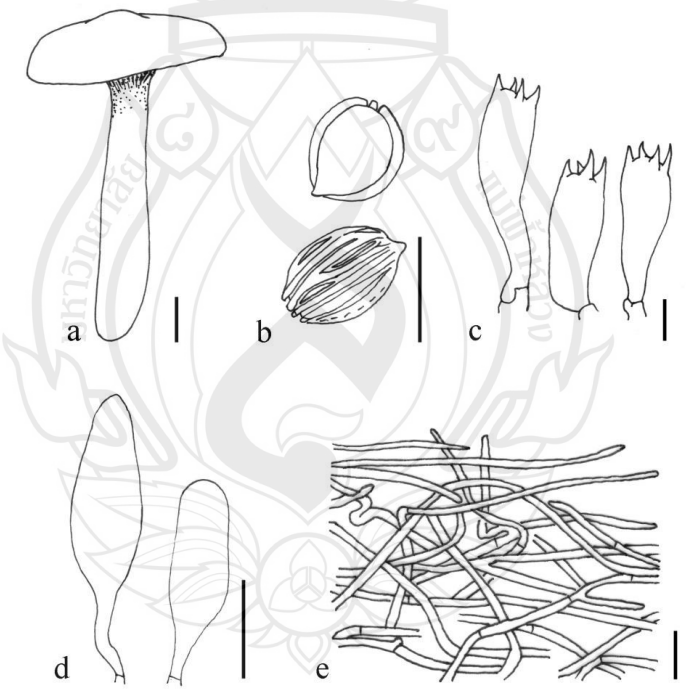
Phylloboletellus is a monotypic genus established by R. Singer and A.P.L. Digilio in 1951 (Singer & Digilio, 1951; Nuhn et al., 2013). Its type species, *P. chloephorus*, was described from specimens collected in subtropical or tropical montane forests on soil in Tucuman, Argentina (Singer & Digilio, 1951; Bandala et al., 2004). *Phylloboletellus* is ectomycorrhizal and exhibits partial parasitic behaviour (Singer, 1981; Bandala et al., 2004; Nuhn et al., 2013). This rare genus is found across Central and South America, including Argentina, Bolivia, and Mexico (Zhang & Li, 2018; He et al., 2019).

Phylloboletellus is characterised by its stipitate-pileate basidiomata, with acute, incurved pileus margins that are glabrous and vary in colour from yellow-orange to orange-reddish or brown (Singer, 1962; Qin et al., 2024). Lamellae are decurrent and somewhat intervenose, yellowish-green to olive-brown, usually forked and turn blue when bruised (Singer, 1962; Qin et al., 2024). The stipe is cylindrical, with a surface covered in brownish clumps or fibrils (Bandala et al., 2004; Qin et al., 2024). *Phylloboletellus* lacks a veil, and its context turns blue upon injury (Bandala et al., 2004; Farid et al., 2018; Qin et al., 2024). The basal mycelium is yellow (Bandala et al., 2004). Basidiospores are subglobose to short-ellipsoid with longitudinal, continuous, or bifurcate ribs (Singer, 1962; Bandala et al., 2004; Farid et al., 2018; Qin et al., 2024). Basidia are clavate, thin-walled, hyaline, clamped, and typically four-spored (Bandala et

al., 2004). Hymenial cystidia are utriform, thin-walled, and clamped (Bandala et al., 2004). Stipitipellis are trichodermoid, composed of undifferentiated cylindrical terminal hyphae (Bandala et al., 2004). Clamp connections in hyphae are rare and generally false or incomplete (Singer, 1981). Odour is weak or pleasant, while the taste is bitter (Bandala et al., 2004).

Qin et al. (2024) utilised morphological characteristics and phylogenetic analyses (LSU) to delineate *Phylloboletellus* species from other genera. *Phylloboletellus* is closely related to *Boletellus* Murrill; however, the former is distinct by its decurrent lamellate hymenophore (Pegler & Young, 1981). Additionally, *Boletellus* exhibits numerous clamp connections (Singer, 1981).

Type species: *Phylloboletellus chloephorus* Singer



Note a Basidiomata. b Basidiospores. c Basidia. d Hymenial cystidia. e Pileipellis. Scale bar: a = 1 cm, b–d = 10 µm, e = 25 µm.

Source Redrawn from Bandala et al. (2004). For original basidiomata, refer to GBIF (2025).

Figure 5.64 *Phylloboletellus chloephorus* (Bandala 3584, holotype)

5.3.1.68 *Phyllobolites* Singer

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.65

Classification: *Boletaceae, Boletales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Phyllobolites was established by Rolf Singer in 1942 based on a specimen of *P. miniatus* collected in Surinam, Brazil (Singer, 1964b, 1986; Farid et al., 2018). This species was initially described as *Paxillus miniatus* Rick (Singer, 1964b, 1986; Farid et al., 2018). Species of *Phyllobolites* are soil-dwelling, likely ectomycorrhizal, and form associations with *Leguminosae* plants, typically growing gregariously (Singer, 1981b; Farid et al., 2018). Members of *Phyllobolites* have a global distribution, including Brazil, China, Colombia, Guyana, Indonesia, New Zealand, Papua New Guinea, Singapore, Sri Lanka, and Togo (Singer, 1981b; Linhares, 2018). Index Fungorum (2025) lists three records of *Phyllobolites,* whereas Species Fungorum (2025) recognises only two species.

The basidiomata of *Phyllobolites* are characterised by a red pileus, with ocher to whitish lamellae that are often forked, and a stipe with a membranous ring derived from a partial veil (Singer, 1964b, 1986; Zhang & Li, 2018; Farid et al., 2018). The white context remains unchanged upon bruising (Singer, 1964b, 1986; Zhang & Li, 2018; Farid et al., 2018). The basidiospores are fusiform, verrucose, and produce an ochraceous spore print (Singer, 1964b, 1986; Farid et al., 2018). The fungi also feature abundant pseudocystidia, and their pileipellis range from ixotrichoderm to ixocutis (Singer, 1964b, 1986; Farid et al., 2018). Hyphae in the hymenophoral trama are subparallel to slightly divergent and exhibit gelatinisation (Singer, 1964b, 1986; Farid et al., 2018).

Species identification within *Phyllobolites* relies entirely on macro- and micro-morphological characteristics (Singer, 1981b; He et al., 2019). Morphologically, the genus is closely related to *Neopaxillus* Singer of the *Paxillaceae* Lotsy but differs in pigmentation, spore shape, and the presence of a veil and pseudocystidia (Singer, 1981b). Additionally, *Phyllobolites* can be distinguished from *Paxilloboletus* Furneaux, De Kesel & F.K. Khan. by its verrucose basidiospores and the complete presence of velum on the stipe (Badou et al., 2022). Although some sequences of *Phyllobolites* are available in

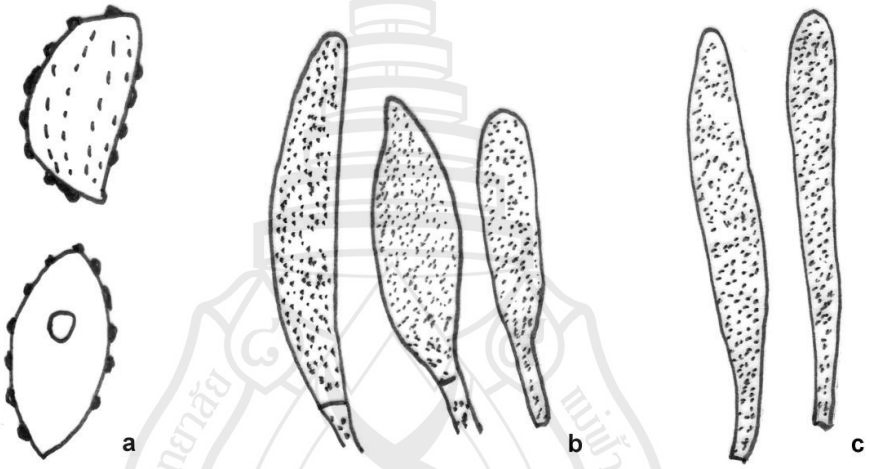
NCBI (2025), they have not been verified with authentic publications. A comprehensive re-description incorporating molecular data is needed to resolve its classification (Watling, 2008; Farid et al., 2018).

Type species: *Phyllobolites miniatus* (Rick) Singer

Basionym: *Paxillus miniatus* Rick

Other accepted species:

P. russuloides (Petch) Singer



Note a Basidiospores, ×2000. b Dermatopseudocystidia, ×100. c Pseudocystidia of the hymenium, ×1000.

Source Redrawn from Singer (1981b).

Figure 5.65 *Phyllobolites miniatus*

5.3.1.69 *Pseudoboletus* Šutara

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.66

Classification: *Boletaceae, Boletales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Pseudoboletus was established by J. Šutara in 1991, with *P. parasiticus* (Šutara 1991) as its type species. This species was originally described as *Boletus parasiticus* Bull. from basidiomata of *Scleroderma* Pers. collected in France (Šutara, 1991). *Pseudoboletus* exhibits mycoparasitic behaviour on other Boletales, including

Scleroderma, *Pisolithus* Alb. & Schwein., and *Astraeus* Morgan, or it forms ectomycorrhizal associations with *Quercus* and *Pinus* species (Tedersoo et al., 2010; Nuhn et al., 2013; He et al., 2019; Cortés-Pérez et al., 2023). *Pseudoboletus* species are distributed worldwide (Cortés-Pérez et al., 2023). Notably, *P. parasiticus* has been listed as a rare and endangered fungal species in Ukraine (Heluta, 2018).

Pseudoboletus is characterised by epigeal, pileate, centrally stipitate basidiomata with a tubulate hymenophore and is attached to *Scleroderma* or *Astraeus* Morgan (Watling, 2008). Pileus is convex to semi-globate, minutely tomentose, becoming smooth with age, sometimes cracking, and exhibits a straw colour or ochraceous with a wavy margin (Watling, 2008). The stipe is cylindric-curved, tapering, and concolourous with the pileus, with a sterile surface covered by a filamentous trichoderm or cutis, lacking caulobasidia (Šutara, 1991; Watling, 2008; Cortés-Pérez et al., 2023). Tubes are adnate to subdecurrent, initially ochraceous lemon-yellow, then ochreous to rust-coloured (Watling, 2008). Basidiospores are elongate-fusoid to cylindric, inamyloid, acyanophilic, and ornamented, which vary from reticulately venose to pitted, producing an olivaceous snuff-brown spore deposit (Watling, 2008; Cortés-Pérez et al., 2023). Basidia are clavate, hyaline, thin-walled, and four-spored (Watling, 2008). Cheilocysidia and pleurocystidia are fusiform, cylindric to lageniform, with apical swelling, numerous, and hyaline (Watling, 2008). Pileipellis is a trichoderm, either hyaline or ixocutis, and clamp connections are absent (Watling, 2008).

Cortés-Pérez et al. (2023) described a new species, *P. silvaticus*, based on morphological characteristics and phylogenetic analyses (ITS, LSU, and *tef-1α*). The species was collected from basidiomata of *Scleroderma nitidum* Berk., which were associated with *Quercus skinerii* (Cortés-Pérez et al., 2023). Index Fungorum (2025) lists eight records of *Pseudoboletus,* while Hyde et al. (2024a) recognised only three species worldwide.

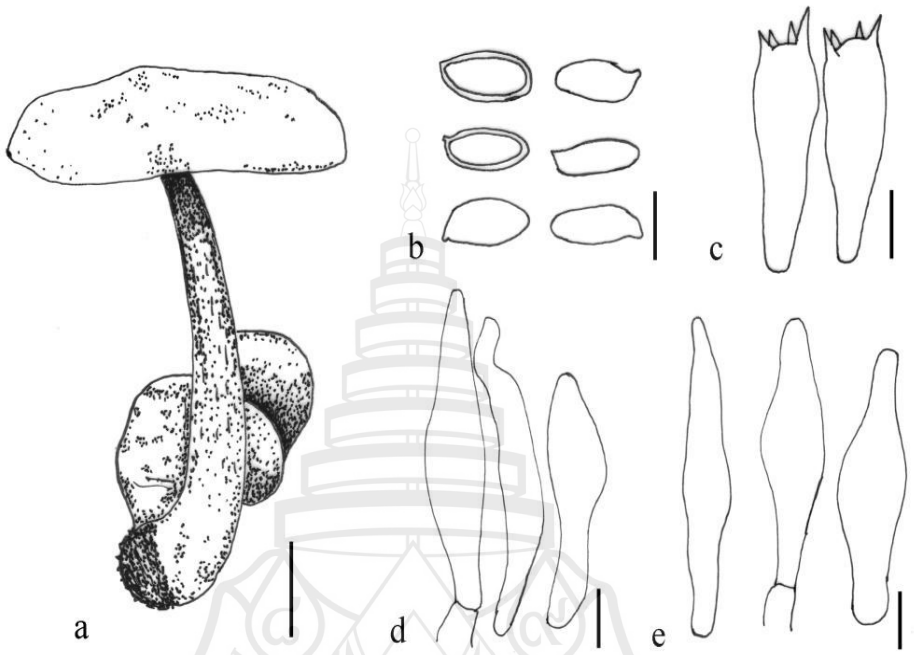
Type species: *Pseudoboletus parasiticus* (Bull.) Šutara

Basionym: *Boletus parasiticus* Bull.

Other accepted species:

P. astraeicola (Imazeki) Šutara

P. silvaticus Cortés-Pérez & Ram.-Cruz



Note a Basidiomata. b Basidiospores. c Basidia. d Pleurocystidia. e Cheilocystidia. Scale bar: a = 1.5 cm, b–e = 10 μm.

Source Redrawn from Cortés-Pérez et al. (2023). For original basidiomata, refer to Cortés-Pérez et al. (2023).

Figure 5.66 *Pseudoboletus silvaticus* (Cortés-Pérez 1870, holotype)

5.3.1.70 *Strobilomyces* Berk.

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.67

Classification: *Boletaceae, Boletales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Strobilomyces Berkeley belongs to the family *Boletaceae* (Akata, 2012) and is commonly known as the old man of the woods (in Europe). *Strobilomyces* is cosmopolitan in distribution (Sato et al., 2005; Akata, 2012), and East Asia has been shown to be the center of species diversity for this genus (Han et al., 2018a). Species of *Strobilomyces* form ectomycorrhizal associations with *Casuarinaceae*,

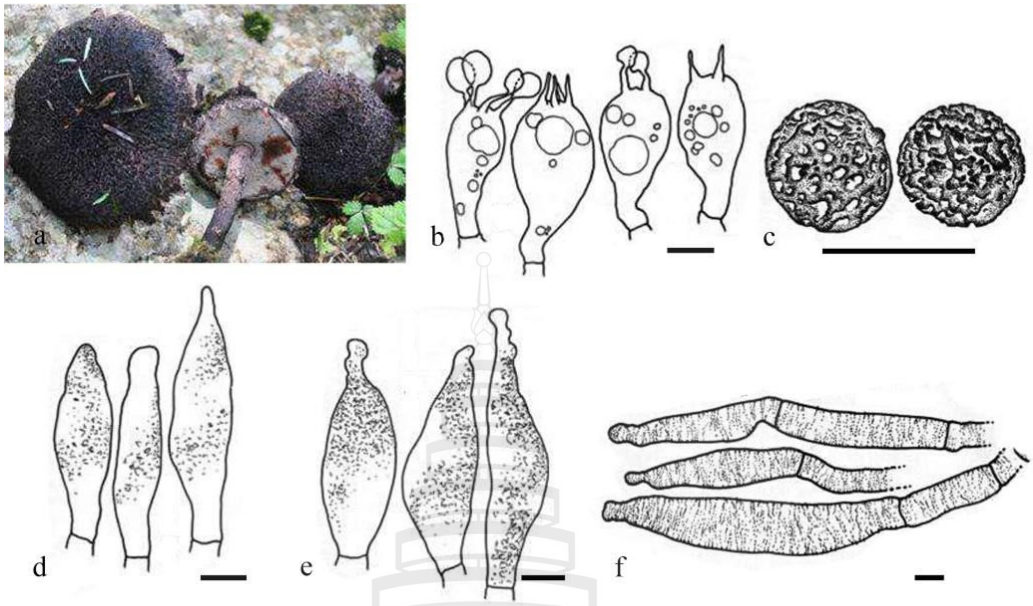
Dipterocarpaceae, *Fabaceae*, *Fagaceae*, *Myrtaceae*, and *Pinaceae* (Sato et al., 2017; Han et al., 2018a; Han et al., 2020). Morphologically, usually dry pileus, coarsely to scaly, black, blackish-brown, reddish-brown, greyish, or golden yellow cap with partial veils (Arora, 1986; Singer, 1986; Akata, 2012; Han et al., 2018a). Pore surface is white when young and becomes black with maturity (Das et al., 2014). Stipe is dry, woolly to shaggy and partly reticulated or smooth with or without an annulus, mostly concolourous to pileus (Arora, 1986; Akata, 2012; Das et al., 2014). Upon bruising, the stipe flesh converts from reddish to blackish and blackish brown (Singer, 1986; Antonín et al., 2015) with blackish brown to black spores (Das et al., 2014). Basidiospores are globose to broadly ellipsoid with partial to complete reticulate and subcristate to verrucose ornamentation (Singer, 1986; Das et al., 2014; Antonín et al., 2015). Its asexual morph is unknown (He et al., 2019).

Antonín et al. (2015) described a new species, *Strobilomyces pteroreticulosporus*, based on morphological characteristics, ecological data, and molecular analyses (ITS and *rpb1*). In addition, Han et al. (2018a) used four gene markers (*rpb1*, *rpb2*, *tef-1α*, and *cox3*) to support a new taxon, *Strobilomyces rubrobrunneus*. Based on combined analysis of phylogeny, morphology, host tree associations, and geographical distribution patterns, the new classification consists of two sections, *Strobilomyces* and *Echinati* (Han et al., 2020). Pegler and Young (1981) erected a new genus, *Afroboletus* Pegler & T.W.K. Young, to include species of *Echinati*. However, phylogenetic analysis reveals that both *Strobilomyces* and *Afroboletus* are monophyletic and form a sister group (Han et al., 2020). Index Fungorum (2025) lists 84 records of *Strobilomyces,* but Han et al. (2020) recognised only 31 species.

Type species: *Strobilomyces strobilaceus* (Scop.) Berk.

Basionym: *Boletus strobilaceus* Scop.

Other accepted species: Refer Species Fungorum (search *Strobilomyces*)



Note a *Strobilomyces sikkimensis* basidiomata. b *Strobilomyces polypyramis* b Basidia. c Basidiospores. d Cheilocystidia. e. Pleurocystidia. f Terminal cells of hyphal elements. Scale bar: b−f = 10 μm.

Source Das et al. (2014). Redrawn from Das et al. (2014).

Figure 5.67 *Strobilomyces sikkimensis* and *S. polypyramis*

5.3.1.71 *Veloporphyrellus* L.D. Gómez & Singer

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.68

Classification: *Boletaceae, Boletales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Veloporphyrellus was established by L.D. Gómez and R. Singer in 1984, with *V. pantoleucus* (Singer & Gómez, 1984) as its type species. The type species was described based on specimens collected from soil in the montane forest of *Quercus* and *Magnolia* in Costa Rica (Singer & Gómez, 1984). Members of *Veloporphyrellus* form ectomycorrhizal associations with plants from *Caesalpiniaceae*, *Dipterocaceae*, *Fagaceae*, and *Pinaceae* families (Li et al., 2014). Species of *Veloporphyrellus* are found across North and Central America, southeastern Asia, and Africa (Li et al., 2014).

Veloporphyrellus is characterised by the stipitate-pileate basidiomata, with a distinct membranous veil or an appendiculate pileal margin which often embraces the apex of the stipe (Singer & Gómez, 1984; Li et al., 2014; Wu et al., 2016b). The pileus has a white to pallid context, while the hymenophore ranges from white to pinkish (Singer & Gómez, 1984; Li et al., 2014; Wu et al., 2016b). Basidiospores are smooth, with pinkish to brownish pink in spore print (Singer & Gómez, 1984; Li et al., 2014; Wu et al., 2016b). The pileipellis is trichodermial in structure (Singer & Gómez, 1984; Li et al., 2014; Wu et al., 2016b).

Veloporphyrellus was originally considered monophyletic (Li et al., 2014). However, Wu et al. (2016b) found that *Veloporphyrellus* species cluster into two distinct clades. The genus shares the characteristics of membranous veil remnants on the pileus margin with *Austroboletus* (Corner) Wolfe, *Boletellus* Murrill, *Leccinum* Gray, *Strobilomyces* Berk., and *Suillus* Gray. However, *Veloporphyrellus* differs from *Boletellus*, *Leccinum*, and *Suillus* by having a pale pinkish to light pinkish or greyish pink hymenophore and a pink to ocher-purple spore print (Li et al., 2014). It is distinct from *Austroboletus* and *Strobilomyces* by its smooth basidiospores (Li et al., 2014). Species Fungorum (2024) recognises ten species of *Veloporphyrellus* worldwide.

Type species: *Veloporphyrellus pantoleucus* L.D. Gómez & Singer

Other accepted species:

V. africanus Watling

V. alpinus Yan C. Li & Zhu L. Yang

V. castaneus Yan C. Li & Zhu L. Yang

V. conicus (Ravenel) B. Ortiz, Yan C. Li & Zhu L. Yang

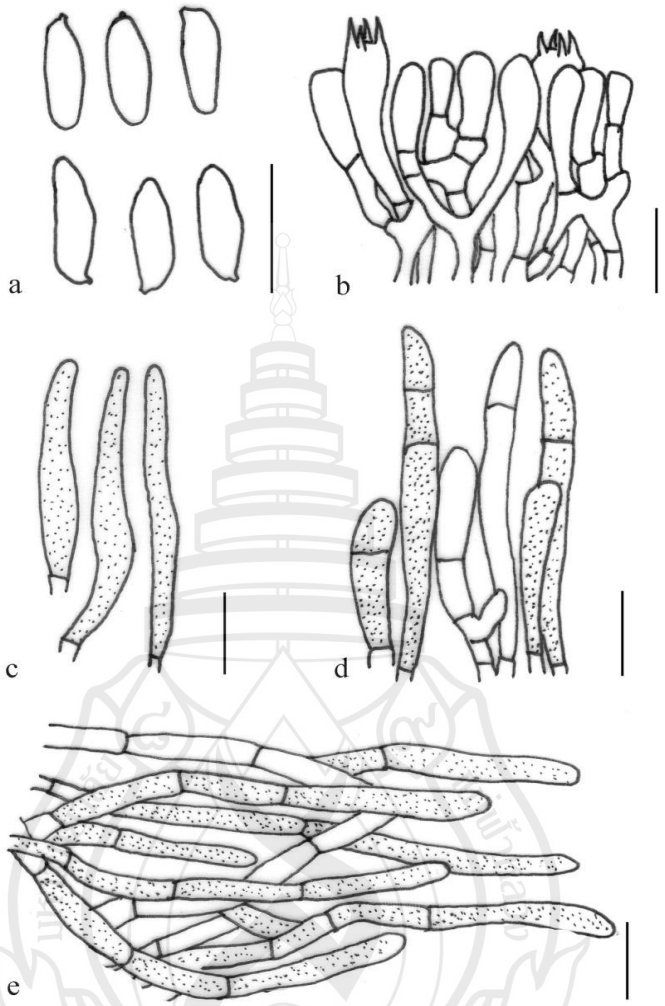
V. gracilioides Yan C. Li & Zhu L. Yang

V. latisporus J. Khan & S. Ullah

V. pseudovelatus Yan C. Li & Zhu L. Yang

V. velatus (Rostr.) Yan C. Li & Zhu L. Yang

V. velpinus T.H.G. Pham, O.V. Morozova, A.V. Alexandrova & E.S. Popov



Note a Basidiospores. b Basidia and basidioles. c Pleurocystidia. d Cheilocystidia. e Pileipellis. Scale bar: a–e = 20 μm.

Source Redrawn from Li et al. (2014). For original basidiomata, refer to Li et al. (2014).

Figure 5.68 *Veloporphyrellus alpinus*

Coniophoraceae Ulbr., in Lindau, *Krypt.-Fl. Anfäng.* (Berlin) 3(Aufl. 1): 120

Coniophoraceae was established by G. Lindau (1928) with *Coniophora* DC. as its type genus (Lindau, 1928). *Coniophoraceae* is characterised by its crust-like basidiomata (He et al., 2024). He et al. (2024) reported six genera in this family: *Chrysoconia* McCabe & G.A. Escobar, *Coniophora*, *Coniophoropsis* Hjortstam &

Ryvarden, *Gyrodontium* Pat., *Penttilamyces* Zmitr., Kalinovskaya & Myasnikov, and *Sedecula* Zeller. Members of *Coniophoraceae* are distributed worldwide and are saprophytic, with some species being pathogenic (*Coniophora puteana* (Schumach.) P. Karst.), causing brown rot (Irbe et al., 2011; He et al., 2019).

5.3.1.72 *Coniophora* DC.

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.69

Classification: *Coniophoraceae, Boletales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

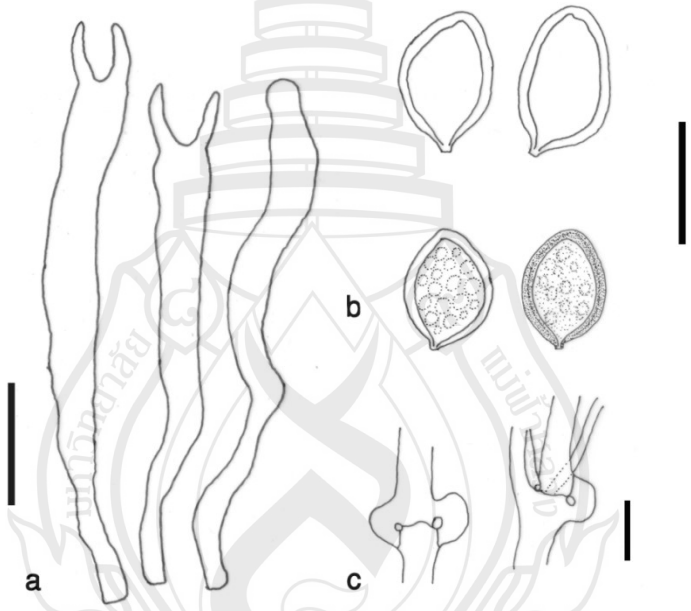
Coniophora DC. was established by De Candolle in 1815 under Basidiomycota, Boletales, Coniophoraceae (Blanco et al., 2009). *Coniophora* is a widespread corticioid (patch-forming) fungus in temperate and boreal regions (Binder & Hibbett, 2006; Kauserud et al., 2007; Dueñas et al., 2023). *Coniophora* was first reported in the Cape Verde Archipelago (Dueñas et al., 2023). *Coniophora arida* and *C. olivacea* were investigated based on morphological and combined molecular analyses of ITS, *tef*-1α, and *tub* genes (Kauserud et al., 2007). However, due to the limited number of macro- and micro-morphological characteristics, distinguishing species remains difficult (Kauserud et al., 2007). *Coniophora* can be found both domestically and in woodlands, with some bearing parasite behaviour (Schmidt et al., 2002). Most *Coniophora* are brown-rotting fungi in all kinds of wood, causing economic loss in the timber sector, and *Coniophora eremophila* causes progressive dieback of lemon trees (Adaskaveg et al., 2001; Schmidt et al., 2002; Dueñas et al., 2023). *Coniophora* is distinctive by resupinate, effused, fleshy, adnate, and membranaceous basidiomata; the hymenophore is usually smooth to tuberculate, with the presence of hyphal strands at the margin (Hallenberg, 1985; Li & He, 2023). This genus exhibits mono-, di-, or trimitic hyphal systems; most generative hyphae are clampless, with scattered double or verticillate clamps in wider marginal generative hyphae, clavate basidia, cylindrical to utriform, with two to four sterigmata but without basal clamps (Ginns, 1982; Hallenberg, 1985; Adaskaveg et al., 2001; Dueñas et al., 2023). The basidiospores are broadly ellipsoid, ellipsoid to ovoid, or subfusiform, and apiculate, with the presence of an apical germ pore, thick-walled,

smooth, yellowish to brownish, and more or less dextrinoid and cyanophilous reactions (Ginns, 1982; Hallenberg, 1985; Dueñas et al., 2023; Li & He, 2023). The basidiomata of *Coniophora* species produce xerocomic acid (Schmidt et al., 2002). *Coniophora* comprises 20 accepted species, according to Wijayawardene et al. (2020).

Synonymy: *Coniophorella* P. Karst.

Type species: *Coniophora membranacea* DC.

Other accepted species: (Species Fungorum – search *Coniophora*)



Note a Basidia. b Basidiospores. c Marginal generative hyphae with multiple clamps. Scale bar: a–b = 20 µm, c = 10 µm.

Source Redrawn from Carlier et al. (2004).

Figure 5.69 *Coniophora bimacrospora* (MUCL 45009, holotype)

5.3.1.73 *Gyrodontium* Pat.

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.70

Classification: *Coniophoraceae, Boletales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Gyrodontium was established by Patouillard in 1900 and is typified by *G. sacchari* (Leonardo-Silva et al., 2023). *Gyrodontium* is cosmopolitan, except in Antarctica, mainly in pantropical regions of the world (Carlier et al., 2004; Robledo et al., 2014; He et al., 2019; Leonardo-Silva et al., 2023). Index Fungorum (2025) lists 9 records of *Gyrodontium*; however, Hyde et al. (2024a) accepted only two species worldwide. Species of *Gyrodontium* cause brown rot and occur primarily on dead wood and in man-made environments such as wooden houses and bridges (Carlier et al., 2004).

Gyrodontium is characterised by resupinate to piliate basidiomata and yellowish olive to olive brown to brown toothed hymenium, which is cylindrical to angular (Carlier et al., 2004). *Gyrodontium* bears a monomitic hyphal system with clampless generative hyphae and ellipsoid, yellowish thick-walled basidiospores (Carlier et al., 2004). Basidiome context bears thick-walled, yellowish chlamydospores (Carlier et al., 2004).

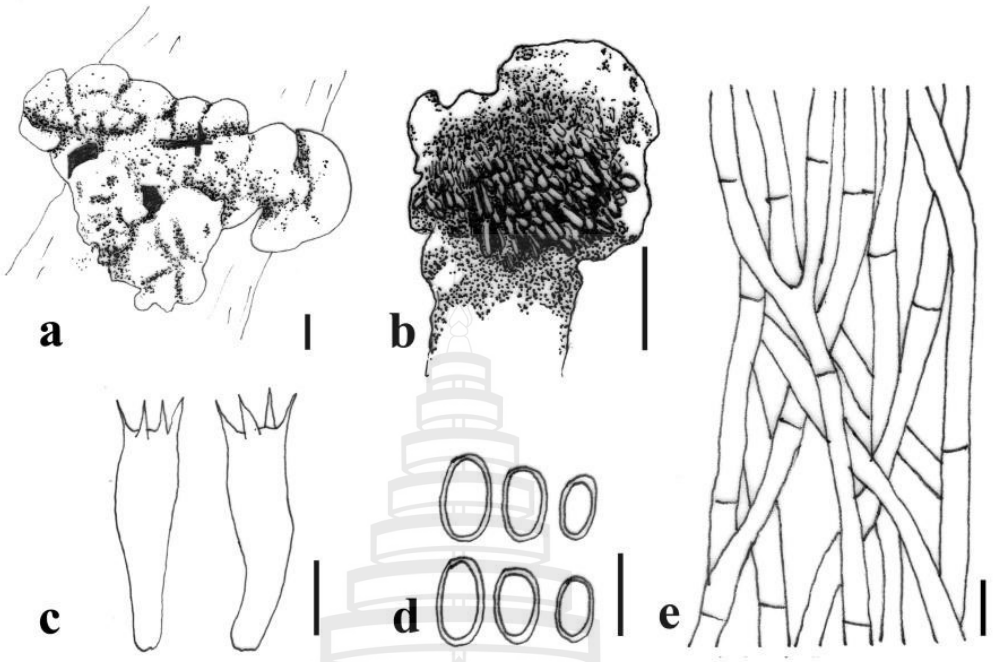
Species of *Gyrodontium* were previously classified as *Hydnum* due to spores produced in a structure resembling tooth-like or spinous hymenophores (Leonardo-Silva et al., 2023). Subsequently, with advancements in molecular phylogenetics, they were transferred to *Gyrodontium* (Leonardo-Silva et al., 2023). Binder et al. (2010) employed six-locus analysis (ITS, LSU, SSU, *rpb1*, *rpb2*, and *tef-1α*) to differentiate strains of *Agaricales*, *Boletales*, and *Atheliales*, including *Gyrodontium sachhari*. *Gyrodontium* is closely related to *Coniophora* in phylogenetic analyses, and both species bear simple septate generative hyphae; however, *Gyrodontium* has a toothed hymenial surface, whereas *Coniophora* has smooth basidiomata (Carlier et al., 2004; Valenzuela et al., 2012).

Synonymy: *Boninohydnum* S. Ito & S. Imai

Type species: *Gyrodontium sachhari* (Spreng.: Fr.) Hjortstam

Basionym: *Hydnum sacchari* Spreng.

Other accepted species: (Species Fungorum – search *Gyrodontium*)



Note a Pilial surface of basidiomata. b Hymenial surface of basidiome. c Basidia. d Basidiospores. e Hypahe of hymenophoral trama. Scale bars: a–b = 1 cm, c−e = 5 µm.

Source Redrawn from: a–b = Leonardo-Silva et al. (2023), c−e = Valenzuela et al. (2012).

Figure 5.70 *Gyrodontium sachhari*

Paxillaceae Lotsy, *Vortr. bot. Stammesgesch.* 1: 706

Paxillaceae was established by J.P. Lotsy (1907) with *Paxillus* Fr. as the type genus (Lotsy, 1907). *Paxillaceae* accommodates lamellate, truffle-like, and boletoid mushrooms and is characterised by the presence of clamp connections and brown staining due to the presence of involutin (Singer, 1986; He et al., 2024). Members of *Paxillaceae* are distributed worldwide and form ectomycorrhizal associations with tree roots (He et al., 2019). He et al. (2024) reported 11 genera in this family: *Alpova* C.W. Dodge, *Austrogaster* Singer, *Gyrodon* Opat., *Hoehnelogaster* Lohwag, *Hydnomerulius* Jarosch & Besl, *Meiorganum* R. Heim, *Melanogaster* Corda, *Neoalpova* Vizzini, *Paragyrodon*

(Singer) Singer, *Paralpova* Cabero & P. Alvarado, and *Paxillus*. Some species of this family are edible (*Paxillus involutus* (Batsch) Fr.) (He et al., 2019).

5.3.1.74 *Gyrodon* Opat.

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.71

Classification: *Paxillaceae, Boletales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Gyrodon was established by Opatowski to accommodate a single species, *Gyrodon sistotremoides* (Fr.) Opat. (synonym: *Gyrodon lividus* (Bull.) Sacc. (Snell, 1941). *Gyrodon*, an ectomycorrhizal fungal genus, has been reported from temperate and tropical regions (Saccardo, 1888; Pegler & Young, 1981; Singer, 1989; Kumla et al., 2017). The asexual morph of the genus is unknown (He et al., 2019). *Gyrodon lividus* is reported to be ectomycorrhizal only with *Alnus* (Karadelev et al., 2007).

Morpho-taxonomic studies were performed to differentiate at the species level, along with multi-locus genes (ITS and LSU) for *G. suthepensis* (Kumla et al., 2017). Index Fungorum (2025) lists 58 records of *Gyrodon,* but some species have been transferred to *Tylopilus*, *Suillus*, *Bothia*, *Boletinellus*, *Boletellus*, *Buchwaldoboletus*, *Phylloporus*, *Paragyrodon*, *Xerocomus*, and *Gyrodontium*. Hyde et al. (2024a) recognised only 13 species worldwide.

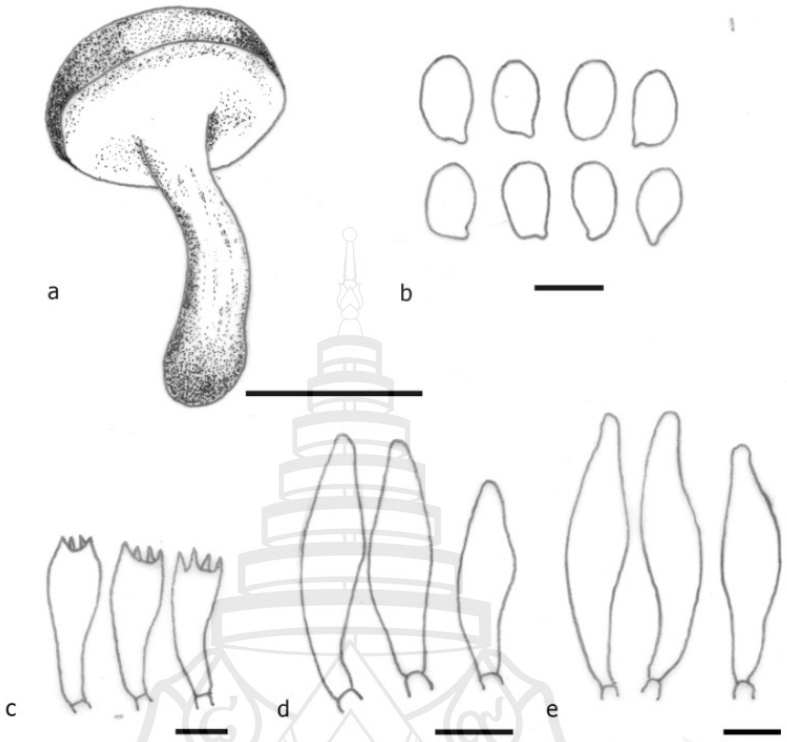
Some edible ectomycorrhizal mushroom species, such as *G. lividus* and *G. suthepensis*, possess antioxidant properties (Celal, 2018; Wanwaen & Youpensuk, 2019). Production trials of edible *Gyrodon* species have been done (Wanwaen & Youpensuk, 2019).

Synonymy: *Anastomaria* Raf., *Campbellia* Cooke & Massee, *Gilbertina* R. Heim, *Pseudogyrodon* Heinem. & Rammeloo, *Rodwaya* Syd. & P. Syd., *Uloporus* Quél.

Type species: *Gyrodon lividus* (Bull.) Sacc.

Basionym: *Boletus lividus* Bull

Other accepted species: (Species Fungorum – search *Gyrodon*)



Note a. Basidiomata, b. Basidiospores, c. Basidia, d. Pleurocystidia, e. Cheilocystidia. Scale bar: a = 5 cm, b = 5 µm, c–e = 10 µm.

Source Redrawn from Kumla et al. (2017).

Figure 5.71 *Gyrodon suthepensis*

5.3.1.75 *Paxillus* Fr.

Index Fungorum, FacesofFungi, MycoBank, GenBank, Fig. 5.72

Classification: *Paxillaceae, Boletales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Paxillus Fr. was established by Fries in 1821 (Jargeat et al., 2016). *Paxillus* species form ectomycorrhizal relationships with a range of host plants and are widely distributed in the northern hemisphere (Vellinga et al., 2012). Index Fungorum (2025) reports 185 records of *Paxillus*, while Hyde et al. (2024a) recognised approximately 70 species worldwide. Vellinga et al. (2012) reported two main species clusters: *Paxillus rubicundulus* P.D. Orton, related species associated with *Alnus* hosts, and *P. involutus*

complexes with a range of host trees. *Paxillus* fruiting bodies are fleshy, range from medium to large, and exhibit ochraceous-yellow to chestnut-brown or dark-brown colours. Pileus is funnel-shaped, with an involute margin in young sporophores. Lamellae are deeply decurrent, interveined towards the stipe, easily detachable, and reddening or browning tissues on bruising (Gelardi et al., 2014). The trichodermal pileipellis consists of filamentous hyphae, bi-lateral divergent hymenophoral trama, and an absent lateral stipe stratum (Šutara, 1992; Watling, 2008; Gelardi et al., 2014). Basidiospores are broadly ellipsoid, smooth, and cyanophilic (Šutara, 1992; Watling, 2008; Gelardi et al., 2014). The spore print is rusty brown to reddish brown. Clamp connections are present (Šutara, 1992; Watling, 2008; Gelardi et al., 2014).

Paxillus involutus was the only species within *Paxillus* for several decades, serving as the type species (Jargeat et al., 2016). Based on species of the Northern Hemisphere, *Paxillus* has been verified as monophyletic (Watling, 2008; Vellinga et al., 2012; Gelardi et al., 2014). Bresinsky et al. (1999) reported that taxa from the Southern Hemisphere form a separate lineage. The challenge of identifying species, given the polymorphic basidiome, is resolved by using the ITS gene as a genetic marker (Hahn & Agerer, 1999a; Gelardi et al., 2014).

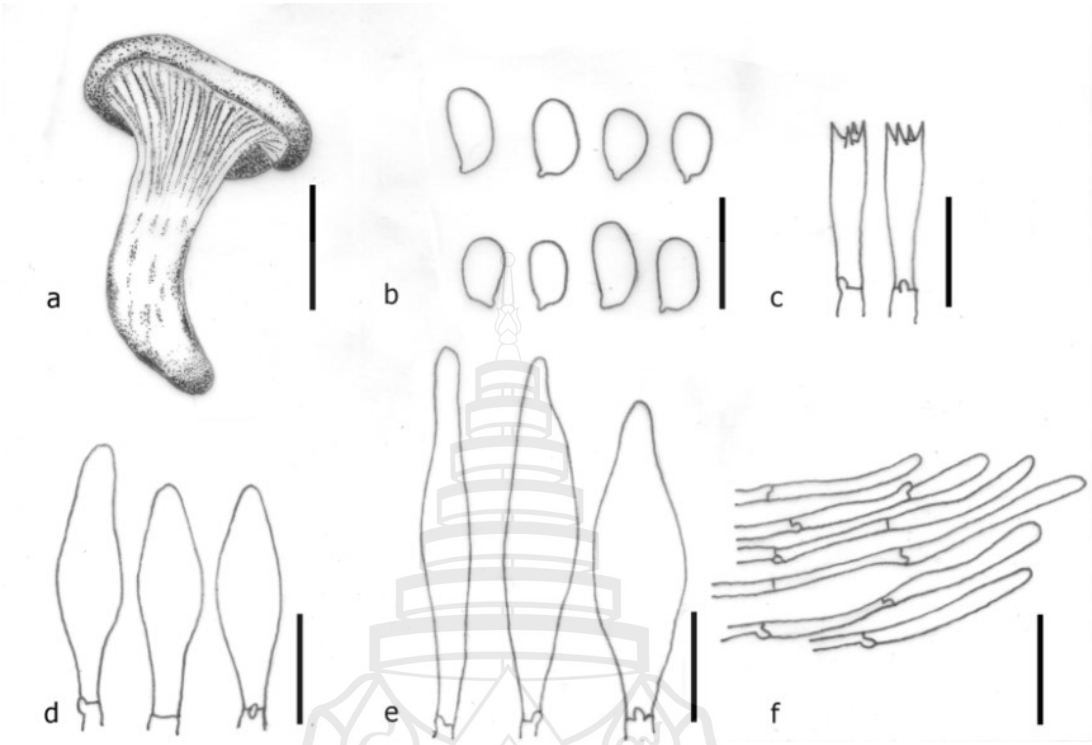
The type species *P. involutus* is poisonous due to immune haemolysis (Winkelmann et al., 1986; Jarosch & Bresinsky, 1999; Anthowiak et al., 2003).

Synonymy: *Parapaxillus* Singer; *Paxillopsis* E.-J. Gilbert; *Rhymovis* Pers. ex Rabenh.; *Ruthea* Opat.

Type species: *Paxillus involutus* (Batsch) Fr.

Basionym: *Agaricus involutus* Batsch

Other accepted species: (Species Fungorum – *Paxillus*)



Note a Basidiomata. b Basidiospores. c Basidia. d Cheilocystidia. e Pleurocystidia. f Pileipellis. Scale bar: a = 2.5 cm, b = 10 μm, c–e = 20 μm, f = 40 μm.

Source Redrawn from Gelardi et al. (2014).

Figure 5.72 *Paxillus orientalis*

Hymenochaetales Oberw.

Hymenochaetaceae Donk, *Bull. bot. Gdns Buitenz.* 17(4): 474

Hymenochaetaceae was established by M.A. Donk in 1948, with *Hymenochaete* Lév. as the type genus (Donk, 1948). He et al. (2024) recognised 45 genera worldwide in this family. The family is characterised by annual to perennial, resupinate, effused-reflexed, pileate to stipitate, and brownish basidiomata, with poroid or corticioid hymenophore, a xanthochroic reaction in KOH, and presence or absence of setoid elements (Wu et al., 2022). *Hymenochaetaceae* are distributed worldwide and are saprophytic, causing white rot (Hyde et al., 2024a). Species within the family, including *Fomitiporella* Murrill, *Porodaedalea* Murrill, *Pyrrhoderma* Imazeki, and

Sanghuangporus Sheng H. Wu, L.W. Zhou & Y.C. Dai, are ecologically and economically important (Wu et al., 2022; Hyde et al., 2024a; Zhao et al., 2024b).

5.3.1.76 *Asterodon Pat.*

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.73

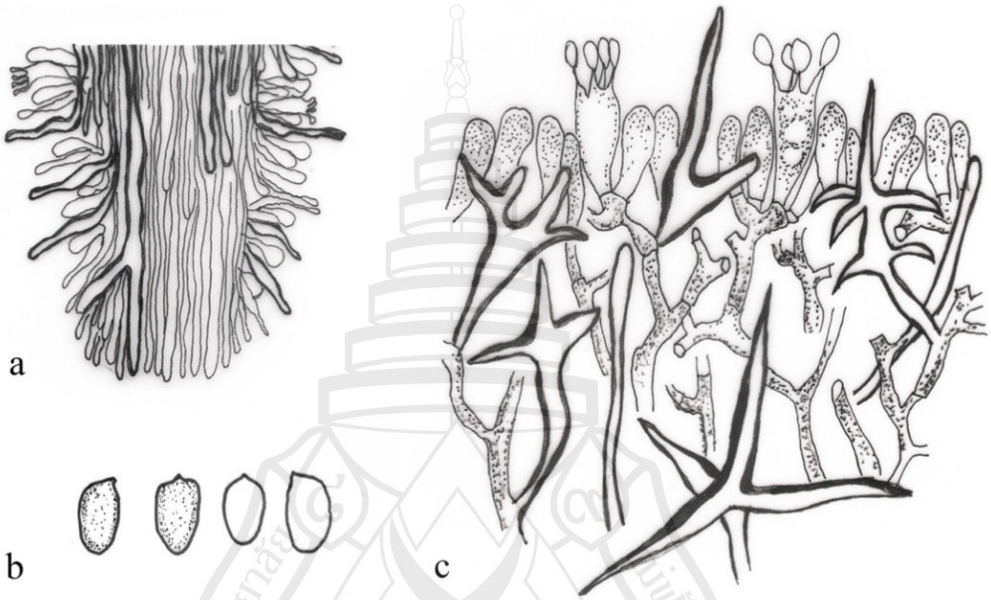
Classification: *Hymenochaetaceae, Hymenochaetales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Asterodon is a monotypic hydnoid genus established by Patouillard in 1894 with the type species *Asterodon ferruginosum* (Wagner & Fischer, 2002a). *Asterodon* was previously classified in *Hymenochaetaceae* (Wang et al., 2023b). Index Fungorum (2025) lists 10 records of *Asterodon*; however, Hyde et al. (2024a) recognised only two species worldwide. Members of this genus usually grow on rotten coniferous wood and are widespread in the northern temperate region (Corner, 1948; Pegler & Young, 1993; He et al., 2019). *Asterodon* is distinctive by the epixylous, perennial, wholly resupinate, widely effused, separable, and umber to fulvous shape of basidiomata (Banker, 1914; Corner, 1948), and produces a setulose with reddish straight, simple (spine-like) or branched setae (branch at right angles into 3 or 4 spines) of hymenium (Banker, 1914). Corfixen (1990) reported that the basidiomata usually bear mycelial setae, followed by more or less branched solitary tramal setae and finally hymenial setae. Pegler and Young (1993) reported that the asterosetae of *Asterodon* are never dextrinoid, dimitic with generative hyphae simple-septate, hyaline to pale brown, and skeletal hyphae unbranched, or rarely bifurcate, aseptate, smooth, brownish ochraceous, and thick-walled in the hyphal system (Gorjón, 2020). Basidia are clavate with four sterigmata and simple-septate at the base (Gorjón, 2020). Basidiospores are hyaline, broadly ellipsoid, aguttate, and smooth (Banker, 1914). To identify *Asterodon* species, a combined morphological and phylogenetic analysis (ITS and LSU) was performed. Once, *Asterodon* was transferred from *Hymenochaetaceae* to *Asterodontaceae* based on its distinct morphological characteristics (Wang et al., 2023b). However, later phylogenetic analyses again placed *Asterodon* in *Hymenochaetaceae* (Larsson, 2007; Wang et al., 2023b). *Asterodon* is related to *Hymenochaete* but differs mainly in the branched asterosetae

(Gorjón, 2020). Further study is required with non-European specimens (Fiasson & Niemela, 1984).

Synonymy: *Hydnochaete* Peck, *Hydnochaetella* Sacc.

Type species: *Asterodon ferruginosus* Pat.



Note a Longitudinal section of the tip of a spine. b Basidiospores. c Section of the hymenium between two spine bases. Scale bar: a, c = ×500, b = ×1000.

Source Redrawn from Corner (1948).

Figure 5.73 *Asterodon ferruginosus*

5.3.1.77 *Onnia* P. Karst.

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.74

Classification: *Hymenochaetaceae, Hymenochaetales, Agaricomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

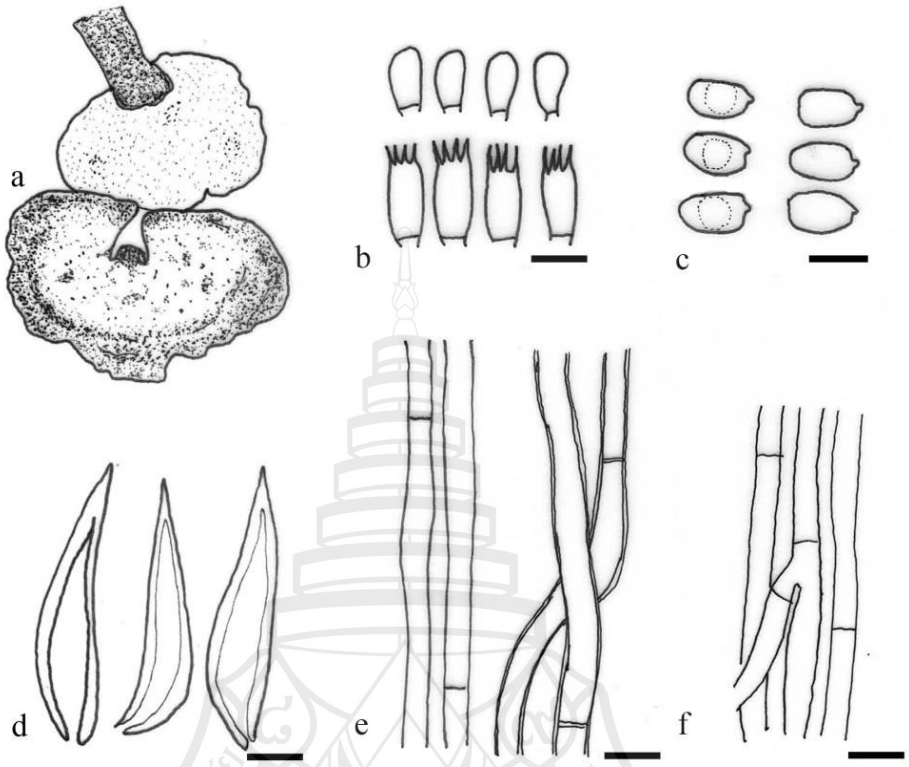
Onnia P. Karst, a wood-inhabiting fungus, was established by Karsten in 1889 with the type species *Polyporus circinatus* Fr. (*Onnia tomentosa* [Fr.] P. Karst.) (Zhao et al., 2022b). Almost all species grow on gymnosperms (Germain et al., 2009; Ryvarden & Melo, 2014; Zhao et al., 2022b).

Onnia is characterised by basidiomata that are annual, sessile, or stipitate, with a duplex context, and bear hooked hymenial setae (Niemelä, 2005; Dai, 2010; Ji et al., 2017). The hyphal system is monomitic, characterised by simple septate generative hyphae (Niemelä, 2005; Dai, 2010; Ji et al., 2017). Basidiospores are cylindrical or ellipsoid, hyaline, thin-walled, smooth, nonamyloid, nondextrinoid, and acyanophilous (Niemelä, 2005; Dai, 2010; Ji et al., 2017). Both morphology and phylogeny (ITS and LSU) are used to identify *Onnia* species (Ji et al., 2017; Zhao et al., 2022b). Zhao et al. (2022) employed multiple genes (ITS, LSU, *rpb*1, *rpb*2, and *tef*-1α) to estimate divergence times using molecular clock analysis. Phylogenetically, *Onnia* is closely related to *Porodaedalea* Murill., but morphologically the latter has a perennial growth habit, pileate basidiomata lacking a stipe, dimitic hyphal system, and straight setae (Ji et al., 2017; Zhao et al., 2022b). Morphologically, *Onnia* resembles *Inonotopsis* Parmasto, but the latter has resupinate basidiomata without setae (Ji et al., 2017). Index Fungorum (2025) reports 18 records of *Onnia,* but Hyde et al. (2024a) recognised only 9 species worldwide. Some species are pathogens causing Tomentosus root rot on Pinaceae trees (Germain et al., 2009; Ryvarden & Melo, 2014; Zhao et al., 2022b). Ethanol extracts from *Onnia tomentosa* have strong anti-proliferative activity, indicating that it is an edible and medicinal mushroom (Lee et al., 2022).

Type species: *Onnia* circinate (Fr.) P. Karst.

Basionym: *Trametes circinata* Fr.

Other accepted species: (Species Fungorum – search *Onnia*)



Note a Basidiomata. b Basidia and Basidioles. c Basidiospores. d Setae. e Hyphae from context. f Hyphae from trama. Scale bar: a, d–f = 10 µm, c = 5 µm.

Source Redrawn from Dai (2010).

Figure 5.74 *Onnia tomentosa*

Auriculariales Bromhead

Incertae sedis

5.3.1.78 *Basidiodendron* Rick

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.75

Classification: *Incertae sedis, Auriculariales, Auriculariomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Rick (1938) established *Basidiodendron* as a monotypic genus, with *B. luteogriseum* as the type species based on a specimen collected from wood in Brazil. This classification was reaffirmed by Robena Lunk-Allen in 1963 (Luck-Allen, 1963). Species

of *Basidiodendron* are widespread across Eurasia, Europe, North and South America, and Africa (He et al., 2019; Spirin et al., 2020, 2021).

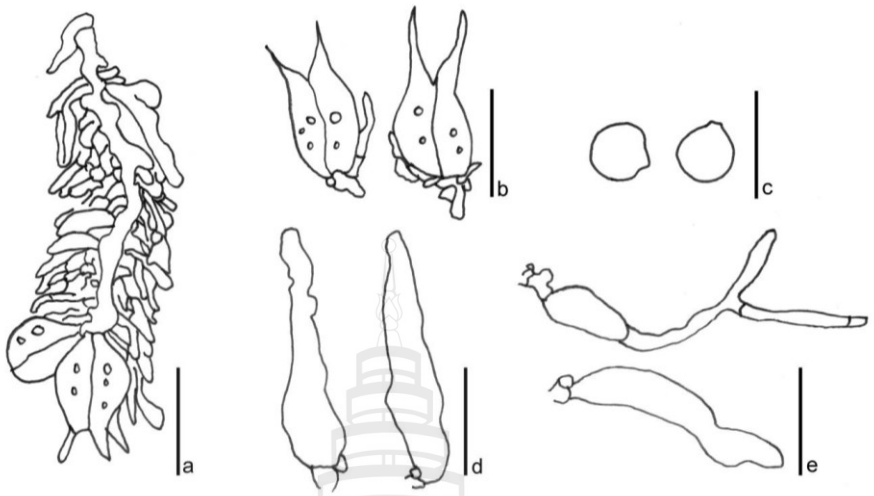
Basidiodendron is characterised by effused, wood-inhabiting basidiomata with a smooth or minutely warted hymenophore (Luck-Allen, 1963; Spirin et al., 2021). The basidiomata are invisible when young but become visible as they mature (Kotiranta & Saarenoksa, 2005). Fresh specimens are bluish-grey, turning pale cream or ochre with brownish spots as they dry, and quickly turning yellow when treated with KOH (Kotiranta & Saarenoksa, 2005). The basidiospores are smooth and occasionally produce secondary basidiospores (Kotiranta & Saarenoksa, 2005).

The basidia are distinctive, featuring a four-celled, longitudinally septate structure located at the tips of long, sinuous hyphae. These hyphae are covered along their length by shields of collapsed basidia and are clamped (Kotiranta & Saarenoksa, 2005; Spirin et al., 2020). Gloeocystidia are prominent with longitudinal septation (Luck-Allen, 1963; Kotiranta & Saarenoksa, 2005; Spirin et al., 2021).

Spirin et al. (2021) used morphological characteristics and phylogenetic analyses (ITS, LSU, and *tef-1α*) to delineate species within *Basidiodendron.* Index Fungorum (2025) lists 50 records of *Basidiodendron,* whereas Wijayawardene et al. (2022) recognised approximately 15 species worldwide. *Basidiodendron* can be distinguished from morphologically similar genera, such as *Bourdotia* (Bres.) Bres. & Torrend, *Ductifera* Lloyd, and *Exidiopsis sensu lato* (Bref.) Möller, by its waxy or arid, non-hygroscopic basidiomata and comparatively shorter basidia, which lack a basal stalk (Luck-Allen, 1963; Wells & Raitviir, 1975; Spirin et al., 2021). Phylogenetic analysis further supports the distinction between *Basidiodendron* and *Bourdotia* (Weiß & Oberwinkler, 2001; Spirin et al., 2020).

Type species: *B. luteogriseum* Rick

Other accepted species: (Species Fungorum – search *Basidiodendron*)



Note a Basidia-bearing hypha covered by collapsed basidial cells. b Basidia. c Basidiospores. d Normally developed gloeocystidia. e Gloeocystidia with hyphoid apical outgrowths. Scale bar: a−e = 10 µm.

Source Redrawn from Spirin et al. (2020).

Figure 5.75 *Basidiodendron globisporum* (Spirin 7040)

5.3.1.79 *Ceratosebacina* P. Roberts

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.76

Classification: *Incertae sedis, Auriculariales, Auriculariomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Ceratosebacina was established by Peter Roberts in 1993, with *C. longispora* as the type species, based on a specimen collected from a fallen *Quercus* branch in Devon, England (Roberts, 1993). The name, *Ceratosebacina,* was from a combination of *Ceratobasidium* D.P. Rogers and *Sebacina* Tul., reflecting the horned ('*cerato*') nature of the basidia (Roberts, 1993). Members of *Ceratosebacina* are reported in Europe and the USA (GBIF, 2024).

Ceratosebacina has resupinate, inconspicuous, effused, smooth, thin, and waxy-gelatinous basidiomata (Roberts, 1993; Weiß & Oberwinkler, 2001). The hyphae are clamped and proliferate from the base of the basidium, while hyphidia are absent

(Roberts, 1993). Basidia are 2-4 septate, globose or ovoid, with short, often lateral stalks, longitudinal septation, and clamps at the base (Roberts, 1993; Weiß & Oberwinkler, 2001). Sterigmata are 2-4 per basidium, appearing rigid and occasionally septate (Roberts, 1993). Basidiospores are elongated, often replicating, and germinate through one or more germ tubes (Roberts, 1993). Globose microconidia, a unique character, have been observed in cultures of *C. longispora* (Ingold, 1992).

Species within *Ceratosebacina* are distinguished using combined morphological and phylogenetic analysis (LSU) (Weiß & Oberwinkler, 2001). Any resupinate tremellaceous fungi used to be placed in *Exidiopsis* (Bref.) Möller (Roberts, 1993). Later, Roberts (1993) proved that *Ceratosebacina* differs from *Exidiopsis* (Bref.) Möller by its visible, wide, and non-gelatinised hyphae, absence of hyphidia, *Ceratobasidium*-like basidia, and sterigmata. Morphologically, *Ceratosebacina* resembles the *Ceratobasidiales* Jülich more than the *Tremellales* Fr. (Roberts, 1993). Three species are recognised (He et al., 2019).

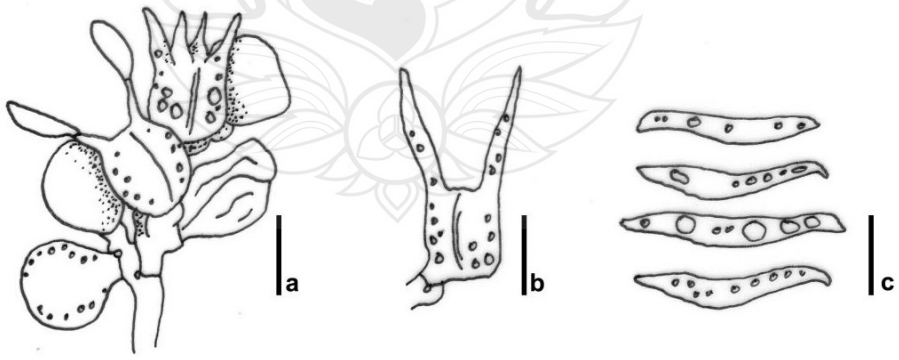
Type species: *Ceratosebacina longispora* (Hauerslev) P. Roberts

Basionym: *Sebacina longispora* Hauerslev

Other accepted species:

C. calospora (Bourdot & Galzin) P. Roberts

C. prolifera (D.P. Rogers) P. Roberts



Note a, b Basidia. c Basidiospores. Scale bar: a−c = 10μm.

Source Redrawn from Roberts (1993). For original basidiomata, refer to GBIF (2024).

Figure 5.76 *Ceratosebacina longispora* (P. Roberts 319)

5.3.1.80 *Endoperplexa* P. Roberts

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.77

Classification: *Incertae sedis, Auriculariales, Auriculariomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Endoperplexa was established by Peter Roberts in 1993, with the type species *Endoperplexa dartmorica* (Roberts, 1993). *Endoperplexa* species are saprobic (Roberts, 1993). The name *Endoperplexa* is derived from a combination of the Greek and archaic Latin "*endo*", meaning "within", and the Latin "*perplexus*", meaning "confused", referring to the gelatinised and obscure hymenial structure (Roberts, 1993).

The basidiomata of *Endoperplexa* are thin, effused, resupinate, and farinaceous to thinly ceraceous (Roberts, 1993). Hyphae are thin, inconspicuous, and often nodulose in the hymenium, with or without clamp connections, forming a branching, basidia-bearing hymenium within a dense gelatinous matrix (Roberts, 1993). New hyphae emerge from the base of mature basidia (Roberts, 1993). Cystidia are scattered, hyaline, thin-walled, and cylindrical (Roberts, 1993). Basidia are 2-4 septate, globose to wide ellipsoid, and clamped at the base, with each basidium bearing 2-4 sterigmata (Roberts, 1993). Basidiospores are small, ranging from globose to ovoid to ellipsoid (Roberts, 1993).

Endoperplexa is differentiated from the closely related genus *Exidiopsis* (Bref.) Möller by its inconspicuous basidiomata, narrow and nodulose hyphae, small and subglobose basidia, absence of hyphidia, and presence of hyaline cystidia (Roberts, 1993). *Endoperplexa* is distinguished from another related genus, *Basidiodendron* Rick, where basidia are successively produced on continually extending stalk cells (Roberts, 1993). Both morphological and phylogenetic analyses (ITS and LSU) have been used to differentiate species within *Endoperplexa* (Weiss et al., 2004; Kühdorf et al., 2014). Index Fungorum (2025) reports seven species, while He et al. (2019) recognised only six species worldwide.

Synonymy: *Opadorhiza* T.F. Andersen & R.T. Moore

Type species: *Endoperplexa dartmorica* P. Roberts

Other accepted species:

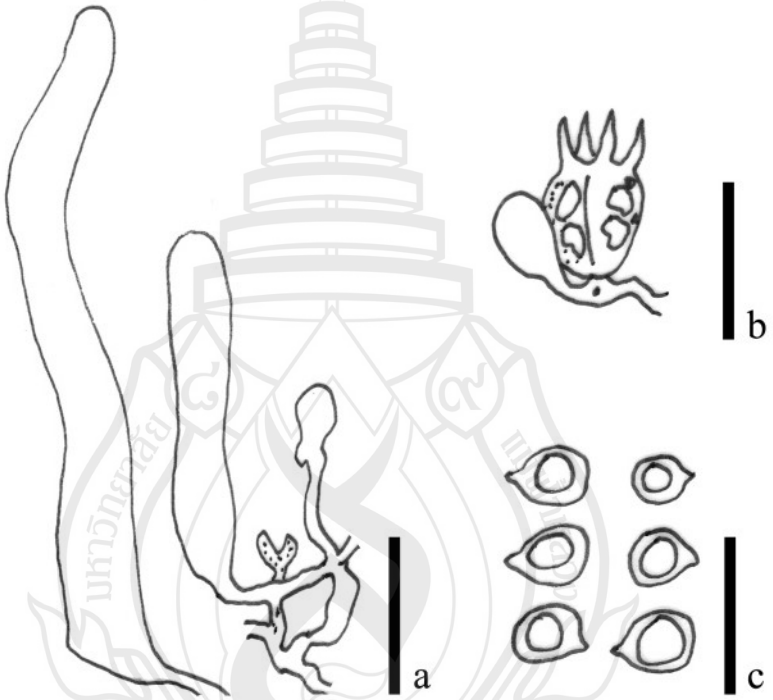
E. enodulosa (Hauerslev) P. Roberts

E. obscura (G.W. Martin) P. Roberts

E. phlebioides P. Roberts

E. subfarinacea (Hauerslev) P. Roberts

E. tortola P. Roberts



Note a Cystidia. b Basidia, showing proliferation from the sub-basidial clamp connection. c Basidiospores. Scale bar: a–c = 10 μm.

Source Redrawn from Roberts (1993). For original basidiomata, refer to GBIF (2024).

Figure 5.77 *Endoperplexa dartmorica* (P. Roberts 382, holotype)

5.3.1.81 *Hauerslevia* P. Roberts

Index Fungorum, Facesoffungi, MycoBank, Fig. 5.78

Classification: *Incertae sedis, Auriculariales, Auriculariomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

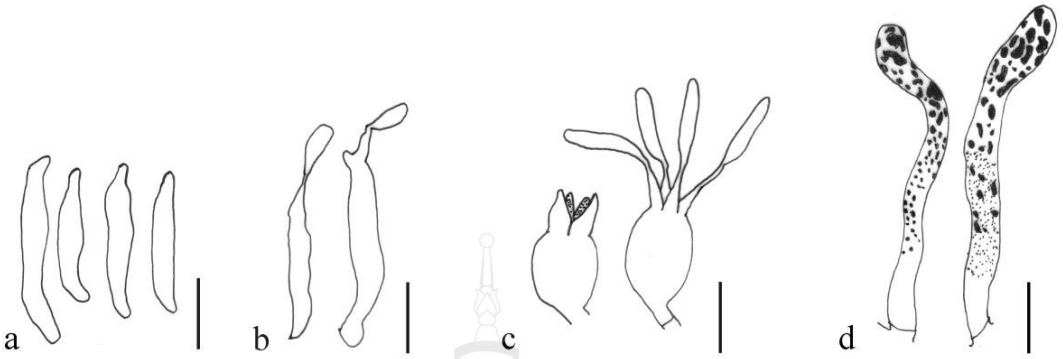
Hauerslevia is a monotypic genus established by P. Roberts in 1998, with its type species, *H. pulverulenta* (Roberts, 1998). The name honours Danish mycologist K. Hauerslev (Roberts, 1998). The type species was originally described as *Sebacina pulverulenta* Hauerslev, within *Tremellaceae* Fr., based on specimens collected on the bark of a broadleaf tree in Stigsnaes, Denmark (Hauerslev, 1976; Roberts, 1998). This genus is considered rare in parts of Europe, including Denmark, France, the UK, and the European part of Russia (Roberts, 1998; Garnier-Delcourt et al., 2010; Bolshakov et al., 2022). The genus has been included in the list of protected generic names for fungi (Kirk et al., 2013).

Hauerslevia is characterised by thin, effused, greyish, and somewhat ceraceous resupinate basidiomata, with a thin, open-textured hymenium composed of a single layer of basidia intermixed with cystidia (Roberts, 1998). The basidiospores are elongated and capable of producing secondary spores by replication (Roberts, 1998). Basidia are subglobose to ellipsoid, bear a lateral stalk, and are 4-spored, while the sterigmata are widest at the base, closely set, and become contiguous towards the base (Roberts, 1998). Cystidia are tubular, thin-walled, hypha-like structures, often sinuous, with prominently cyanophilic granules at their apex (Roberts, 1998). Hyphae are hyaline, thin-walled, and lack clamp connections (Roberts, 1998).

Due to a lack of molecular sequences, delineation from closely related genera is solely based on morphological characteristics (He et al., 2019). *Hauerslevia* resembles *Ceratobasidium* D.P. Rogers and *Ceratosebacina* P. Roberts in hymenial structure, hyphae, and basidia (Roberts, 1998). However, it can be distinguished from these genera as *Ceratobasidium* possesses aseptate basidia, and *Ceratosebacina* has septate basidia.

Type species: *Hauerslevia pulverulenta* (Hauerslev) P. Roberts

Basionym: *Sebacina pulverulenta* Hauerslev



Note a Basidiospores. b Basidiospores, self-replicating. c Basidia. d Cystidia. Scale bar: a–d = 10 μm.

Source Redrawn from Roberts (1998). For original basidiomata, refer to GBIF (2025).

Figure 5.78 *Hauerslevia pulverulenta*

5.3.1.82 *Heterorepetobasidium* Chee J. Chen & Oberw.

Index Fungorum, Facesoffungi, MycoBank, Fig. 5.79

Classification: *Incertae sedis, Auriculariales, Auriculariomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Heterorepetobasidium was established by D.J. Chen, F. Oberwinkler & Z.C. Chen in 2002, with its type species *H. subglobosum* (Chen et al., 2002). This species was described from specimens collected on decaying wood in Taiwan, China (Chen et al., 2002). At the same time, Chen et al. (2002) described another new species, *H. ellipsoideum* Oberw. & Chee J. Chen, from Taiwan, China.

Heterorepetobasidium is characterised by thin, effused, whitish, creamy, or translucent basidiomata that are waxy when fresh and horny when dry (Chen et al., 2002). The basal hyphae are thin, mostly tortuous, and clamped (Chen et al., 2002). Hyphidia are branched protruding into the hymenium and are present rarely (Chen et al., 2002). Basidiospores are hyaline, thin-walled, smooth, and inamyloid, and they germinate through secondary spores (Chen et al., 2002). Basidia are subglobose to clavate or pyriform with longitudinal partial septation and develop terminally from small, clamped generative hyphae (Chen et al., 2002). The sterigmata are swollen at the base

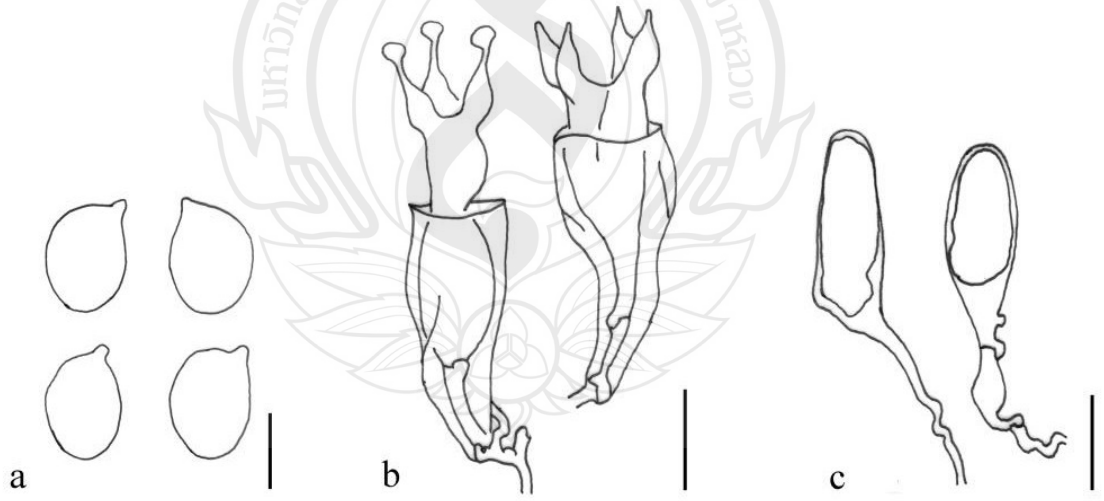
while abruptly tapering into spiculae. New basidia grow through the mature ones in a repetobasidial development pattern, leaving old basidia as sheaths around them (Chen et al., 2002). Gloeocystidia arise terminally or laterally from the basal or sub-hymenium, while pleurogleocystidia bear lateral hyphal appendages (Chen et al., 2002). Dolipores are with continuous parenthesomes, each perforated only centrally by one micropore (Chen et al., 2002).

Species delineation of *Heterorepetobasidium* from other closely related genera is solely based on morphological characteristics due to the lack of molecular sequences (He et al., 2019). Morphologically, this genus is similar to *Repetobasidium* J. Erikss. and *Repetobasidiellum* J. Erikss. & Hjortstam (Eriksson et al., 1981; Oberwinkler & Tschen, 1989). However, the latter genera are distinct by the lack of partially septate basidia, secondary spores, and gloeocystidia (Chen et al., 2002).

Type species: *Heterorepetobasidium subglobosum* Chee J. Chen & Oberw.

Other accepted species:

H. ellipsoideum Oberw. & Chee J. Chen



Note a Basidiospores. b Basidia. c Gloeocystidia. Scale bar: a = 5 µm, b–c = 10 µm.

Source Redrawn from Chen et al. (2002).

Figure 5.79 *Heterorepetobasidium subglobosum*

Incertae sedis

Cantharellales Gäum.

Aphelariaceae Corner, *Beih. Nova Hedwigia* 33: 5

Aphelariaceae was established by Corner in 1970 and typified by the genus *Aphelaria* Corner (Corner, 1950). The family includes three genera, *Aphelaria*, *Phaeoaphelaria* Corner, and *Tumidapexus* D.A. Crawford (Hyde et al., 2024a). *Aphelariaceae* is characterised by orthotropic, branched basidiomata, with rounded or flattened fertile branches and a sterile base, presence of monomitic hyphal system, and ellipsoidal or drop-shaped, smooth, in amyloid basidiospores (Bondartseva & Zmitrovich, 2023). Members of the family are saprobic, occurring in soil or wood (Bondartseva & Zmitrovich, 2023).

5.3.1.83 *Aphelaria* Corner

Index Fungorum, Facesoffungi, MycoBank, Fig. 5.80

Classification: *Aphelariaceae, Cantharellales, Incertae sedis, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Aphelaria, a genus within clavarioid fungi, was established by E.J.H. Corner in 1950 and typified with *A. dendroides* (Jungh.) Corner (Corner, 1950). The first description of *A. dendroides* was based on specimens collected from soil in forests in Java, Indonesia (Junghuhnius, 1838); however, species of *Aphelaria* are widespread in distribution (He et al., 2019). Index Fungorum (2025) lists 26 species of *Aphelaria,* while Hyde et al. (2024a) recognised approximately 20 species worldwide. *Aphelaria* is characterised by tough, consistent basidiomata, flattened branching, and hyaline basidiospores (Corner, 1950). This genus was divided into two subgenera: *Aphelaria* with normal clavarioid basidia with clamped hyphae, and subgenus *Tremellodendropsis* with subtremellaceous basidia and without clamps (Corner, 1953). Crawford (1954) elevated *Tremellodendropsis* to genus level, introducing the new species *T. transpusio* D.A. Crawford.

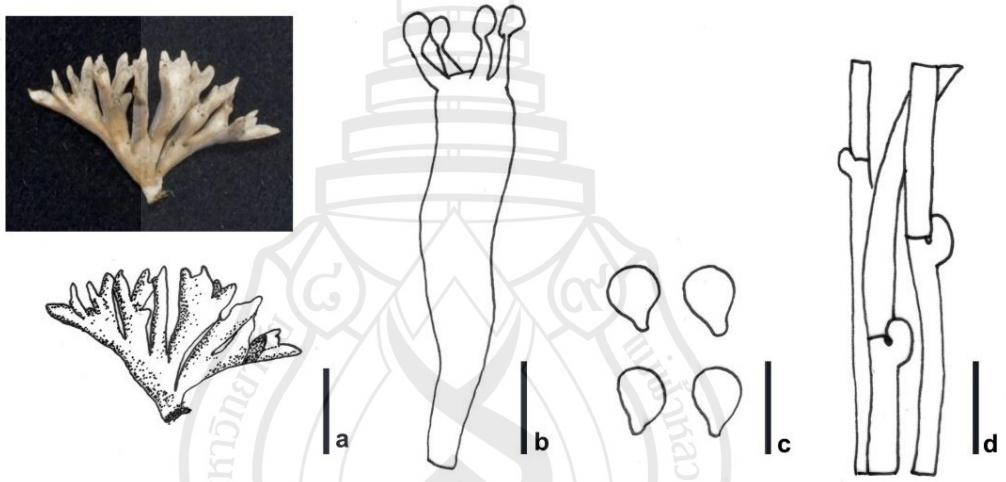
Basidiomata of *Aphelaria* are usually sub-sessile, branched, and covered with a hard, pale mealy-crustaceous bark on the outside (Junghuhnius, 1838). Basidia are

typically clavate, generally with four sterigmata (Corner, 1966a). Basidiospores are smooth, thin-walled ellipsoid to subcylindrical (Corner, 1966a). Cystidia are lacking (Corner, 1966a). The hyphal system is monomitic (Corner, 1966a). Identification of *Anastrophella* species is solely based on morphological characteristics, as no molecular evidence has been reported (He et al., 2019).

Type species: *Aphelaria dendroides* (Jungh.) Corner

Basionym: *Clavaria dendroides* Jungh.

Other accepted species: (Species Fungorum – search *Aphelaria*)



Note a Basidiomata. b Basidia. c Basidiospores. d Clamped, inflated hyphae. Scale bar: a = 1 cm, b−d = 10µm.

Source Redrawn from Desjardin and Perry (2015) and Roberts (1999). a = DED8317, b−d = K(M) 58046

Figure 5.80 *Aphelaria subglobispora*

Ceratobasidiaceae G.W. Martin, *Lloydia* 11: 114

Ceratobasidiaceae is a family of cryptic fungal species established by G.W. Martin (1948) with *Ceratobasidium* D.P. Rogers as the type genus (Martin, 1948). The family consists of six genera: *Ceratobasidium, Ceratoporia* Ryvarden & de Meijer, *Ceratorhiza* R.T. Moore, *Rhizoctonia* DC, *Scotomyces* Jülich, and *Thanatephorus* Donk

(He et al., 2019). Members of this family are distributed worldwide and can be plant pathogens, saprotrophic, or orchid mycorrhizal symbionts (Oberwinkler et al., 2013; Veldre et al., 2013; O'Donnell et al., 2025). These species spend most of their lifecycle in the simple morphologically asexual stage and form irregular sclerotia or as necrotic lesions in plant tissues (Veldre et al., 2013). Some genera of *Ceratobasidiaceae* have economic and ecological importance. For instance, the pathogenic genus *Rhizoctonia* causes significant damage in staple crops (potato and paddy) (Okubara et al., 2014). The family accommodates ancestral fungi forming mycorrhizal symbiosis with orchids (Yukawa et al., 2009).

5.3.1.84 *Ceratoporia* Ryvarden & de Meijer

Index Fungorum, Facesoffungi, MycoBank, Fig. 5.81

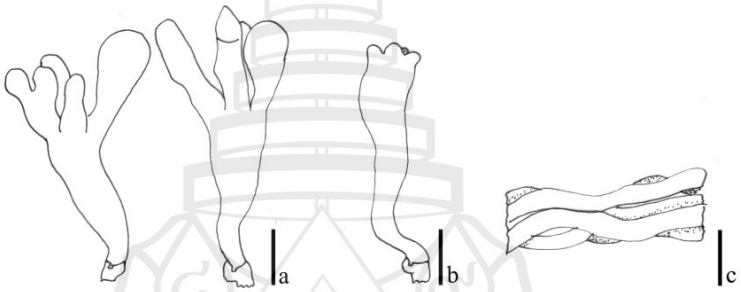
Classification: *Ceratobasidiaceae, Cantharellales, Incertae sedis, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Ceratoporia, a monotypic taxon, was established by Leif Ryvarden & André A. R. de Meijer in 2002 (Ryvarden & de Meijer, 2002). The type species *C. perplexa* was described in a sample collected from a decayed dicotyledonous branch in Paraná, Brazil (Ryvarden & de Meijer, 2002). *Ceratoporia* is found in neotropical regions and exhibits a saprobic habit (Ryvarden & de Meijer, 2002). The taxonomic classification of *Ceratoporia* is under *Ceratobasidiaceae* in Index Fungorum and MycoBank; however, Hyde et al. (2024a) have placed it under *Cantharellales* genera *incertae sedis*.

The basidiomata of *Ceratoporia* are annual, resupinate, with white to cream pore surfaces, thin-walled, and round to angular pores (Ryvarden & de Meijer, 2002). The hyphal system is monomitic and consists of generative hyphae with clamps that are strongly twisted, especially close to the clamps (Ryvarden & de Meijer, 2002). Basidia are clavate, featuring a clamp at the base and large cylindrical sterigmata (Ryvarden & de Meijer, 2002). Basidiospores are cylindrical, smooth, thin-walled, and do not react with Melzer's reagent (Ryvarden & de Meijer, 2002). Dendrohyphidia are present in the hymenium, whereas cystidia, when present, are thin-walled and pointed (Ryvarden & de Meijer, 2002).

The identification of *Ceratoporia* species is based solely on morphological characteristics, as no molecular evidence has been reported (He et al., 2019). *Ceratoporia* is recognised as the first poroid genus within *Ceratobasidiales*, which is typically characterised by resupinate, smooth, and corticoid genera (Ryvarden & de Meijer, 2002). Ceratobasidiales includes species featuring basidia with large tubular sterigmata and strongly twisted hyphae, which distinguishes it from the *Polyporaceae* (Ryvarden & de Meijer, 2002).

Type species: *Ceratoporia perplexa* Ryvarden & de Meijer



Note a Basidia. b Immature basidia. c Hyphae from subiculum. Scale bar: a−c = 10 µm.
Source Redrawn from Ryvarden and de Meijer (2002).

Figure 5.81 *Ceratoporia perplexa* (holotype)

5.3.1.85 *Scotomyces* Jülich

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.82

Classification: *Ceratobasidiaceae, Cantharellales, Incertae sedis, Agaricomycetes, Agaricomycotina, Basidiomycota*, Fungi

Scotomyces, a monotypic genus, was established by Jülich in 1978 based on the description of *Corticium fallax* G. Cunn. (Jülich, 1978). This specimen, described as the type species, was collected on *Beilschmiedia tawa* in New Zealand (Jülich, 1978). *Scotomyces subviolaceus* is saprophytic, found under decaying tree trunks (Gungor et al., 2013). According to Index Fungorum (2025), there are two species of *Scotomyces,* although He et al. (2019) recognised only one. *Scotomyces subviolaceus* is listed as rare in the draft European Red List (Ambrosio, 2014). The taxonomic classification of

Scotomyces is under *Ceratobasidiaceae* in Index Fungorum and MycoBank; however, Hyde et al. (2024a) have placed it under *Hydnaceae* Chevell.

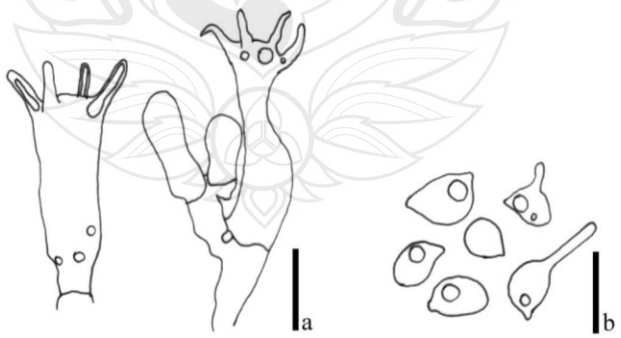
The basidiomata of *Scotomyces* are annual, resupinate, effused, and more or less adnate, exhibiting a powdery, soft-membranaceous texture and an indistinct margin. They lack rhizomorphs or hyphal strands (Jülich, 1978; Gungor et al., 2013; Zíbarová & Holec, 2021). Their colour ranges from greyish olive to dark grey-violet, lighter than fresh specimens. They are non-cracking and non-detachable (Gungor et al., 2013; Zíbarová & Holec, 2021). The hymenial surface is smooth, featuring vertically branched hyphae (Jülich, 1978; Gungor et al., 2013).

Microscopically, the hyphal system is monomitic, consisting of hyaline, thin-walled, cylindrical, clamped, and non-agglutinated hyphae (Jülich, 1978; Gungor et al., 2013). Cystidia are absent (Jülich, 1978). The basidia are hyaline, thin-walled, cylindrical to narrowly clavate, and possess four long sterigmata (Jülich, 1978; Ellis & Ellis, 1990). The basidiospores are smooth, varying from hyaline to light brown to dark brown, thin-walled, more or less ellipsoid, and guttulate, inamyloid, and non-cyanophilic (Jülich, 1978; Gungor et al., 2013).

Synonymy: *Hydrabasidium* Park.-Rhodes

Type species: *Scotomyces subviolaceus* (Peck) Jülich

Basionym: *Hypochnus subviolaceus* Peck



Note a Basidia. b Basidiospores. Scale bar: a–b = 10 μm.

Source Redrawn from Zíbarová and Holec (2021). For original basidiomata, refer to Zíbarová and Holec (2021).

Figure 5.82 *Scotomyces subviolaceus* (HR B010800)

Hydnaceae Chevall., *Fl. gén. env. Paris* (Paris) 1: 270

Hydnaceae is a diverse family established by F.F. Chevallier in 1826 with *Hydnum* L. as the type genus (Chevallier, 1826). The family consists of 18 genera: *Adamflakia* Diederich & Lawrey, *Bergerella* Diederich & Lawrey, *Bryoclavula* H. Masumoto & Y. Degawa, *Burgella* Diederich & Lawrey, *Burgellopsis* Diederich & Lawrey, *Burgoa* Goid., *Cantharellus* Adans. ex Fr., *Clavulina* J. Schrot., *Craterellus* Pers., *Hydnum*, *Membranomyces* Jülich, *Minimedusa* Weresub & P.M. LeClair, *Multiclavula* R.H. Petersen, *Neoburgoa* Diederich, E. Zimm. & Lawrey, *Parmeliicida* Diederich, F. Berger, Etayo & Lawrey, *Rogersiomyces* J.L. Crane & Schokn., *Sistotrema* Fr., and *Sistotremella* Hjortstam (He et al., 2024a). *Hydnaceae* produce complex fleshy basidiomata and are diverse in forms, such as cantharelloid, hydnoid, polyporoid, and clavarioid (Cao et al., 2021a; He et al., 2024). The basidia are stichic, with more than four sterigmata (Cao et al., 2021a). Members of the family are distributed worldwide and are predominantly ectomycorrhizal (He et al., 2024). Notably, species of *Bryoclavula* and *Multiclavula* form lichens in association with algae (Cao et al., 2021a). Some genera of the family produce edible mushrooms, including *Cantharellus*, *Craterellus*, and *Hydnum* (He et al., 2024).

5.3.1.86 *Clavulina* J. Schröt.

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.83

Classification*: Hydnaceae, Cantharellales, Incertae sedis, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Clavulina was introduced by J. Schröter in 1888 (Schröter, 1888). *Clavulina* is a coral mushroom. This fungus is a globally distributed ectomycorrhizal fungus found in both temperate and tropical forests, thriving in deciduous and mixed woodland (Henkel et al., 2011; Njue et al., 2017; Wu et al., 2019b; Huang et al., 2023). Index Fungorum (2025) reports 172 records of *Clavulina*; however, Wijayawardene et al. (2022) recognised only 75 species worldwide. Species of *Clavulina* display high morphological variability and irregular branching (Henkel et al., 2005; Njue et al., 2017). *Clavulina* basidiomata are clavarioid to coralloid, occasionally resupinate, effused, simple or

branched, with colours ranging from white to grey or purple (He et al., 2016; Huang et al., 2023). The context of basidiomata is white or various colours, waxy-fibrous or rather brittle (He et al., 2016). Microscopically, the hyphal system is monomitic with clamp connections and bears incrustations or ornamentation (Corner, 1950; Henkel et al., 2011; Uehling et al., 2012a; He et al., 2016; de Meiras-Ottoni & Gibertoni, 2023). Basidia are cylindrical to sub-clavate, generally bear two cornute sterigmata, and often develop a transversal septum after the release of the basidiospores (Huang et al., 2023). Basidiospores are smooth, hyaline, globose to subglobose with one or several translucent guttules (Henkel et al., 2011; Felipe, 2012; Wu et al., 2019b; Huang et al., 2023; de Meiras-Ottoni & Gibertoni, 2023). Molecular phylogenetic analysis confirms *Clavulina* as monophyletic (Olariaga et al., 2009; Wu et al., 2019b; de Meiras-Ottoni & Gibertoni, 2023). Both morphological and molecular data are used for species-level identification of *Clavulina* (He et al., 2016). Recent studies used morphology and multigene analysis (ITS, LSU, and *rpb2*) to describe new species (Eduardo et al., 2019; Wu et al., 2019b; Huang et al., 2023).

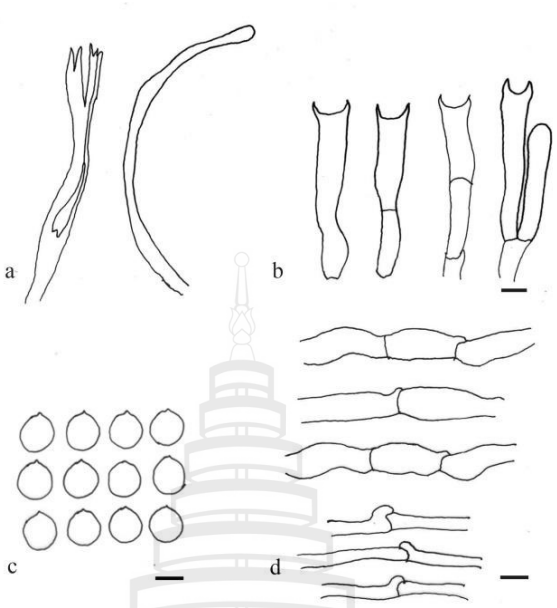
Clavulina cinerea (Bull) J. Schröt is considered medicinally useful and prized as food for chronically ill people due to its rich nutritive value (Agrahar & Subbulakshmi, 2005; Njue et al., 2017; Wu et al., 2019b). Some species have insecticidal properties against *Drosophila melanogaster* (Mier et al., 1996; Njue et al., 2017)

Synonymy: *Stichoramaria* Ulbr.

Type species: *Clavulina cristata* (Holmsk.) J. Schröt.

Basionym: *Ramaria cristata* Holmsk.

Other accepted species: (Species Fungorum – search *Clavulina*)



Note a Basidiomata. b Basidia. c Basidiospores. d Hyphae. Scale bar: b–d = 10 μm.
Source Redrawn from He et al. (2016).

Figure 5.83 *Clavulina livida*

5.3.1.87 *Corallofungus* Kobayasi

Index Fungorum, Facesoffungi, MycoBank, Fig. 5.84

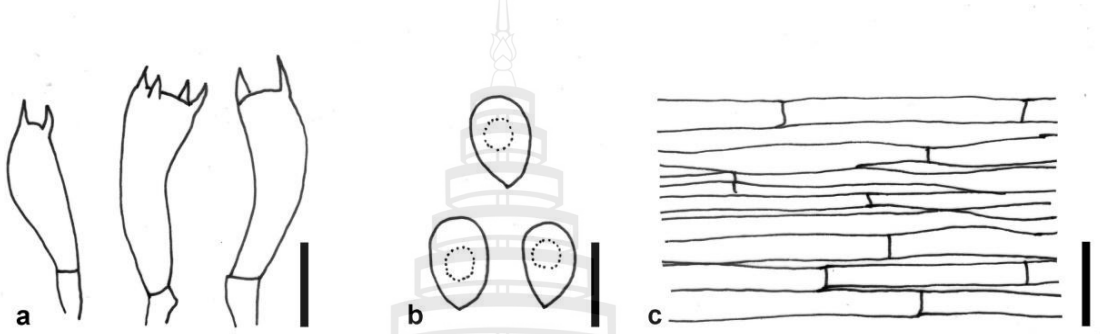
Classification: *Hydnaceae, Cantharellales, Incertae sedis, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Corallofungus is a monotypic genus established by Yosio Kobayasi in 1983, typified by *C. hatakeyamanus* (Kobayashi, 1983). The type specimen was collected from a mixed forest in Japan (Kobayashi, 1983). *Corallofungus* was classified in *Aphyllophorales* Rea., due to the coralloid morphology (Kobayashi, 1983). However, *Corallofungus* was reclassified under *Cantherelleles* (Bondartseva & Zmitrovich, 2023). Bondartseva and Zmitrovich (2023) have raised doubts about the synonymy of this genus with *Clavulina* J. Schröt., indicating a need for modern interpretation.

He et al. (2019) reported that identification of *Corallofungus* is solely based on morphological characteristics due to the lack of molecular evidence. The basidiomata of *Corallofungus* are globose, fleshy, and fragile, initially white and becoming creamy as

they mature (Kobayashi, 1983). The columnar branches are covered by an irregular hymenium (Kobayashi, 1983). Each basidium bears 2 or 4 sterigmata, while the basidiospores are globose and hyaline (Kobayashi, 1983). Hyphae are septate and branched (Kobayashi, 1983).

Type species: *Corallofungus hatakeyamanus* Kobayasi



Note a Basidia. b Basidiospores. c Trama. Scale bar: a−c = 10 μm.

Source Redrawn from Kobayashi (1983). For original basidiomata, refer to Kobayashi (1983).

Figure 5.84 *Corallofungus hatakeyamanus*

5.3.1.88 *Repetobasidiellum* J. Erikss. & Hjortstam

Index Fungorum, Facesoffungi, MycoBank, Fig. 5.85

Classification: *Hydnaceae, Cantharellales, Incertae sedis, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

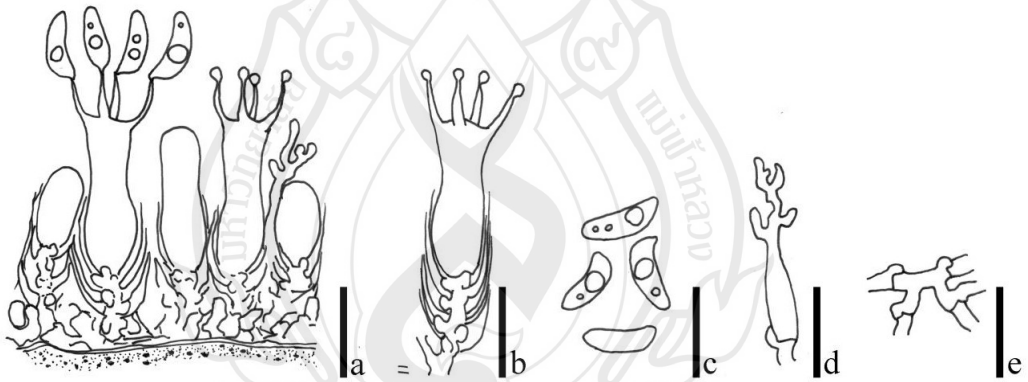
Repetobasidiellum was established by Eriksson and Hjortstam in 1981 to accommodate the monotypic *R. fusisporum*, which was designated as the type species (Eriksson et al., 1981). The type specimen was collected from dead rhachis of a fern in Sweden (Eriksson et al., 1981). *Repetobasidiellum fusisporum* has also been reported in the Netherlands, Europe (Veerkamp, 2013).

The basidiomata of *Repetobasidiellum* are small, thin, orbicular, and closely adnate, appearing smooth and ceraceous when fresh, and crustaceous upon drying, with a pale greyish-brown colouration (Eriksson et al., 1981). The hyphal system is monomitic with highly branched hyphae (Eriksson et al., 1981). The dendrohyphidia are thin-walled,

sparsely branched, and broad at the base (Eriksson et al., 1981). Basidia are initially subglobose and later urn-shaped, occurring in short intervals, with older basidia forming a dense sheath around their bases (Eriksson et al., 1981). The basidiospores are sublunate to subfusiform, smooth, thin-walled, containing one or more oil-drops, inamyloid and non-cyanophilous (Eriksson et al., 1981).

Identification of the *Repetobasidiellum* relies exclusively on morphological characteristics due to the absence of molecular evidence (He et al., 2019). While *Repetobasidiellum* resembles *Repetobasidium* J. Erikss. in basidia arrangement, it differs by having urniform-shaped basidia, whereas those in *Repetobasidium* are ovate (Eriksson et al., 1981). Furthermore, *Repetobasidiellum* has sterile, branched hyphae in the hymenium, known as dendrohyphidia, which are absent in *Repetobasidium*.

Type species: *Repetobasidiellum fusisporum* J. Erikss. & Hjortstam



Note a A section through basidiomata. b Basidia. c Basidiospores. d Dendrohyphidia. e Branching hyphae. Scale bar: a–e = 10 μm.

Source Redrawn from Eriksson et al. (1981).

Figure 5.85 *Repetobasidiellum fusisporum* (Hallingback 24884, holotype)

5.3.1.89 *Rogersiomyces* J.L. Crane & Schokn.

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.86

Classification: *Hydnaceae, Cantharellales, Incertae sedis, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Rogersiomyces was established by J.L. Crane and J.D. Schoknecht to accommodate a single species, *R. okefenokeensis*, as the type species (Crane & Schoknecht, 1978). The specimen was collected from submerged decayed leaves of angiosperms and *Taxodium ascendens* Brongn. in the Okefenokee Swamp National Wildlife Refuge, Georgia, USA (Crane & Schoknecht, 1978). Initially, *Rogersiomyces* was classified under the family *Filobasidiaceae* L.S. Olive due to the presence of an apobasidium with elongated metabasidial sprouts (Crane & Schoknecht, 1978; Psurtseva et al., 2016). Another new species, *Rogersiomyces malaysianus*, which was collected from Vietnam, was previously classified as *Hyphobasidiofera malaysiana* K. Matsush. & Matsush. (Psurtseva et al., 2016). It has since been reclassified under *Hydnaceae* (Psurtseva et al., 2016). The specimen was collected from the bark of a broadleaf tree and was described as a new species and genus (Matsushima & Matsushima, 1996; Psurtseva et al., 2016). Phylogenetic analyses using ITS, LSU, and SSU loci, along with morphological characteristics, were conducted to identify *R. malaysianus* (Psurtseva et al., 2016). Only two species of *Rogersiomyces* are recognised (He et al., 2019).

Basidiomata of *Rogersiomyces* consist of fasciculate, loose, aseptate apobasidia and basidiospores germinating directly into hyphae (Crane & Schoknecht, 1978; Kirschner & Chen, 2003). The presence of apobasidia is thought to be an adaptation to aquatic habitats (Crane & Schoknecht, 1978; Kirschner & Chen, 2003). The basidia are obclavate with prominent, truncate sterigmata (Crane & Schoknecht, 1978). The basidiospores are symmetrically borne, non-apiculate, and germinate directly into hyphae (Crane & Schoknecht, 1978).

Kirschner and Chen (2003) collected *R. kenfenokeensis* from insect tunnels in pine bark, revealing additional morphological characteristics, including septal pores observed using a scanning electron microscope. This perforated parenthesomata provided a basis for positioning *Rogersiomyces* within *Holobasidiomycetes* (Psurtseva et al., 2016). Psurtseva et al. (2016) also presented molecular evidence, culture morphology, lifecycle karyology, and mating experiments for *R. malaysianus*. Molecular studies indicated a close relationship between *Rogersiomyces* and *Sistotrema* sensu lato and

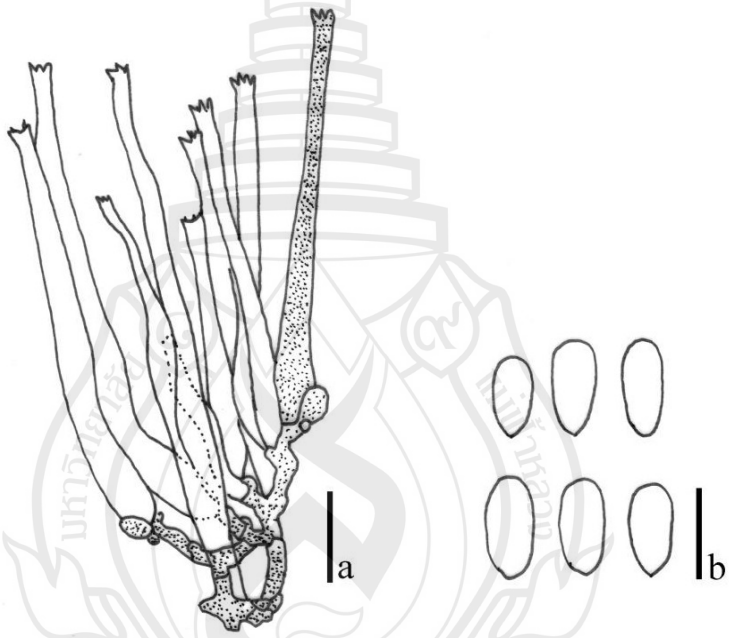
Hydnum sensu stricto (Psurtseva et al., 2016). However, the precise taxonomic position of the genus remains unclear, indicating the need for further research (Psurtseva et al., 2016).

Synonymy: *Hyphobasidiofera* K. Matsush. & Matsush.

Type species: *Rogersiomyces okefenokeensis* J.L. Crane & Schokn.

Other accepted species:

R. malaysianus (K. Matsush. & Matsush.) Zmitr.



Note a Cluster of basidia, presence of cytoplasm indicated with dots, empty in some cases, and collapsed basidia without dots. b Basidiospores. Scale bar: a−b = 10 µm.

Source Redrawn from Kirschner & Chen (2003).

Figure 5.86 *Rogersiomyces okefenokeensis* (R. Kirschner 532)

Gloeophyllales Thorn

Gloeophyllaceae Jülich, *Biblthca Mycol.* 85: 368

Gloeophyllaceae was established by W. Jülich (1982) with *Gloeophyllum* P. Karst. as the type genus (Jülich, 1982). The family consists of ten genera: *Boreostereum*

Parmasto, *Chaetodermella* Rauschert, *Gloeophyllum*, *Griseoporia* Ginns, *Heliocybe* Redhead & Ginns, *Hispidaedalea* Y.C. Dai & S.H. He, *Neolentinus* Redhead & Ginns, *Osmoporus* Singer, *Paratrichaptum* Corner, and *Veluticeps* Cooke (He et al., 2024). Members of *Gloeophyllaceae* are distributed worldwide and are saprophytic, causing brown rot on wood (He et al., 2019). Some species are edible, including *Neolentinus lepideus* (Fr.) Redhead & Ginns (Dai et al., 2010), and some species are medicinal, such as *N. adhaerens* (Alb. & Schwein.) Redhead & Ginns (Dai & Yang, 2008).

5.3.1.90 *Chaetodermella* Rauschert

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.87

Classification: *Gloeophyllaceae, Gloeophyllales, Incertae sedis, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

In 1982, Malencon classified a specimen collected from Sweden under the name *Chaetoderma* luna (Romell ex D.P. Rogers & H.S. Jacks.) Parmasto (Malençon, 1982). However, this epithet was invalid, being a homonym of the algal genus *Chaetoderma* Kützing (Larsson et al., 2020). Thus, Rauschert established the genus *Chaetodermella* in 1988 to accommodate this species (Larsson et al., 2020). Subsequently, a new species, *Chaetodermella incrassata,* was also included in the genus (Larsson et al., 2020).

The basidiomata of *Chaetodermella* species are resupinate, thick, dense, pale grey to ochraceous, and often exhibit a rimose texture (Ginns, 1998). Basidiospores are cylindrical to suballantoid, thin-walled, and smooth (Ginns, 1998; Ram et al., 2021). Basidia are clavate to cylindrical, elongated, basally clamped, and bear four sterigmata (Ginns, 1998; Ram et al., 2021). Cystidia are long, clavate to cylindrical, thick-walled, and clamped at the base (Ginns, 1998; Ram et al., 2021). The hyphal system is monomitic with clamped generative hyphae (Ram et al., 2021). A phylogenetic analysis indicates *Chaetodermella luna* forming a sister clade to *Veluticeps berkeleyana* Cooke (Garcia-Sandoval et al., 2011). *Chaetodermella luna* causes a brown rot on fallen logs of *Larix sibirica*, *Picea obovate,* and *Pinus syvestris* in coniferous forests (Ginns, 1998; Ezhov & Zmitrovich, 2015).

Synonymy: *Chaetoderma* Parmasto

Type species: *Chaetodermella luna* (Romell ex D.P. Rogers & H.S. Jacks.) Rauschert

Basionym: *Peniophora luna* Romell ex D.P. Rogers & H.S. Jacks.

Other accepted species:

Chaetodermella incrassata (Malençon) K.H. Larss. & Ryvarden

Note a Basidiomata showing a hymenial surface on decaying wood. b Basidia. c Basidiospores. d Cystidia. Scale bar: a = 1 cm, b–d = 10 µm.

Source Redrawn from Ram et al. (2021). For original basidiomata, refer to Ram et al. (2021).

Figure 5.87 *Chaetodermella incrassata*

Incertae sedis

5.3.1.91 *Pileodon* P. Roberts & Hjortstam

Index Fungorum, FacesofFungi, MycoBank, Fig. 5.88

Classification: *Incertae sedis, Gloeophyllales, Incertae sedis, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

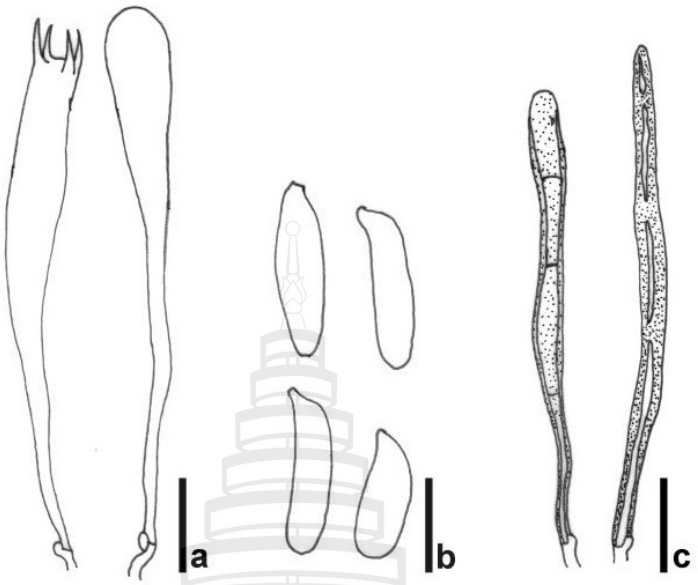
Pileodon was established by Roberts and Hjorstam in 1998 and typified by *Pileodon megasporus* (Hjortstam et al., 1998; Nakasone, 2004). The basidiomata of *Pileodon* are tough, woody, perennial, sessile, and effuse-reflexed, and the hymenial surface is finely odontioid and uniformly brown (Hjortstam et al., 1998). Basidiospores are large, initially hyaline and later brown, thin to slightly thick-walled, inamyloid, indextrinoid, and acyanophilous (Hjortstam et al., 1998). Basidia are large, stalked, and each bearing four sterigmata (Hjortstam et al., 1998). Cystidia are absent (Hjortstam et al., 1998). The hyphal system is dimitic, with hyaline, clamped generative hyphae, and thick-walled, often nodulose skeletal hyphae (Hjortstam et al., 1998). *Pileodon* is rare, with only two species, *P. megasporus* (Hjortstam et al., 1998) and *Pileodon philippinensis* (Nakasone, 2004). There is no molecular evidence to support these classifications (He et al., 2019).

Pileodon shares some similarities with *Veluticeps* and *Campylomyces* (Nakasone, 2004). However, the basidiomata of *Pileodon* and *Veluticeps* are large, thick, pileate to effuse-reflexed, tough, and woody, in contrast to *Campylomyces*, whose basidiomata are small, thin, cupulate with involute, free margins, and have a ceraceous texture (Nakasone, 2004). Additionally, the tissues of *Pileodon* and *Veluticeps* exhibit a xanthochroic reaction, which is only temporary in *Campylomyces* (Nakasone, 2004). Moreover, *Pieodon* blackens in KOH, unlike *Campylomyces* (Nakasone, 2004).

Type species: *Pileodon megasporus* P. Roberts & Hjortstam

Other accepted species:

Pileodon philippinensis (Bres.) Nakasone



Note a Mature and immature basidia. b Basidiospores. c Skeletal cystidia from hyphal pegs. Scale bar: a–c = 10 µm.

Source Redrawn from Nakasone (2004). For original basidiomata, refer to Nakasone (2004).

Figure 5.88 *Pileodon philippinensis* (K(M) 102896, lectotype)

Gomphales Jülich

Gomphaceae Donk, *Persoonia* 1(4): 406

Gomphaceae was established by M.A. Donk in 1961 with *Gomphus* Pers. as the type genus (Donk, 1961). The family consists of 13 genera: *Araeocoryne* Corner, *Delentaria* Corner, *Destuntzia* Fogel & Trappe, *Gautieria* Vittad., *Gloeocantharellus* Singer, *Gomphus*, *Phaeoclavulina* Brinkmann, *Protogautieria* A.H. Sm., *Pseudogomphus* R. Heim, *Ramaria* Fr. ex Bonord., *Ramaricium* J. Erikss., *Terenodon* Maas Geest., and *Turbinellus* Earle (He et al., 2024). Members of the family are distributed worldwide and are either saprophytic (wood-decaying) or ectomycorrhizal (He et al., 2019). Some species in this family are edible and medicinal, including *Gomphus clavatus* (Pers.) Gray,

Ramaria flava (Schaeff.) Quél., and *Turbinellus floccosus* (Dai et al., 2010; Gursoy et al., 2010; Makropoulou et al., 2012; Lamus et al., 2015; He et al., 2019).

5.3.1.92 *Gomphus* Pers.

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.89

Classification: *Gomphaceae, Gomphales, Phallomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Gomphus is a widespread terrestrial gomphoid genus (Segedin, 1984; Giachini, 2004; Liu et al., 2022a). This genus was established by Persoon in 1797 (Liu et al., 2022a). *Gomphus* sensu lato is a polyphyletic group with multiple genera: *Gloeocantharellus* Singer, *Gomphus* sensu stricto, *Phaeoclavulina* Brinkmann, and *Turbinellus* Earle (Giachini & Castellano, 2011; Liu et al., 2022a; Fan et al., 2023). Fan et al. (2023) reported that *Gomphus* sensu lato and *Ramaria* sensu lato are paraphyletic within Gomphaceae. The pileus of *Gomphus* is fan-shaped to slightly funnel-shaped and bright violet, pale olivaceous or brown; hymenium is 'merulioid' wrinkled to almost poroid, and violet venaceous brown to milky coffee colour; basidiospores have verrucose non-anastomosed ornamentation, present clamped hyphae (Giachini & Castellano, 2011; Giachini et al., 2012).

Previously, new species were described based on morphology only (Barbara, 1984). Liu et al. (2022a) used both morphological and phylogenetic studies (ITS and LSU) to identify a new species, *Gomphus matijun.* Fan et al. (2023) used the combinations of three molecular markers, ITS, LSU, and *tef1-α,* for phylogenetic analysis of *Gomphus* specimens and established a new species, *Gomphus violoaceus*. Index Fungorum (2025) lists 69 records of *Gomphus*, but He et al. (2019) recognised only 7 species: *G. brunneus* (Heinem.) Corner, *G. clavatus* (Pers.) Gray, *G. crassipes* (Kuntze) Maire, *G. ludovicianus* R.H. Petersen, Justice & D.P. Lewis, *G. orientalis* R.H. Petersen & M. Zang, *G. violoaceus* Xue-Ping Fan & Zhu L. Yang, and *G. matijun* J.W. Liu & F.Q. Yu (Zang, 1996; Liu et al., 2022a; Fan et al., 2023).

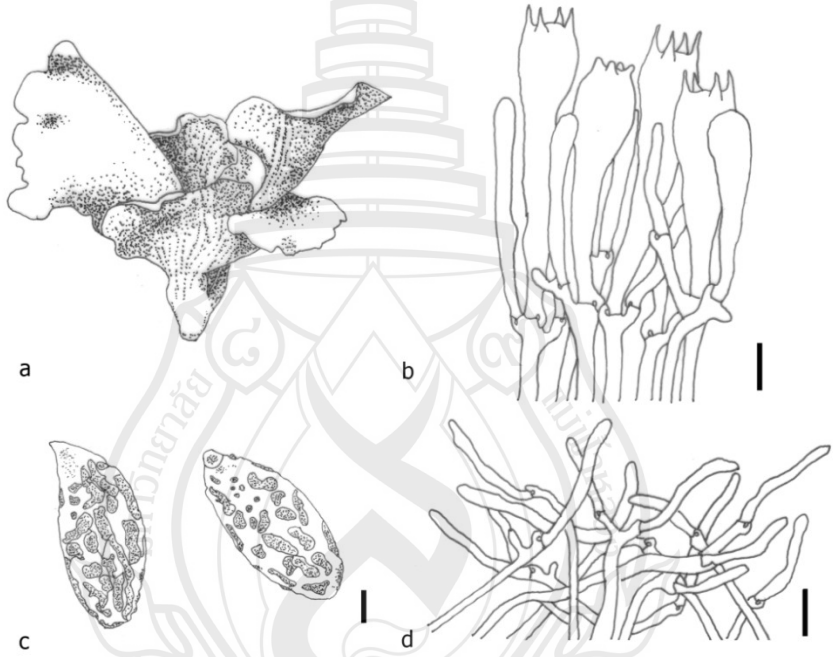
Gomphus clavatus is considered a medicinal mushroom due to its antioxidant and chemopreventive properties and is a widely consumed and tasty edible mushroom (Pilz et al., 2003; Makropoulou et al., 2012).

Synonymy: *Gomphora* Fr., *Neurophyllum* Pat.

Type species: *Gomphus clavatus* (Pers.) Gray

Basionym: *Merulius clavatus* Pers.

Other accepted species: (Species Fungorum – search *Gomphus*)



Note a Basidiomata. b Hymenium and sub-hymenium. c Basidiospores. d Longitudinal section of pileipellis. Scale bar: b–d = 10 µm, c = 2 µm.

Source Redrawn from Fan et al. (2023). For original basidiomata, refer to Fan et al. (2023).

Figure 5.89 *Gomphus orientalis*

5.3.1.93 *Turbinellus* Earle

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.90

Classification: *Gomphaceae, Gomphales, Phallomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota*, Fungi

Turbinellus was established by F.S. Earle in 1909, with *T. floccosus* as the type species (Earle, 1909). The latter was originally described as *Cantharellus floccosus* from specimens associated with *Fagus* in Pennsylvania, USA (Schweinitz, 1832). The genus has undergone several revisions. It was once transferred to *Gomphus* Pers., then to *Cantharellus* Adans. ex Fr., and later back to *Gomphus,* and exhibits challenges in species delineation due to limited morphological differentiation (Giachini & Castellano, 2011). Index Fungorum (2025) lists 17 records of *Turbinellus*, while Species Fungorum (2025) recognises only 16 species worldwide. Some species, including *T. floccosus*, form ectomycorrhizal associations with *Abies*, *Pinus*, *Pseudotsuga*, *Tsuga*, and *Quercus* (González-Ávila et al., 2013; Lamus et al., 2015). Members of *Turbinellus* are distributed worldwide, except Antarctica and Australia (Giachini et al., 2012; Lamus et al., 2015).

Members of *Turbinellus* are characterised by persistent, stalked, funnel-shaped, cantharelloid-like basidiomata (Lamus et al., 2015). The pileus is orange-yellow to orange scarlet, blood red, pale orange, orange, or brown, often changing on drying, and the scale colour is darker than the pileus (Giachini & Castellano, 2011). The hymenium is strongly decurrent, and hymenial folds are deeply wrinkled with longitudinal orientation (Giachini et al., 2012). The stipe is tall, robust, fleshy, and well-rooted in the substrate (Giachini et al., 2012). Basidiospores are verrucose, ellipsoid to obovoid (Giachini et al., 2012). The hyphae are clampless (Giachini et al., 2012).

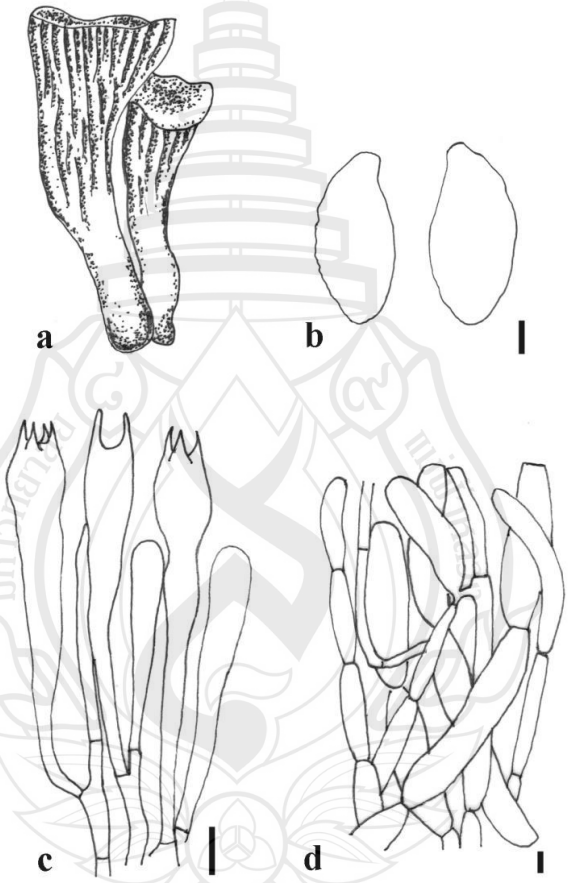
The classification of *Turbinellus* within *Gomphaceae, Gomphales, Phallomycetidae, Agaricomycetes, Agaricomycotina,* and *Basidiomycota* is in agreement with Index Fungorum, MycoBank, GenBank, UNITE, and the Outline of fungi and fungus-like organisms (Hyde et al., 2024a). Recently, Fan et al. (2023) described nine new species of *Turbinellus* using multi-gene phylogenetic analysis (ITS, LSU, and *tef1-α*), along with morphological characteristics. Some species, such as *T. floccosus*, are valued as edible (Lamus et al., 2015). In controlled cultivation, Lamus et al. (2015) have

successfully inoculated a pure culture of *T. floccosus* with *Abies religiosa* and confirmed ectomycorrhizal associations.

Type species: *Turbinellus floccosus* (Schwein.) Earle ex Giachini & Castellano

Basionym: *Cantharellus floccosus* Schwein.

Other accepted species: (Species Fungorum – search *Turbinellus*)



Note a Basidiomata. b Basidiospores. c Basidia and basidioles. d Pileipellis Scale bar: b = 2 µm, c–d = 10 µm.

Source Redrawn from Fan et al. (2023). For original basidiomata, refer to Fan et al. (2023).

Figure 5.90 *Turbinellus flavidus* (HKAS 99946, holotype)

Phallales E. Fisch.

Phallaceae Corda, *Icon. fung.* (Prague) 5: 29

Phallaceae was established by A.C.J. Corda (1842) and typified with *Phallus* Junius ex L. (Corda, 1842). The family consists of 11 genera: *Aporophallus* Möller, *Aserocybe* Lév., *Echinophallus* Henn., *Endophallus* M. Zang & R.H. Petersen, *Itajahya* Möller, *Mutinus* Fr., *Phallus*, *Staheliomyces* E. Fisch., *Staurophallus* Mont., *Stephanophallus* MacOwan, and *Xylophallus* (Schltdl.) E. Fisch. (He et al., 2024). Species of *Phallaceae* are characterised by pseudostipitate basidiomata, with an unbranched apical part (Corda, 1842; Melanda et al., 2021). Members of this family are distributed worldwide and are terrestrial and saprotrophic (He et al., 2019). Some species are considered edible, including *Phallus fragrans* M. Zang (Dai et al., 2010).

5.3.1.94 *Aseroe* Labill.

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.91

Classification: *Phallaceae, Phallales, Phallomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Aseroe was introduced by Labillardiere (1806), with *A. rubra* Labill. as the type species. The type species was found solitary on the ground or on rotting wood (Cunningham, 1931). The taxonomic classification of *Aseroe* is under *Phallaceae* in Index Fungorum and MycoBank; however, GenBank and Hyde et al. (2024a) have placed it under *Clathraceae* Chevall.

The genus is distinguished by basidiomata composed of a receptacle and a well-differentiated, sterile, hollow, cylindrical stipe, which arises from a white volva (Cunningham, 1931; Dring, 1980; Baseia & Calonge, 2005). This phalloid genus is pantropical, including Africa (Kasuya, 2007). Cunningham (1931) reported the presence of a diaphragm at the apex of the stem with a small central perforation. The egg shape is obovate, with a whitish to grey-brown colour, and numerous and paired awl-like branching arms can be observed from this stage (Cunningham, 1931; Dring, 1980). The receptacle margin branches out, and the disc, branch, or both bear mucilaginous, olivaceous, and fetid gleba on its upper surface (Cunningham, 1931; Dring, 1980; Baseia

& Calonge, 2005; Kasuya, 2007). The arms are numerous, long, acute, generally paired, with numerous chambers, and expand horizontally at maturity (Dring, 1980). The origin of this species may be from the plants having arms with paired tubes (Dring, 1980). Basidiospores are smooth, continuous, and elliptical (Cunningham, 1931). Although Index Fungorum (2025) has listed 44 records of *Aseroe*, Species Fungorum (2025) recognises only seven species worldwide.

Type species: *Aseroe rubra* Labill.

Other accepted species:

A. calathiscus Schltdl.

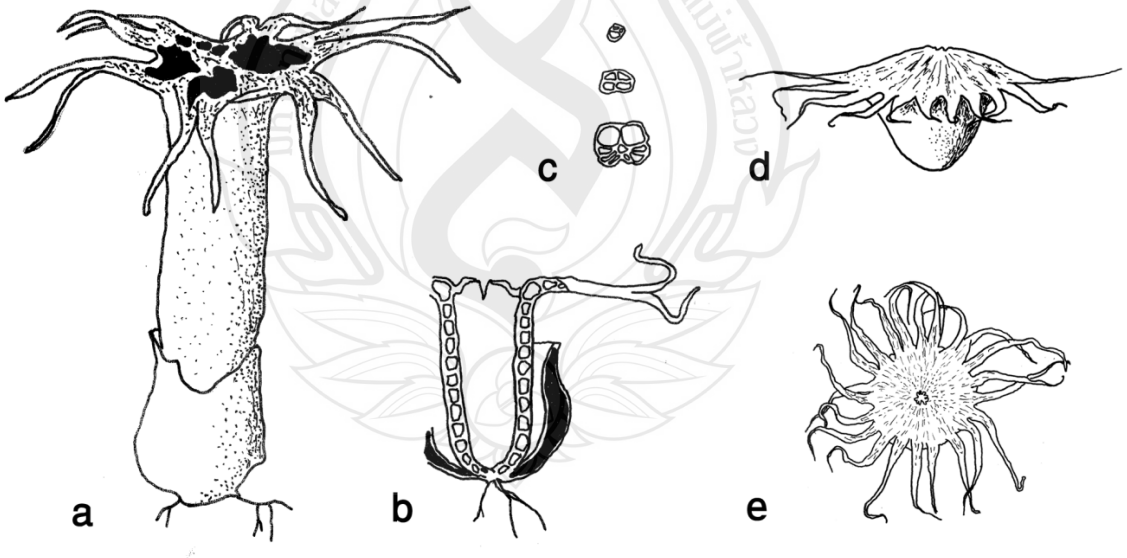
A. coccinea Imazeki & Yoshimi ex Kasuya

A. corrugata Colenso

A. genovefae Decary

A. multiradiata Zoll.

A. pallida Lloyd



Note a Carpophore. b Section of carpophore. c Section of an arm from base to apex. d, e. *Aseroe rubra* var. *junghuhnii*.

Source Redrawn from Dring (1980).

Figure 5.91 *Aseroe rubra*

5.3.1.95 *Blumenavia* Moller

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.92

Classification: *Phallaceae, Phallales, Phallomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota*, Fungi

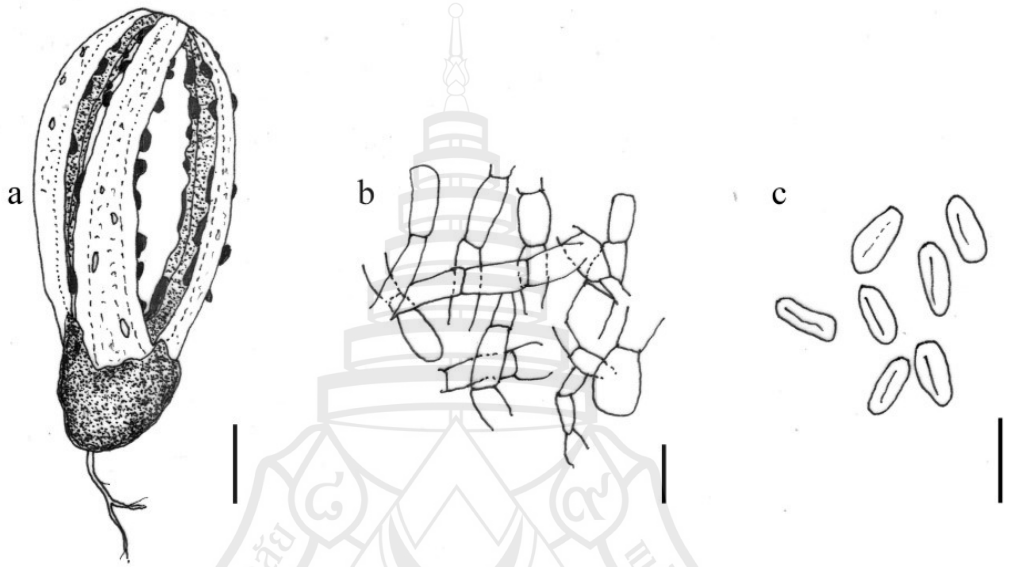
Blumenavia Moller is a clathroid genus established by Alfred Moller (1895) to accommodate *Blumenavia rhacodes* Moller (Trierveiler-Pereira et al., 2014). *Blumenavia* is also recognised by cage fungi or lattice stinkhorns (Miller & Miller, 1988; Pegler & Gomez, 1994; Recla et al., 2023). The etymological name of this genus was derived from Blumenau City, Santa Catarina (Brazil), where the German naturalist Alfred Moller lived (Trierveiler-Pereira et al., 2014). The taxonomic classification of *Blumenavia* is under *Phallaceae* in Index Fungorum, MycoBank, and GenBank; however, Hyde et al. (2024a) have placed it under *Clathraceae* Chevall.

Blumenavia is distinguished from other clathroids as the gleba or spore-bearing mass is spread on lateral projections and lacerations from the column occupying the external borders of the whole length of the arms, which are also called ‘wings’ or ‘teeth’ (Trierveiler-Pereira et al., 2014; Melanda et al., 2020). *Blumenavia* species typically bear a small number of columns with no transverse arms (Vargas-Rodriguez & Vazquez-Garcia, 2005). Additionally, *Blumenavia* is distinct from the genus *Clathrus* Micheli ex L. as the columns are free at the base and united at their apices with membranous glebifers attached to the two inner angles of the column (Dring, 1980; Sáenz, 1980; Vargas-Rodriguez & Vazquez-Garcia, 2005; Rodrigues & Baseia, 2013). Index Fungorum (2025) reports seven records of *Blumenavia*. A recent taxonomic revision based on morphological and phylogenetic evidence (ITS, LSU, *atp6*, *rpb*2, and *tef-1α*) also reported seven species (Melanda et al., 2020; Recla et al., 2023). The morphological traits used to delimit species are basidiomata staining, number and anatomy of arms, and basidiospore dimensions (Vargas-Rodriguez & Vazuez-Garcia, 2005; Melanda et al., 2020). Lloyd (1909) placed *Blumenavia* as a synonym of *Laternea* Turpin, a position followed by Rick (1961); however, most authors continued treating

Blumenavia as an independent genus (Dennis, 1953; Dring, 1980; López et al., 1981; Miller & Miller, 1988; De Toledo, 1995; Trierveiler-Pereira et al., 2014).

Type species: *Blumenavia rhacodes* Moller

Other accepted species: (Species Fungorum – search *Blumenavia*)



Note a Basidiomata. b Hyphae of the apical exoperidium. c Basidiospores. Scale bar: a = 2 cm, b = 5 μm, c = 10 μm.

Source Redrawn: a from Trierveiler-Pereira et al. (2014), b–c from Velloso et al. (2021).

Figure 5.92 *Blumenavia rhacodes*

5.3.1.96 *Clathrus* P. Micheli ex L.

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.93

Classification: *Phallaceae, Phallales, Phallomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

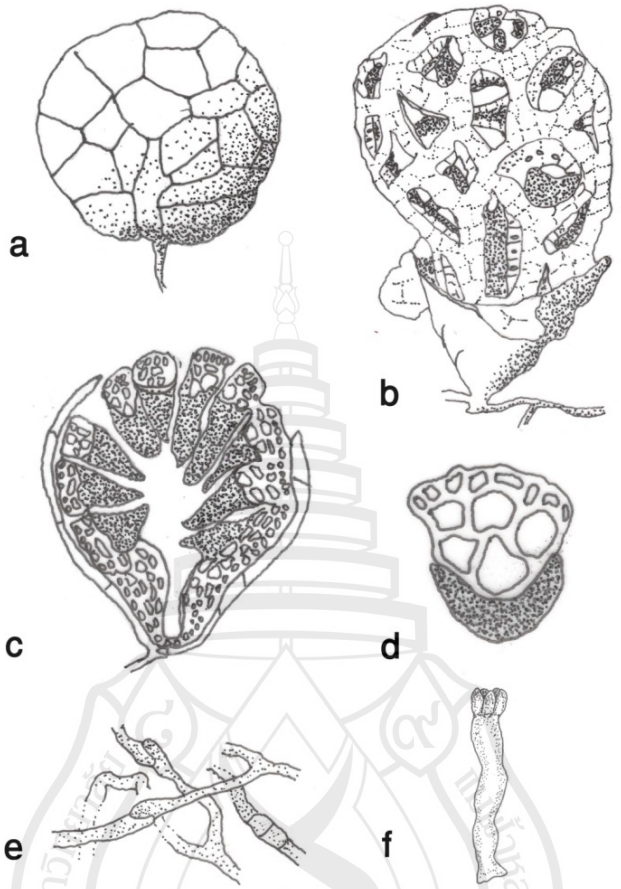
Clathrus has been reported from different continents as widespread, especially from North Africa to Northern Europe (Dring, 1980; Ivancevic & Tatic, 2004; Lécuru et al., 2013). Miller and Miller (1988) and Fazolino et al. (2010) described the characteristic features of *Clathrus* as a latticed, clathrate receptacle with hollow, tubular arms that arise from basal tissue within the volva. Dring (1980) described *Clathrus* with egg sub-globose

to obpyriform, cream to greyish fawn, smooth surface with reticulations; dehiscence irregular from the apex, leaving the lower meshes of the receptacle encased in a volva; sectioning shows thin peridium, gelatinous layer, traversed by conspicuous, white, peridial sutures. Receptacle obovoid, with an almost regular network of meshes, more or less isodiametric, with distinct outside and inside colour. Arms are salmon pink outside, scarlet within, tapering to an extreme base, triangular in section, with frequent large openings to the exterior; context of the arms spongy with one wide inner tube, tubes irregular in diameter; gleba attached to the inner face of arms, olive green before dehiscence and changing to olive brown, odour strong like decaying meat. Spores bacilloid and almost hyaline. Flies and other insects are attracted because of the unpleasant odour, which helps in dispersal of basidiospores (Maldonada-Ramírez & Torrres-Pratts, 2005; Fazolino et al., 2010). *Clathrus* has thinning of arms towards the base of the receptacle, differing from other laternoid series, which have free arms (Dring, 1980). The type sample was described by Micheli (1729) from Italy. The taxonomic classification of *Clathrus* is under *Phallaceae* in Index Fungorum; however, MycoBank, GenBank, and Hyde et al. (2024a) have placed it under *Clathraceae* Chevall.

Synonymy: *Anthurus* Kalchbr. & MacOwan, *Clathrella* E. Fisch., *Colonnaria* Raf., *Dycticia* Raf., *Linderia* G. Cunn., *Linderiella* G. Cunn.

Type species: *Clathrus ruber* Micheli ex Persoon

Other accepted species: (Species Fungorum – search *Clathrus*)



Note a Egg stage of basidiomata. b Mature receptacle. c Section of egg. d Diagrammatic sections of the arm with the gleba. e Hyphae in the gelatinised matrix, with occasional clamp-connection. f Basidia.

Source Redrawn: a–d = Dring (1980), e–f = Roberts (1988).

Figure 5.93 *Clathrus ruber*

5.3.1.97 *Colus* Cavalier & Sechier

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.94

Classification: *Phallaceae, Phallales, Phallomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota*, Fungi

Colus is a clathroid fungus that occurs singly or in small groups, and is commonly known as cage fungi (Akata & Gurkanli, 2018). The genus was introduced by

Cavalier and Sechier in 1835 (Cavalier & Sechier, 1835). *Colus* is saprobic and has widespread distribution (He et al., 2019).

Colus is characterised by basidiomata with a branched ovoid to pyriform receptacle, bearing a rudimentary pseudo-stipe with a whitish to greyish volva (Calonge, 1998; Akata & Gurkanli, 2018). The egg remnants are a whitish volva that remains at the base. The internal surface of the arched reticulum is covered with olive to olive-brown mucilaginous gleba (Calonge, 1998; Akata & Gurkanli, 2018). Basidiospores are ellipsoid, hyaline, and smooth (Calonge, 1998; Akata & Gurkanli, 2018). The taxonomic classification of *Clathrus* is under *Phallaceae* in Index Fungorum, MycoBank, and GenBank; however, Hyde et al. (2024a) have placed it under *Clathraceae* Chevall.

Species are delineated from similar genera based on morphological characteristics and phylogenetic analysis. Phylogenetic study of an old phalloid sample, based on LSU and SSU, showed it as *Colus hirudinosus* (Melanda et al., 2021). Index Fungorum (2025) lists 16 records of *Colus*, of which 9 record epithets have been transferred to *Pseudocolus* and *Lysurus*. Akata and Gurkanli (2018) recognised only 7 species: *Colus giganteus* Dörfelt & Bumžaa, *C. hirudinosus* Cavalier & Séchier, *C. muelleri* E. Fisch., *C. pusillus* (Berk.) Reichert, *C. stahelii* (E. Fisch.) Reichert, *C. subpusillus* Dring, and *C. treubii* (C. Bernard) Reichert.

Type species: *Colus hirudinosus* Cavalier & Sechier

Other accepted species:

C. giganteus Dörfelt & Bumžaa

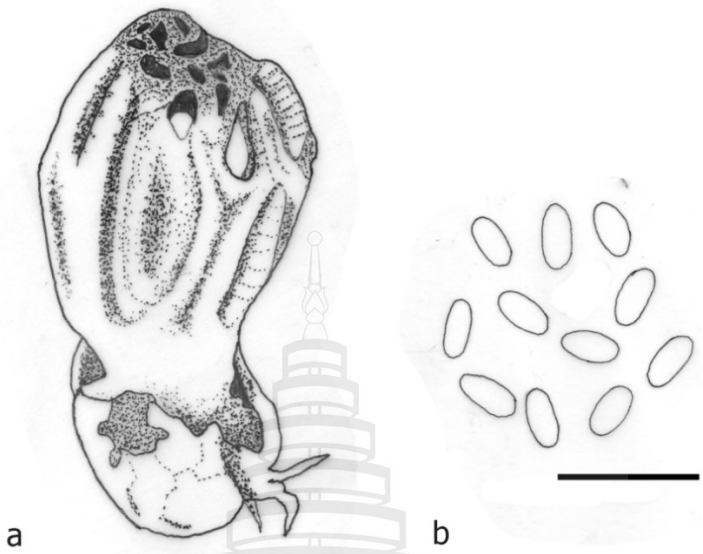
C. muelleri E. Fisch.

C. pusillus (Berk.) Reichert

C. stahelii (E. Fisch.) Reichert

C. subpusillus Dring

C. treubii (C. Bernard) Reichert



Note a Mature basidiomata. b Basidiospores. Scale bar: b = 10 µm.

Source Redrawn from Akata and Gurkanli (2018).

Figure 5.94 *Colus hirudinosus*

5.3.1.98 *Echinophallus* Henn.

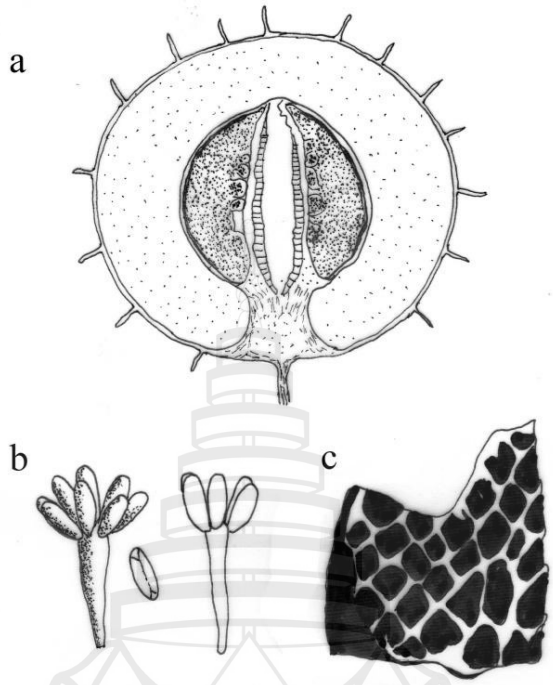
Index Fungorum, Facesoffungi, MycoBank, Fig. 5.95

Classification: *Phallaceae, Phallales, Phallomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Echinophallus is a genus belonging to the family *Phallaceae. Echinophallus* was established by Hennings (1898) to accommodate the terrestrial fungus, *Echinophallus lauterbachii* (He et al., 2019). *Echinophallus* is a phalloid and monotypic genus that is distinctive in bearing spinulose volva and unextended stipes (Kobayasi, 1937). *Echinophallus* is a primitive type because the basidiomata remain an egg, even at maturity (Kobayasi, 1937). Index Fungorum (2025) reports three records of *Echinophallus*, whereas Wijayawardene et al. (2022) accepted only one species. No molecular evidence is available for the genus in GenBank.

Type species: *Echinophallus lauterbachii* (Henn.) Henn.

Basionym: *Ithyphallus lauterbachii* Henn.



Note a Section of basidiomata, ×5. b Basidia and basidiospores, ×3000. c Part of the pileus showing a reticulated surface, ×11.

Source Redrawn from Kobayasi (1937).

Figure 5.95 *Echinophallus lauterbachii*

5.3.1.99 *Laternea* Turpin

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.96

Classification: *Phallaceae, Phallales, Phallomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Laternea was established by Turpin in 1822, with type species *L. triscapa* Turpin (Sáenz, 1976). The characteristic feature of the genus is a ‘lantern’ suspended from the apex of the receptacle (Linder, 1928; Dennis, 1953a). Stipes are united above, subtend from the junction of the apices to form an angular body, and the outline of the receptacle is subovate (Linder, 1928). Columns are slender, smooth, and usually three (Linder, 1928). *L. triscapa* has a deep orange lantern with three supporting arms (Dennis,

1953a). The asexual morph of *Laternea* is unknown (He et al., 2019). An additional species *L. pusilla* is also known (Pinzón Osorio et al., 2017; He et al., 2019). The type species was collected from a sugarcane field near a forest, and *L. pusilla* was found on the ground (Dennis, 1953a). The taxonomic classification of *Laternea* is under *Phallaceae* in Index Fungorum, MycoBank, and GenBank; however, Hyde et al. (2024a) have placed it under *Clathraceae* Chevall.

Type species: *Laternea triscapa* Turpin

Other accepted species:

L. brasiliensis (E. Fisch.) Long & Stouffer

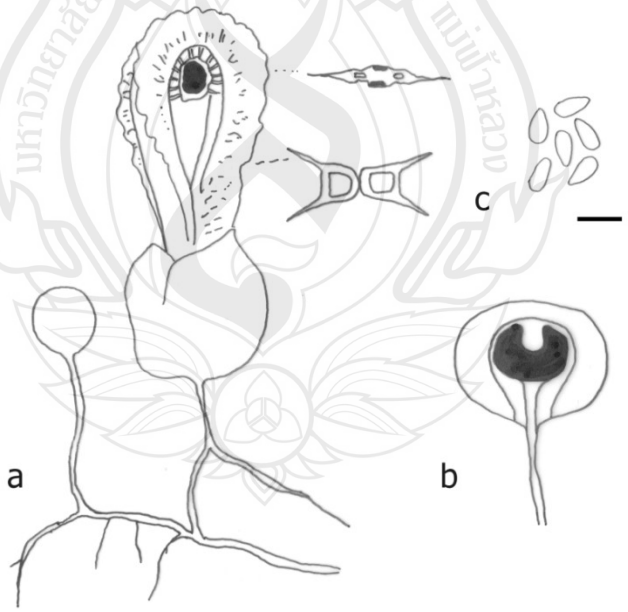
L. columnata Nees

L. cristata Lloyd

L. dringii A. López, D. Martínez & J. García

L. pusilla Berk. & M.A. Curtis

L. spegazzinii Lloyd



Note a Fructification with transverse sections of the receptacle. b Vertical section of young fruiting body. c Basidiospores. Scale bar: c = 4 µm.

Source Redrawn from: a–b = Dennis (1953a), c = Pinzon Osorio et al. (2017).

Figure 5.96 *Laternea pusilla*

5.3.1.100 *Ligiella* J. A. Sáenz

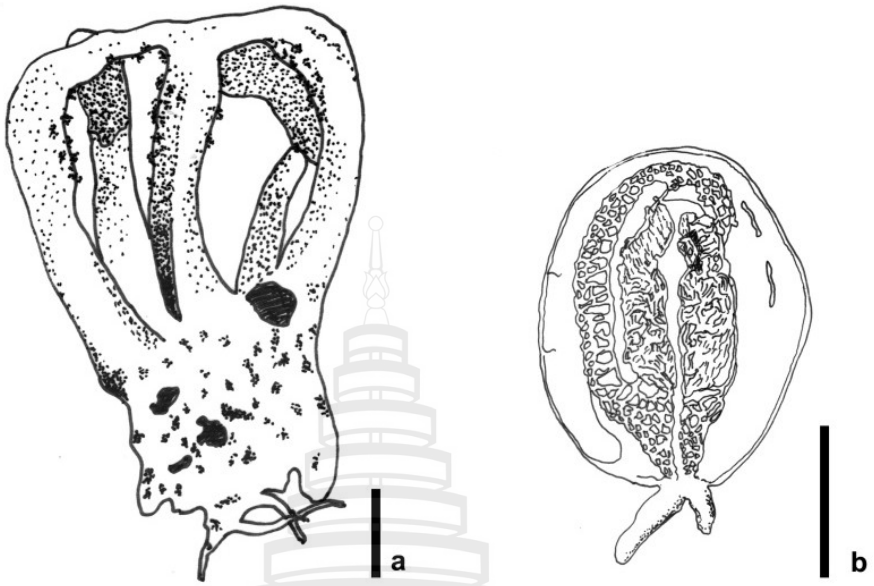
Index Fungorum, Facesoffungi, MycoBank, Fig. 5.97

Classification: *Phallaceae, Phallales, Phallomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Ligiella was established by J.A. Saenz, consisting of a single species, *Ligiella rodrigueziana* (Sáenz, 1980). It was first described from humus and rotten wood in Costa Rica (Sáenz, 1980). The unopened angiocarpic fruiting body "myco-egg" is spheroid to abovoid (Sáenz, 1980). The receptacle originates from a single primordial tissue and branches into arms above the rhizomorph (Sáenz, 1980). The receptacle consists of 4 or 5 smooth white arms that irregularly converge at the top and are free at the base (Sáenz, 1980). Each arm bears distinct glebiferous tissue on its inner surface (Sáenz, 1980). The glebiferous tissues are segmented into rough elliptical plates, and each arm is connected at the edges at the bottom (Sáenz, 1980). At maturity, the arms curve inward at the base (Sáenz, 1980). The gleba consists of dark-olive discrete bodies, and the context is permeated with prosenchymatic structures that are aromatic and non-phalloid (Sáenz, 1980). The fruiting bodies are interconnected by stolon-like rhizomorphs (Sáenz, 1980).

A comparative anatomical study of the form, structure, and location of the specialized glebiferous tissue, the glebiferous chamber, and gleba in *Laternea* Turpin and *Ligiella* supported the validity of *Ligiella* (Sáenz et al., 1983). Gleba is single and continuous with the internal layer of peridium in *Laternea*, whereas gleba in *Ligiella* is compound and not continuous (Sáenz, 1980). *Ligiella* and *Phallus fragrans* have a medullary zone (Sáenz, 1980). *Ligiella* has 4–5 lateral glebiferous tissue units, whereas *Laternea* has only one glebiferous tissue at the summit (Sáenz, 1980). No molecular data are available (He et al., 2019). The taxonomic classification of *Ligiella* is under *Phallaceae* in Index Fungorum, and MycoBank; however, Hyde et al. (2024a) have placed it under *Clathraceae* Chevall.

Type species: *Ligiella rodrigueziana* J. A. Sáenz



Note a Basidiomata. b Longitudinal section of an unopened egg. Scale bars: a–b = 1 cm.
Source Redrawn from Sáenz (1980).

Figure 5.97 *Ligiella rodrigueziana*

5.3.1.101 *Lysurus* Fr.

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.98

Classification: *Phallaceae, Phallales, Phallomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Lysurus is widespread, particularly in tropical regions (Kirk et al., 2008; Gogoi & Parkash, 2015; He et al., 2019). It is saprobe (Schaffer, 1975; Lodge & Cantrell, 1995; Abrar et al., 2013). ITS sequences are used for phylogenetic analysis of species (Hernández Caffot et al., 2022). The genus includes species with hypogeous to sub-hypogeous immature stages (Hernández Caffot et al., 2022). The characteristic feature of the genus is its morphology with short columnar arms attached at the apex of a cylindrical receptacle (Fischer, 1886b; Teng, 1996; Abrar et al., 2013). The receptacle emerges from a ruptured peridium (Zang & Peterson, 1989; Abrar et al., 2013). Later, the lateral surface of mature receptacle arms bears the gleba that produces a fetid odour

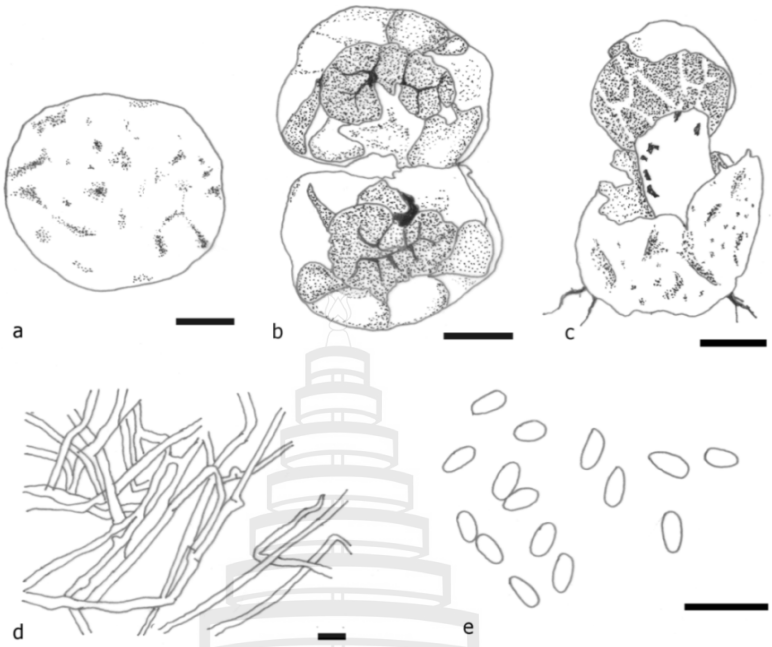
(Miller et al., 1991; Beltrán-Tejera et al., 1998; Cortez et al., 2011; Burk et al., 1982; Abrar et al., 2013). Insects and other invertebrates are attracted to this slimy gleba, which helps spore dispersal (Oliveira & Morato, 2000; Johnson & Jürgens, 2010; Teichert et al., 2012; Pudil et al., 2014; Hernández Caffot et al., 2022). Abrar et al. (2013) studied developmental characters of *Lysurus*, along with morphology and taxonomic characteristics. The common name of *Lysurus cruciatus* is lizard's claw stinkhorn in the USA (Arora, 1986; Abrar et al., 2013). Index Fungorum (2025) has 44 records of *Lysurus*; however, He et al. (2019) have recognised only 30 species worldwide. The taxonomic classification of *Lysurus* is under *Phallaceae* in Index Fungorum, MycoBank, and GenBank; however, Hyde et al. (2024a) have placed it under *Lysuraceae* Corda.

Synonymy: *Aserophallus* Lepr. & Mont., *Desmaturus* (Schltdl.) Kalchbr., *Dictyobole* G.F. Atk. & Long, *Foetidaria* A. St.-Hil., *Kalchbrennera* Berk., *Kupsura* Lloyd, *Lloydia* C.H. Chow, *Lysurus* sect. *Desmaturus* Schltdl., *Lysurus* sect. *Schizmaturus* Corda, *Mycopharus* Petch, *Pharus* Petch, *Schizmaturus* (Corda) Kalchbr., *Simblum* Klotzsch ex Hook., *Sinolloydia* C.H. Chow

Type species: *Lysurus mokusin* (L. f.) Fr

Basionym: *Phallus mokusin* L. f.

Other accepted species: (Species Fungorum – search *Lysurus*)



Note a External view of the immature stage ‘egg-like structure’. b Longitudinal section of the immature stage. c Emerging basidiome. d Clamped hyphae from the mucilage layer. e Basidiospores. Scale bar: a–c = 1 cm, d–e = 1 µm.

Source Redrawn from Hernández Caffot et al. (2022).

Figure 5.98 *Lysurus fossatii*

5.3.1.102 *Phallus* Junius ex L.

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.99

Classification: *Phallaceae, Phallales, Phallomycetidae, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Phallus Junius ex L. was established by Junius in 1753, with *P. impudicus* L. as the type species. *Phallus* was regarded as a gasteroid genus commonly known as the stinkhorn fungus. *Phallus* species are phylogenetically analysed and described using combined ITS, LSU, and *atp6* to compare at the inter- and intra-species level (Cabral et al., 2019; Sommai et al., 2021). *Phallus* is a distinctive genus in the family *Phallaceae* that produces a net-like veil, varying in colours, such as white, orange, pink, and grey

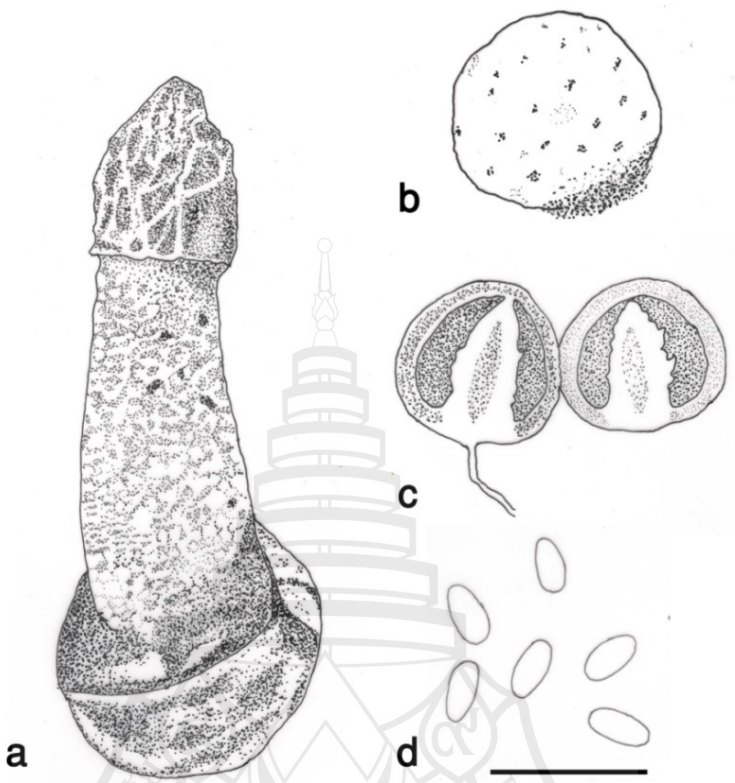
(Fulton, 1889; Li et al., 2016; Cabral et al., 2019). Basidiomata are globose to ovoid, white, soft, and with mycelial cords (Calonge, 1998; Moreno et al., 2009; Yakar & Yasin, 2019). Exoperidium is smooth and membranous, while endoperidium is gelatinous and translucent (Calonge, 1998; Moreno et al., 2009; Yakar & Yasin, 2019). Pseudostipe when mature is cylindrical, erect to curved, hollow, white, spongy, and fragile with conical, mucilaginous, foetid, olive brown, nearly half rounded receptacle (gleba) at the apex and is attached with a stout, white mycelial cord (Calonge, 1998; Moreno et al., 2009; Li et al., 2016; Yakar & Yasin, 2019; Sommai et al., 2021). Basidia are clavate and 6-spored (Yakar & Yasin, 2019). Spores are ellipsoid with a pale yellowish green colour and have a smooth surface (Calonge, 1998; Moreno et al., 2009).

Members of *Phallus* are distributed worldwide (He et al., 2019). The genus is reported growing in rich humus soil, littoral dunes, and fallen decaying hardwood and coniferous forest (Moreno et al., 2009; Rebriev et al., 2014; Yakar & Yasin, 2019). Many species of *Phallus* have been used for centuries and have health benefits such as antioxidant, antimicrobial, immunomodulatory, organoprotective, anticancer, anti-diabetic, and anti-obesity effects (Wang et al., 2021; Mazumder et al., 2022).

Synonymy: *Clautriavia* (Pat.) Lloyd, *Cryptophallus* Peck, *Dictyopeplos* Kuhl & Hasselt, *Dictyophallus* Corda, *Dictyophora* Desv., *Dictyophora* sect. *Clautriavia* Pat., *Hymenophallus* Nees, *Jaczewskia* Mattir., *Junia* Dumort., *Kirchbaumia* Schulzer, *Leiophallus* (Fr.) Nees, *Morellus* Eaton, *Omphalophallus* Kalchbr., *Phallus* sect. *Dictyophora* (Desv.) Kreisel, *Phallus* trib. *Leiophallus* Fr., *Retigerus* Raddi, *Satyrus* Bosc, *Sophronia* Pers.

Type species: *Phallus impudicus* L.

Other accepted species: (Species Fungorum – search *Phallus*)



Note a–c Basidiomata. d Basidiospores. Scale bar: d = 10 µm.

Source Redrawn from Yakar & Yasin (2019).

Figure 5.99 *Phallus impudicus*

Incertae sedis

Polyporales Gäum.

Cerrenaceae Miettinen, Justo & Hibbett, in Justo et al., *Fungal Biol.* 121(9): 817 (2017)

Cerrenaceae is a small family established by O. Miettinen, A. Justo & D.S. Hibbett in 2017 and typified by *Cerrena* Gray (Justo et al., 2017). The family consists of five genera: *Cerrena*, *Irpiciporus* Murrill, *Pseudolagarobasidium* J.C. Jang & T. Chen, *Pseudospongipellis* Y.C. Dai & Chao G. Wang, and *Radulodon* Ryvarden (He et al., 2024). *Cerrenaceae* is characterised by effused to pileate basidiomata, poroid, labyrinthine or spinose hymenophore, monomitic to trimitic hyphal system with clamps,

presence or absence of cystidia, and smooth, non-amyloid, non-dextrinoid basidiospores (Justo et al., 2017; Nakasone & Ortiz-Santana, 2022). Members of this family are distributed worldwide and are mostly saprophytic, causing white-rot in wood, while some species are serious pathogens, endophytes, or symbionts of insects (Nakasone & Ortiz-Santana, 2022; Miettinen et al., 2023).

5.3.1.103 *Radulodon* Ryvarden

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.100

Classification: *Cerrenaceae, Polyporales, Incertae sedis, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

Radulodon was established by Ryvarden with *R. americanus* as the type species (Ryvarden, 1972a), and later redefined by Nakasone (2001). Species of *Radulodon* are saprophytic with a cosmopolitan distribution, mainly in the Northern Hemisphere (Wang & Dai, 2022). Index Fungorum (2025) lists 17 records of *Radulodon*, while Species Fungorum (2025) recognises seven species worldwide. Recently, *R. yunnanensis* Y.C. Dai & Chao G. Wang was described from China, based on morphological characteristics and multi-gene phylogenetic analyses (ITS, LSU, SSU, and *tef-1α*) (Wang & Dai, 2022).

Members of *Radulodon* are characterised by resupinate to effused-reflexed, ceraceous basidiomata, with a hydnoid hymenophore composed of conical, cylindrical, or flattened spines (Ryvarden, 1972a; Nakasone, 2001; Wang & Dai, 2022). Basidiospores are ellipsoid, subglobose to globose, hyaline, thin-to slightly thick-walled, and slightly cyanophilous (Wang & Dai, 2022). Basidia are clavate, 4-spored, and with basal clamp connections (Nakasone, 2001). Cystidia are clavate, obclavate to cylindrical with basal clamp connections (Nakasone, 2001). The hyphal system is dimitic; generative hyphae with clamp connections and sometimes with rarely or frequently branched micro-binding hyphae or thick-walled skeletal hyphae limited to the subiculum and base of spines (Nakasone, 2001; Wang & Dai, 2022).

Phylogenetically, *Radulodon* is a sister genus to *Irpiciporus* Murrill in *Cerrenaceae* Miettinen; however, the latter is distinct by having a monomitic hyphal

system and a lack of cystidia (Murrill, 1905b; Kotlaba & Pouzar, 1957; Wang & Dai, 2022). Morphologically, *Radulodon* resembles *Pseudolagarobasidium* J.C. Jang & T. Chen, yet both form distinct monophyletic groups in multi-gene phylogenetic analyses (Nakasone & Ortiz-Santana, 2022). Additionally, *Pseudolagarobasidium* differs by its soft to firm basidiomata and non-agglutinated hyphae (Nakasone & Ortiz-Santana, 2022).

Type species: *Radulodon americanus* Ryvarden

Other accepted species:

R. acaciae G. Kaur, Avn.P. Singh & Dhingra

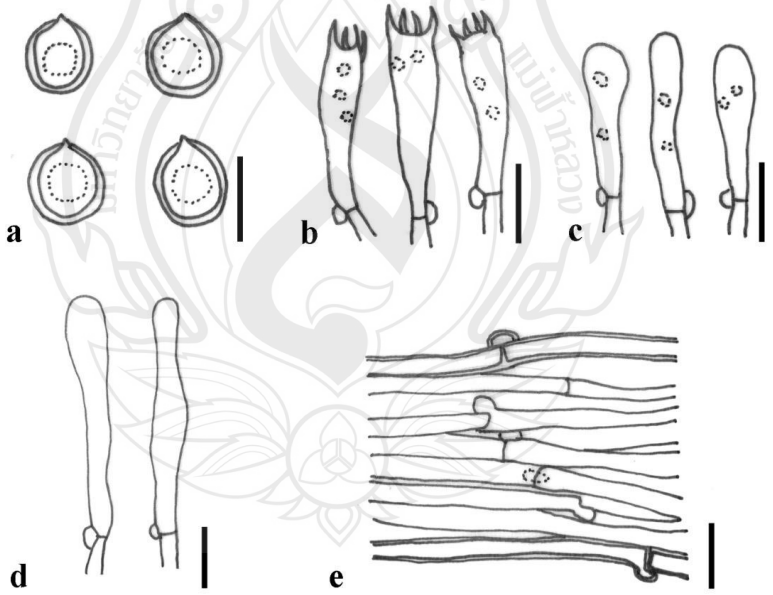
R. casearius (Morgan) Ryvarden

R. erikssonii Ryvarden

R. indicus Jyoti & Dhingra

R. yunnanensis Y.C. Dai & Chao G. Wang

R. pyriformis Hjortstam & Ryvarden



Note a Basidiospores. b Basidia. c Basidioles. d Cystidia. e Hyphae from subiculum. Scale bar: a = 5 µm, b–e = 10 µm.

Source Redrawn from Wang and Dai (2022). For original basidiomata, refer to Wang and Dai (2022).

Figure 5.100 *Radulodon yunnanensis* (Dai 12204)

Incertae sedis

5.3.1.104 *Ryvardenia* Rajchenb.

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.101

Classification: *Incertae sedis, Polyporales, Incertae sedis, Agaricomycetes, Agaricomycotina, Basidiomycota*, Fungi

Ryvardenia was established by M. Rajchenberg in 1994 with *R. cretacea* as the type species (Rajchenberg, 1994; Kirk et al., 2013). The genus name was provided in honour of the polypore specialist Dr. Leif Ryvarden (Rajchenberg, 1994). The type species was originally described as *Polyporus cretaceous* from specimens collected in Tasmania (Rajchenberg, 1994). *Ryvardenia* is an annual, wood-rotting fungus that causes brown rot, distributed in the Southern Hemisphere, including Argentina, Australia, Chile, and New Zealand (Rajchenberg, 1994; He et al., 2019). The genus comprises only two recognised species (He et al., 2019).

Members of *Ryvardenia* are characterised by medium to large-sized, piliate basidiomata (Rajchenberg, 1994). Pileus surface is white or slightly yellowish, while the pore surface is whitish to yellowish-tan, with circular to angular pores (Liu et al., 2023b). The context is chalk white, crumbly, or chalky (Liu et al., 2023b). Basidiospores are ellipsoid to drop-shaped, hyaline, thick-walled, uninucleate, and inamyloid (Rajchenberg, 1994). Cystidia are absent (Liu et al., 2023b). The hyphal system is monomitic to dimitic; generative hyphae are clamped, thin- to thick-walled, while skeletal hyphae are few to abundant and are present only in the dissepiments (Rajchenberg, 1994). The generative hyphae of the advancing mycelium are simple septate (Rajchenberg, 1994).

The classification of *Ryvardenia* under Index Fungorum and UNITE lists it as *incertae sedis* within *Polyporales,* whereas MycoBank, GenBank, and the latest Outline of fungi and fungus-like organisms classified it to *Laricifomitaceae* (*Polyporales*, *Agaricomycetes*) (Hyde et al., 2024a). Phylogenetic analysis (ITS, LSU, SSU, *tef-1α*, *rpb1*, and *rpb2*) conducted by Liu et al. (2023b) on brown-rot fungi within *Polyporales* provided strong support in *Laricifomitaceae*, with *Ryvardenia* forming a monophyletic lineage (Pildain & Rajchenberg, 2013; Liu et al., 2023b). Morphologically, *Ryvardenia*

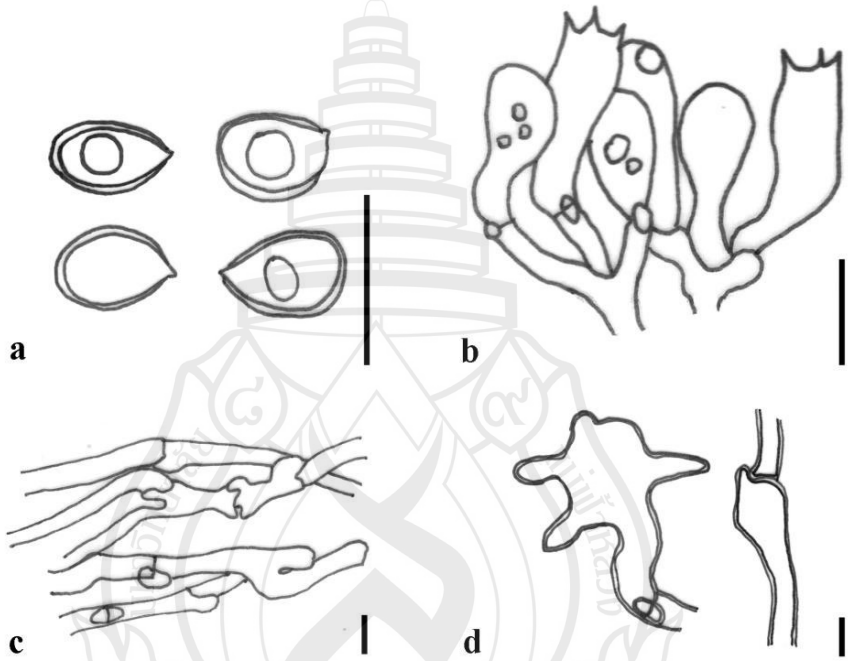
resembles *Fomitopsis s.s.* P. Karst., but differs in having annual basidiomata and a monomitic hyphal system (Rajchenberg, 1994; Han et al., 2016).

Type species: *Ryvardenia cretacea* (Lloyd) Rajchenb.

Basionym: *Polyporus cretaceous* Lloyd

Other accepted species:

Ryvardenia campyla (Berk.) Rajchenb.



Note a Basidiospores. b Basidia and basidioles. c Generative hyphae with thin wall. d Distorted generative hyphae with thick walls. Scale bar: a–d = 10 μm.

Source Redrawn from Rajchenberg (1994). For original basidiomata, refer to Rajchenberg (1994).

Figure 5.101 *Ryvardenia cretacea*

Irpicaceae Spirin & Zmitr., Mycena 3: 48

Irpicaceae is a relatively small but phylogenetically well-defined family within *Polyporales* Gäum., encompassing about 14 corticioid and polyporoid genera (Spirin, 2003; Justo et al., 2017; Chen et al., 2021; Hyde et al., 2024a). Members typically form resupinate to pileate basidiomata, have a monomitic hyphal system with

septate hyphae, thin-walled, smooth, non-amyloid, and acyanophilous basidiospores, and generally lack cystidia (Li et al., 2022b). Most species cause white-rot decay on woody angiosperms, except *Leptoporus* Quél., which produces brown-rot decay (Chen et al., 2021). The type genus *Irpex* Fr. was erected by Fries (1825). Global sampling by Li et al. (2022b) recognised nine clades within *Irpicaceae*, describing seven new species and proposing new combinations, which highlights East Asia as a diversity hotspot for the family.

5.3.1.105 *Irpex* Fr.

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.102

Classification: *Irpicaceae, Polyporales, Incertae sedis, Agaricomycetes, Agaricomycotina, Basidiomycota*, Fungi

Irpex was established by E.M. Fries in 1825, although no type species was specified (Fries, 1825). Later, in 1828, *I. lacteus* was designated as the type species, which was initially classified as *Sistotrema lacteum*, based on specimens collected on a branch of *Fagus* in Sweden (Maas Geesteranus, 1974). Members of *Irpex* are white-rot fungi that colonise dead wood and have a cosmopolitan distribution (He et al., 2019). Index Fungorum (2025) lists 257 records of *Irpex*, whereas Species Fungorum (2025) currently accepts only 62 species worldwide.

Irpex is characterised by effused basidiomata, effused-reflexed, or pileate, typically white, cream, yellowish, or cinnamon in colour (Maas Geesteranus, 1974; Chen et al., 2021). The hymenophore is poroid, irpicoid, or hydnoid (Maas Geesteranus, 1974). The hyphal system is dimitic, with generative hyphae that are simple-septate (Chen et al., 2021). Cystidia, when present, are tramal and subhymenial in origin, cylindrical, conical to subulate, thin- to thick-walled, and often apically or completely incrusted (Maas Geesteranus, 1974; Zmitrovich et al., 2006; Lim & Jung, 2003; Miettinen et al., 2007; Chen et al., 2021). Basidiospores are ellipsoid to somewhat allantoid, smooth, hyaline, inamyloid, acyanophilous (Maas Geesteranus, 1974). Basidia are cylindrical to clavate, 4-spored, and without a basal clamp (Maas Geesteranus, 1974).

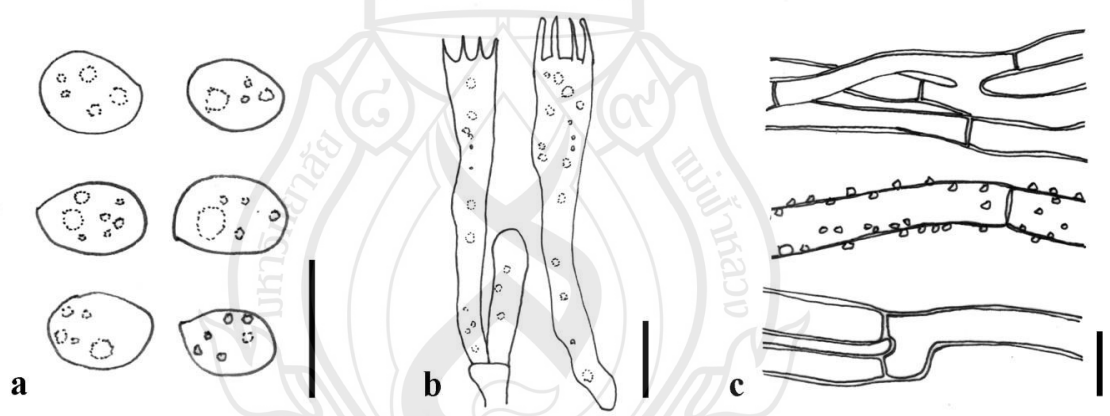
Irpex lacteus has commercial importance due to the production of hydrolases (e.g., endo- and exo-cellulases) and extracellular oxidative enzymes (Lim & Jung, 2003; Yao et al., 2017). This species exhibits resistance to pollutant toxicity and is efficient in biodegradation processes, potentially suitable for extracting ethanol through biological pretreatment of lignocellulose (Novotný et al., 2009; García-Torreiro et al., 2016). Notably, Yao et al. (2017) reported a whole-genome sequence of *I. lacteus* strain F17.

Synonymy: *Australohydnum* Jülich, *Beccaria* Cooke, *Cystidiophorus* Bondartsev & Ljub., *Flavodontia* C.L. Zhao, *Hydnopolyporus* D.A. Reid

Type species: *Irpex lacteus* (Fr.) Fr.

Basionym: *Sistotrema lacteum* Fr.

Other accepted species: (Species Fungorum – search *Irpex*)



Note a Basidiospores. b Basidia. c Subicular hyphae. Scale bar: a–c = 10 μm.

Source Redrawn from Chen et al. (2021). For original basidiomata, refer to Chen et al. (2021).

Figure 5.102 *Irpex lenis* (Wu 1608-22, holotype)

Meripilaceae Jülich, Biblthca Mycol. 85: 378

Meripilaceae, established by Jülich (1982), is a family within *Polyporales* Gäum. The family was typified by *Meripilus* P. Karst. (Jülich, 1982). The taxa of this family are characterised by a poroid hymenium, a monomitic hyphal system with generative hyphae, and globose to subglobose basidiospores (Westphalen et al., 2025).

Traditionally, four genera were recognised by Binder et al. (2013): *Henningsia* Möller, *Meripilus*, *Physisporinus* P. Karst., and *Rigidoporus* Murrill based on morphological characters. They were distinguished mainly by basidiomata consistency, hyphal structure, and presence of cystidia (Ryvarden, 1991). Later, molecular data confirmed *Physisporinus* as part of *Meripilaceae* but showed *Rigidoporus* to be polyphyletic, with its type species in *Hymenochaetales* Oberw. Consequently, all *Rigidoporus* species falling within *Meripilaceae* were transferred to *Physisporinus*, broadening the genus to encompass both resupinate and pileate forms (Wu et al., 2017b). Westphalen et al. (2025) evaluated the monophyly of the genera in this family. They transferred all species of *Physisporinus* to *Meripilus* to avoid any splitting of morphologically indistinguishable groups, resulting in 35 new combinations. Currently, this family is monotypic with only *Meripilus* belonging under it (Hyde et al., 2024a). Recently, five clades within the *Meripilus* clade have been inferred from a combined data set of ITS and LSU (Westphalen et al., 2025).

5.3.1.106 *Mycoacia* Donk

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.103

Classification: *Meruliaceae, Polyporales, Incertae sedis, Agaricomycetes, Agaricomycotina, Basidiomycota*, Fungi

Mycoacia was established by Donk in 1931 as a replacement for the invalid name *Acia* P. Karst. (Donk, 1931). The type species, *Mycoacia fuscoatra*, was initially classified as *Hydnum fuscoatrum* Fr., based on a specimen collected on a rotten trunk of *Fagus* in Sweden (Donk, 1931). Nakasone (1997) later synonymised *Mycoacia* under *Phlebia* Fr. However, Chen et al. (2021) reported that *Mycoacia* form a distinct and well-supported clade in *Meruliaceae*, along with other genera such as *Ceriporiopsis* Domański, *Lilaceophlebia* (Parmasto) Spirin & Zmitr., *Phlebia*, and *Stereophlebia* Zmitr. Species of *Mycoacia* are annual, saprobic, and are distributed worldwide (Yuan & Wan, 2012; He et al., 2019).

Mycoacia is characterised by ceraceous, effused, waxy, and strongly adnate basidiomata, exhibiting a hydnoid hymenophore with conical to cylindrical spines

(Ragab, 1951; Eriksson & Ryvarden, 1976; Yuan & Wan, 2012; Chen et al., 2021). The hyphal system is monomitic, with generative hyphae that are either clamped or simple-septate (Eriksson & Ryvarden, 1976; Yuan & Wan, 2012). Basidiospores are narrowly ellipsoid, cylindrical, or allantoid (Eriksson & Ryvarden, 1976; Yuan & Wan, 2012), while basidia are narrowly clavate (Chen et al., 2021). Cystidia are often present, subulate or fusiform (Chen et al., 2021).

Chen et al. (2021) utilised morphological characteristics and multilocus phylogenetic analyses (ITS, LSU, *rpb1*, *rpb2*, and *tef-1α*) to delineate at the genus level, including *Mycoacia*. Recently, Li et al. (2025) described a new species, *M. beijingensis*, in morphological characteristics and molecular clock analyses. Index Fungorum (2025) lists 55 records of *Mycoacia*, but Species Fungorum (2025) recognises only 17 species worldwide. Notably, the tissue of the type species, *M. fuscoatra*, turns red immediately upon reaction to KOH, a diagnostic feature absent in other species within the genus (Chen et al., 2021).

Synonymy: *Acia* P. Karst., *Ceriporiopsis* Domański, *Gelatoporia* Niemelä, *Porpomyces* Jülich, *Pouzaroporia* Vampola, *Stereophlebia* Zmitr., *Taxomyces* Strobel, A. Stierle, D. Stierle & W.M. Hess

Type species: *Mycoacia fuscoatra* (Fr.) Donk

Basionym: *Hydnum fuscoatrum* Fr.

Other accepted species: (Species Fungorum – search *Mycoacia*)

Note a Basidiomata. b Basidiospores. c Basidia. d Basidioles. e Leptocystidia. f Context hyphae. g Subiculum hyphae. Scale bar: a = 1 cm, b–g = 10 μm.

Source Redrawn from Li et al. (2025). For original basidiomata, refer to Li et al. (2025).

Figure 5.103 *Mycoacia beijingensis* (He 9275, holotype)

Phanerochaetaceae Jülich, Biblthca Mycol. 85: 384

The family *Phanerochaetaceae* is a diverse group of corticioid fungi within *Polyporales* Gäum., causing white-rot. This family was introduced by Eriksson (1958) as subfamily *Phanerochaetoideae* within *Corticiaceae* Herter. It was later validly published by Parmasto (1986) and elevated to family rank by Jülich (1982). The type genus is *Phanerochaete* P. Karst. (Jülich, 1982). Larsson (2007) later also proposed *Phanerochaetaceae* for a clade of corticioid fungi centred on *Phanerochaete*. Most members of this clade are corticioid or hydnoid, simple-septate and monomitic, except *Hapalopilus* P. Karst., a polypore with clamped hyphae (Miettinen et al., 2016). Most of the taxa are saprobic, found as wood decomposers, but some are reported from soil or litter (Justo et al., 2017). This family contains 27 genera worldwide (Hyde et al., 2024a).

5.3.1.107 *Porostereum* Pilát

Index Fungorum, Facesoffungi, MycoBank, GenBank

Classification: *Phanerochaetaceae, Polyporales, Incertae sedis, Agaricomycetes, Agaricomycotina, Basidiomycota*, Fungi

Porostereum was established by Pilát in 1937 with *P. phellodendri* as the type species (Pilát, 1937). Members of this genus exhibit diverse lifestyles, including saprophytic, endophytic, and latent plant pathogen, and are distributed worldwide (Sarkar & Datta, 2024). *Porostereum* is distinct from the closely related genus *Hjortstamia* Boidin & Gilles by consistently having clamped hyphae (Boidin & Gilles, 2002; Wu et al., 2010a). Index Fungorum (2025) lists 20 records of *Porostereum*, but Species Fungorum (2025) accepts only five species worldwide. Molecular data for the type species are not available; therefore, the phylogenetic concept of this genus still requires investigation (Xavier de Lima et al., 2020).

Porostereum is characterised by stereoid basidiomata with effuso-reflexed pileus, smooth hymenium surface (Welden, 1975). The hyphal system is mono-dimitic, with a clamped generative hypha (Boidin & Gilles, 2002; Xavier de Lima et al., 2020). Cystidia are hyaline to brown and thick-walled (Xavier de Lima et al., 2020). Basidia are clavate, and basidiospores are ellipsoid, CB- and IK- (Xavier de Lima et al., 2020).

Members of *Porostereum* are a potential source of metabolites that can be tapped for beneficial purposes (Sarkar & Datta, 2024). *Porostereum umbrinoalutaceum* is reported as an endophyte in basidiomata of *Pleurotus ostreatus*. Sarkar and Datta (2024) have indicated the potential of this fungus in the formulation of bio-fertilisers. This species tolerates toxic metals (Mg, Ca, Fe, Cu, Mn, Zn, Cd) and inhibits the growth of *Alternaria solani* Sorauer and *Penicillium citrinum* Thom in chilli plants (Sarkar & Datta, 2024). Similarly, another endophytic fungus, *P. spadiceum*, modulates endogenous phytohormones of the seedling to normalise the growth of salt-affected plants (Hamayun et al., 2017). The volatile compound produced by this fungus, 3, 5-dichloro-4-methoxybenzaldehyde, exhibited antimicrobial activity against *Clavibacter michiganensis* subsp. *michiganensis*, *Ralstonia solanacearum*, *Alternaria brassicicola*

(Schwein.) Wiltshire, and *Colletotrichum orbiculare* Damm, P.F. Cannon & Crous (Hamamoto et al., 2021; Sarkar & Datta, 2024).

Type species: *Porostereum phellodendri* Pilát

Other accepted species:

P. sharpianum (A.L. Welden) Hjortstam & Ryvarden

P. spadiceum (Pers.) Hjortstam & Ryvarden

P. submembranaceum (Henn.) Ryvarden

P. umbrinoalutaceum (Wakef.) Hjortstam & Ryvarden

Polyporaceae Fr. ex Corda, Icon. fung. (Prague) 3: 49

Polyporaceae is a diverse family of saprobic fungi characterised by soft, tough, often perennial basidiomata with a poroid hymenophore, mostly dimitic to trimitic hyphal system, presence of clamp connections, and thin- to thick-walled basidiospores (Fries, 1838; Corda, 1839; Cui et al., 2019). Although most members are poroid, some, such as *Daedaleopsis* J. Schröt., exhibit gill-like structures where the elongated pores form a corky, labyrinth-like surface. Fries (1838) in his work “Epicrisis Systematis Mycologici seu Synopsis Hymenomycetum” introduced this family as "Polyporei," and later, Corda (1839) validly published the name *Polyporaceae*. The type genus is *Polyporus* P. Micheli ex Adans., one of the earliest described poroid genera established by Micheli (1729) and later sanctioned by Fries (1838). The delimitation of genera and species within *Polyporaceae* is based on microscopic characters, including hyphal systems, basidia types, and context inclusions (Cunningham, 1946). Taxonomic understanding of this family has evolved from morphology-based systems (Murrill, 1903) to molecular phylogenetics, which revealed hidden diversity and led to reclassification of several genera (Justo et al., 2017; He et al., 2019). *Polyporaceae* contains 107 genera (Hyde et al., 2024a) and comprises both white-rot species that degrade lignin and brown-rot species that decompose cellulose and hemicellulose (Ryvarden & Johansen, 1980).

5.3.1.108 *Favolus* Fr.

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.104

Classification: *Polyporaceae, Polyporales, Incertae sedis, Agaricomycetes, Agaricomycotina, Basidiomycota,* Fungi

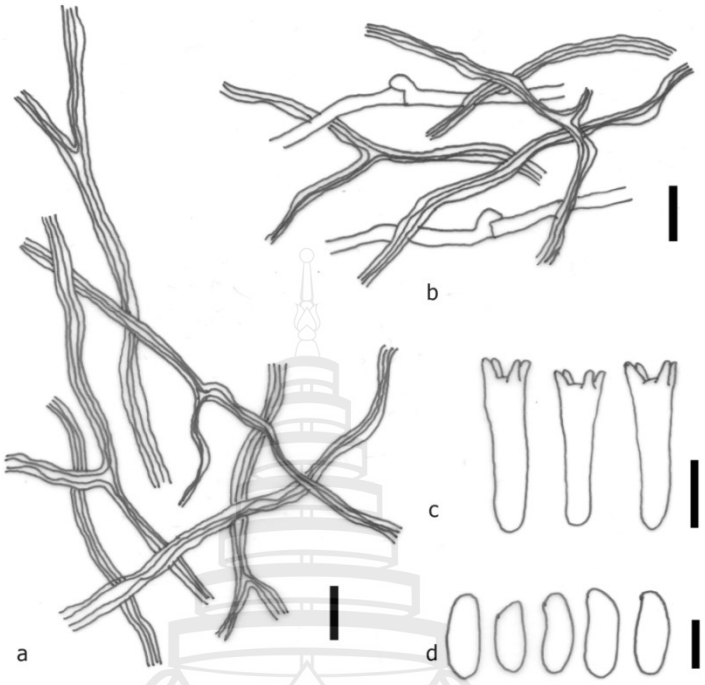
Favolus was established by E.M. Fries in 1828, and the type species is *Favolus brasiliensis* (Murrill, 1905b). *Favolus*, a worldwide distributed monophyletic genus, is a wood-decaying genus containing fleshy basidomata (Sotome et al., 2013; Zhou & Cui, 2017; Palacio et al., 2021a). Basidiomata of *Favolus* generally bear laterally stipitate and radially elongated pores (Sotome et al., 2013; Zhou & Cui, 2017; Palacio et al., 2021a). Another distinctive feature of this genus is a dimitic hyphal system (skeletal-binding hyphae) and thin-walled, smooth, cylindrical to navicular basidiospores (Sotome et al., 2013; Palacio et al., 2021a). *Favolus*, a white rot genus, generally occurs in dead fallen branches (Palacio et al., 2021a). Interestingly, *Favolus* have been reported as hosts for many mycophagous arthropods, adding ecological significance (Amaringo-Cortegano et al., 2013; Santa-Brígida et al., 2019; Falaschi et al., 2019; Palacio et al., 2021a). Some of its species are reported as wild edible mushrooms in Indonesia, Nepal, Papua New Guinea, and the Philippines (Boa, 2004; Christensen et al., 2008; De Leon et al., 2013; Palacio et al., 2021a).

Initially, *Favolus* was placed in one of the six infrageneric morpho-groups under *Polyporus* (Ryvarden & Johansen, 1980; Núñez & Ryvarden, 1995; Ryvarden, 2016; Palacio et al., 2021a). Further taxonomic studies, based on morphological (pilear surface) and phylogenetic data, show *Favolus* is split into two distinct clades, *Favolus* s. str. and *Neofavolus* (Sotome et al., 2013; Palacio et al., 2021a). Zhou and Cui (2017) used an eight-gene phylogeny (ITS, LSU, *tef1-α*, rrnS, *tbb1*, *rpb1*, and *rpb2*) to distinguish among species and identified four new species in the *Favolus* clade. Further, Palacio et al. (2021a) used phylogenetic analysis using combined genes ITS, LSU, and *rpb1* and four new species of *Favolus*. Index Fungorum (2025) lists 237 records of *Favolus*, while Wijayawardene et al. (2022) accepted only 30 species worldwide.

Synonymy: *Poroauricula* McGinty, *Roseofavolus* T. Hatt.

Type species: *Favolus tenuiculus* P. Beauv.

Other accepted species: (Species Fungorum – search *Favolus*)



Note a Skeletal-binding hyphae in the context. b Clamped generative hyphae and skeletal-binding hyphae in the trama. c Basidia. d Basidiospores. Scale bar: a–c = 10 µm, d = 5 µm.

Source Redrawn from Papp and Dima (2017).

Figure 5.104 *Favolus gracilisporus*

5.3.1.109 *Lignosus* Lloyd ex Torrend

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.105

Classification: *Polyporaceae, Polyporales, Incertae sedis, Agaricomycetes, Agaricomycotina, Basidiomycota*, Fungi

Lignosus was initially coined by Lloyd but was validly published by Torrend in 1920, with *L. sacer* as the type species (Torrend, 1920). Members of *Lignosus* are annual, single, terrestrial fungi that cause white-rot and are widely distributed in Africa (e.g., Cameroon, Kenya, and Zimbabwe), Asia (e.g., Indonesia, Malaysia, and South China), and parts of Europe (e.g., Germany) (Tan et al., 2013; Yap et al., 2015; Hu et al., 2017). Index Fungorum (2025) reports eight records of *Lignosus*, while Species

Fungorum (2025) reports only seven species as accepted worldwide. Phylogenetic analyses based on multiple gene regions (ITS, LSU, *rpb2*, and *atp6*) have consistently supported the placement of *Lignosus* within Polyporales (Sotome et al., 2008; Tan et al., 2010; Cui et al., 2011). Tan et al. (2013) described two new species, *L. tigris* and *L. cameronensis*, based on morphological characteristics and phylogenetic analysis (ITS). The basidiomata of *Lignosus* are centrally stipitate and arise from subterranean sclerotia (Tan et al., 2013; Lau et al., 2015). The hyphal system is trimitic, with clamped generative hyphae (Ryvarden & Johansen, 1980; Lau et al., 2015), and the basidiospores are hyaline, cylindrical to ellipsoid (Ryvarden & Johansen, 1980; Lau et al., 2015).

Members of *Lignosus* are also recognised for their medicinal properties, particularly the sclerotia, which are widely utilised in traditional medicine in Southeast Asia and China. They are effective in treating various diseases such as breast cancer, coughs, asthma, and fever (Yap et al., 2013; Lau et al., 2015). In China, *L. rhinocerotis*, also known as *hurulingzhi*, is an edible and medicinal mushroom used to treat liver cancer, gastric ulcers, food poisoning, and chronic hepatitis (Lau et al., 2015; Hu et al., 2017). In Indonesia and Malaysia, *Lignosus* species are locally known as *susu rimau*, meaning “tiger’s milk” or “tiger’s breast” (Werner, 2002; Lau et al., 2015). Notably, *L. rhinocerotis* has been successfully domesticated, and numerous studies have demonstrated its medicinal properties, including anti-inflammatory, antioxidative, antimicrobial, antiviral, anticancer, anticoagulant, and immunomodulatory activities (Abdullah et al., 2013; Lee et al., 2013; Hu et al., 2017).

Type species: *Lignosus sacer* (Afzel. ex Fr.) Torrend

Basionym: *Polyporus sacer* Afzel. ex Fr.

Other accepted species:

L. cameronensis Chon S. Tan

L. ekombitii Douanla-Meli

L. goetzei (Henn.) Ryvarden

L. hainanensis B.K. Cui

L. rhinoceros (Cooke) Ryvarden

L. tigris Chon S. Tan

Note a Basidiomata. b Basidiospores. c Basidia and basidioles. d Tramal hyphae. e Sclerids. Scale bar: a = 2 cm, b–c = 10 µm, d–e = 20 µm.

Source Redrawn from Tan et al. (2013). For original basidiomata, refer to Lau et al. (2015).

Figure 5.105 *Lignosus tigris* (holotype)

5.3.1.110 *Polyporus* P. Micheli ex Adans.

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.106

Classification: *Polyporaceae, Polyporales, Incertae sedis, Agaricomycetes, Agaricomycotina, Basidiomycota*, Fungi

Polyporus, a globally distributed genus (Gilbertson & Ryvarden, 1987; Ryvarden & Gilbertson, 1994; Núñez & Ryvarden, 2001; Gomes-Silva et al., 2012; Dai et al., 2014; Xue & Zhou, 2014), has been separated into smaller genera but is still considered as a ‘mega-genus’ causing white rot of wood (Vlasenko & Vlasenko, 2015). Molecular studies consistently show *Polyporus* as a polyphyletic genus (Krüger et al., 2006; Sotome et al., 2008; Xue & Zhou, 2014). *Polyporus* is divided into six well-

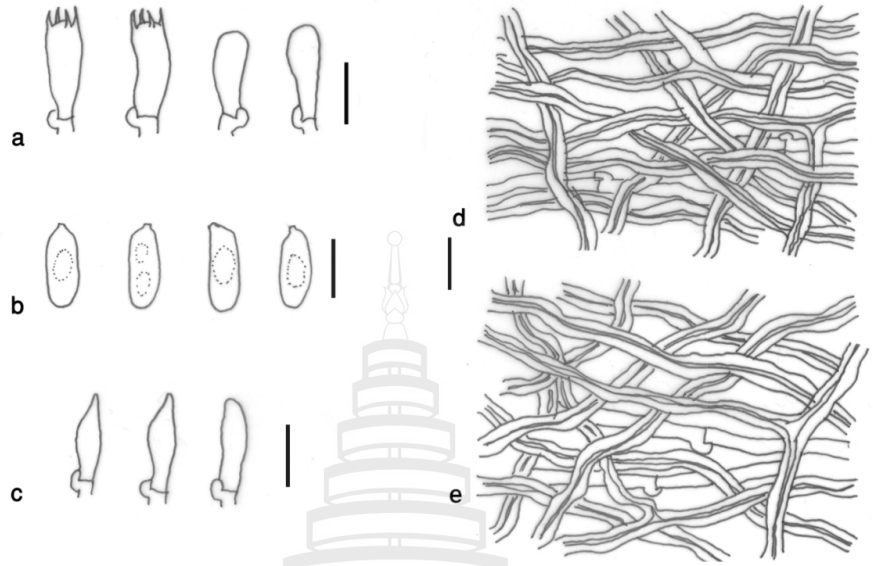
supported, distinct clades, morphological groups without taxonomic rank: *Polyporus*, *Admirabilis*, *Dendropolyporus*, *Melanopus*, *Polyporellus*, and *Favolus* (Núñez & Ryvarden, 1995; Sotome et al., 2008; Dai et al., 2014; Xue & Zhou, 2014; Sotome et al., 2015). Combined molecular analysis of *rpb2* and LSU was used to establish a relationship between *Polyporus* and allied genera (Sotome et al., 2008). Later, Dai et al. (2014) used morphological and phylogenetic analysis (ITS and LSU) and discovered three new species of the group *Melanopus*. Ji et al. (2022) reconfirmed that *Polyporus* and its allied genera fell into six well-supported clades based on phylogenetic analysis of two combined datasets (ITS+LSU) and (ITS+LSU+*ef1-α*+SSU+*rpb1*+*rpb2*+*tub*). *Polyporus* is the type genus of *Polyporaceae* (Hyde et al., 2016).

Polyporus has a well-developed cap with a typical stipitate to substipitate basidiomata (Xue & Zhou, 2013; Vlasenko & Vlasenko, 2015). The hyphal system is dimitic, thick-walled with arboriform skeleto-binding hyphae (Núñez & Ryvarden, 1995; Sotome et al., 2008; Gomes-Silva et al., 2012; Xue & Zhou, 2013; Dai et al., 2014; Xue & Zhou, 2014; Vlasenko & Vlasenko, 2015). Basidiospores are hyaline, thin-walled, cylindrical to subellipsoid, smooth, and have a negative reaction in Melzer's reagent (Gilbertson & Ryvarden, 1987; Núñez & Ryvarden, 1995; Dai et al., 2014; Xue & Zhou, 2014; Vlasenko & Vlasenko, 2015). Hymenium does not bear cystidia (Gomes-Silva et al., 2012; Vlasenko & Vlasenko, 2015). Some species, like *Polyporus tuberaster* and *P. umbellatus,* have been used for centuries as traditional medicine (Sotome et al., 2008; Vlasenko & Vlasenko, 2015; Pasailiuk, 2020). Different ethnic groups in Central and South America consume *Polyporus tenuiculus* (Omarini et al., 2009). Currently, 35 species are accepted under *Polyporus*, with *P. tuberaster* as the type species (Jacq. ex Pers.) (He et al., 2019).

Synonymy: *Dendropolyporus* (Pouzar) Jülich, *Grandinioides* Banker, *Leucoporus* Quél., *Melanopus* Pat., *Mycelithe* Gasp., *Mycobonia* Pat., *Polyporus* subgen. *Dendropolyporus* Pouzar, *Poria* Adans.

Type species: *Polyporus tuberaster* (Jacq. ex Pers.) Fr.

Basionym: *Boletus tuberaster* Jacq. ex Pers.



Note a Basidia and basidioles. b Basidiospores. c Cystidioles. d Hyphae from trama. e Hyphae from context. Scale bar: a = 5 μm, b–e =10 μm.

Source Redrawn from Dai et al. (2014).

Figure 5.106 *Polyporus americanus*

Russulales Kreisel ex P.M. Kirk, P.F. Cannon & J.C. David

Bondarzewiaceae Kotl. & Pouzar, Česká Mykol. 11(3): 163

The family *Bondarzewiaceae* was originally established to include all wood-rotting taxa and was typified with *Bondarzewia* Singer (Kotlaba & Pouzar, 1957). Initially, the family included three genera: *Amylaria* Corner, *Bondarzewia*, and *Hericium* Pers. and was characterised by fleshy basidiomata with poroid, hydnoid, or clavarioid hymenium, annual growth habit, and amyloid basidiospores (Kotlaba & Pouzar, 1957). Stalpers (1979) and He et al. (2024) added other characters such as resupinate, effuse-reflexed, pileate-sessile, pileate-stipitate to clavarioid basidiomata, pseudodimitic to dimitic hyphal system, presence of clamp connections, presence of thick-walled encrusted cystidia, gloeoplerous hyphae, and gloeocystidia may be present, and asperulate to spinulose, verrucose to echinulate, hyaline to pigmented basidiospores. The family is composed of nine genera (He et al., 2024; Hussain et al., 2024; Hyde et al.,

2024a). The members of *Bondarzewiaceae* are widely distributed in tropical, subtropical, and temperate regions (He et al., 2024).

5.3.1.111 *Steccherichium* D.A. Reid

Index Fungorum, Facesoffungi, MycoBank, GenBank, Fig. 5.107

Classification: *Bondarzewiaceae, Russulales, Incertae sedis, Agaricomycetes, Agaricomycotina, Basidiomycota*, Fungi

Steccherichium is a hydnaceous genus established by D.A. Reid in 1963, with *Steccherichium seriatum* (Lloyd) Maas Geest. as the type species (Yuan & Dai, 2008). The wood-decaying genus *Steccherichium* is distributed worldwide (He et al., 2019). This fungus has distinctive effused-reflexed to pileate basidiomata featuring an aculeate hymenial surface (Angelini & Losi, 2024). Basidiospores are ellipsoid, warted, and strongly amyloid (Maas Geesteranus, 1974; Yuan & Dai, 2008; Angelini & Losi, 2024). The hyphal system is monomitic to imperfectly dimitic, with clamped generative hyphae (Yuan & Dai, 2008; Angelini & Losi, 2024). Cystidia are tubular and thick-walled (Yuan & Dai, 2008). Index Fungorum (2025) reported 19 records. However, He et al. (2019) accepted only seven species (Yuan & Dai, 2008).

Yuan and Dai (2008) reported that the species of *Steccherinum* Gray macroscopically resemble those of *Steccherichium*. However, *Steccherinum* has encrusted skeleto-cystidia and smooth, non-amyloid basidiospores (Banker, 1912; Yuan & Dai, 2008). Furthermore, the basidiomata of *Steccherinum* are consistently leathery, while those of *Steccherichium* are corky (Yuan & Dai, 2008). Identification of *Steccherichium* species is solely based on macro- and micromorphology, and no molecular evidence is reported (He et al., 2019).

Type species: *Steccherichium seriatum* (Lloyd) Maas Geest

Basionym: *Hydnum seriatum* Lloyd

Other accepted species:

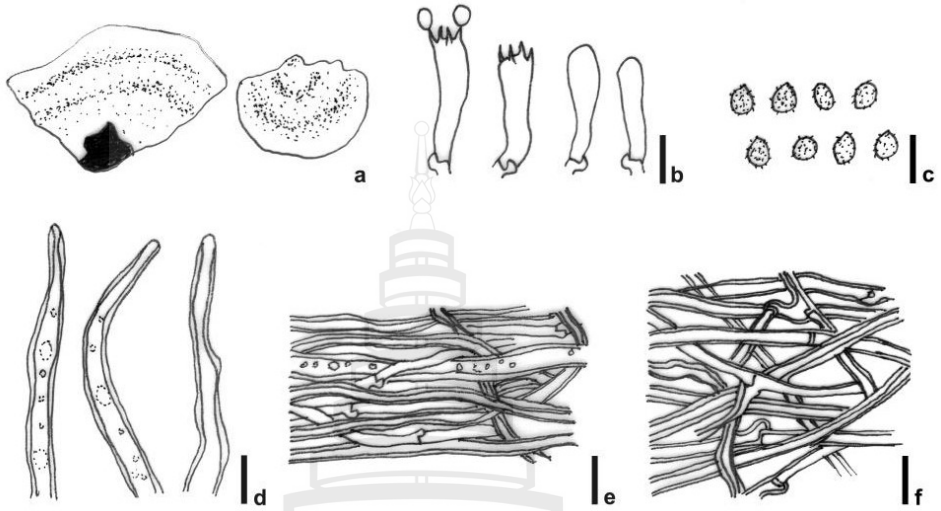
S. abditum Maas Geest.

S. acanthophysium T. Hatt. & Ryvarden

S. dimiticum Douanla-Meli

S. isabellinum Corner

S. rusticum Maas Geest.



Note a Basidiomata. b Basidia and basidioles. c Basidiospores. d Gloeocystidia. e Hypha from trama. f Hyphae from context. Scale bar: b, d–f = 10 μm, c = 5 μm.

Source Redrawn from Yuan and Dai (2008).

Figure 5.107 *Steccherícium seriatum* (Yuan 1629)

5.3.2 Notes on Terms Related to Mycelium-Based Biomaterials

5.3.2.1 3D-Printing with mycelium

3D printing is a technique used to develop products by depositing materials only where needed, thereby limiting waste generation compared to other processes (Mohseni et al., 2023; Soh et al., 2023). Mushroom mycelium is a vegetative part composed of hyphae that is used to bind discrete lignocellulosic particles or substrates to develop mushroom mycelium-based biomaterials (MMBs) (Soh et al., 2023; Khyaju & Luangharn, 2024). In 3D printing of MMBs, mycelium, and byproducts or substrates such as coffee grounds, cardboard, and sugarcane waste are mixed (Mohseni et al., 2023; Soh et al., 2023). Studies have exhibited its ability to easily design printed structures with air channels that facilitate mycelium growth (Soh et al., 2023). A gelling agent such as

chitosan or guar gum is also used along with lignocellulosic substrate in 3D mycelium printing (Elsacker et al., 2022; Soh et al., 2023).

This 3D printing method enabled the development of complex structures without the need to design and fabricate a complex mould (Soh et al., 2023). The major challenges in 3D printing with living organisms such as mushroom mycelium are the maintenance of sterilised conditions throughout the entire process and the utilisation of specialised equipment (Murphy & Atala, 2014; Yan et al., 2018; Mohseni et al., 2023; Soh et al., 2023). Additionally, only fine substrate particles enable the operation of small-nozzled printing equipment, thereby providing higher precision and resolution in the final products (Soh et al., 2023). However, 3D printing with mushroom mycelium and suitable substrates has provided a promising alternative to develop sustainable, non-polluting, and biodegradable materials.

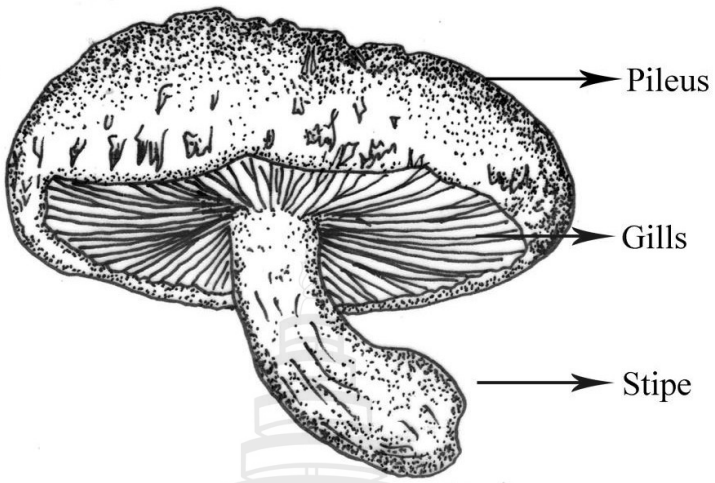
5.3.2.2 Acoustic insulation Fig. 5.108

Acoustic insulation is a method used to minimise sound transmission by absorbing or blocking sound waves. It is installed as panels on ceilings and walls, helping to manage noise in residential, commercial, and industrial settings. Various insulation materials have been developed, such as foam panels, rock mineral wools, fibreglass, plasterboards, and mushroom mycelium-based biomaterials (MMBs) (Bonga et al., 2024). While synthetic insulation materials are widely used globally, they are neither sustainable nor environmentally friendly (Bonga et al., 2024). In contrast, bio-based insulation materials such as MMBs have been tested and manufactured. Companies, including MOGU (www.mogu.bio) and BIOHM (www.biohm.co.uk), produce acoustic panels of MMBs on a commercial scale. MMBs are considered insulation materials due to their lower energy efficiency, sustainability, and biodegradability (Bonga et al., 2024). Their fibrous, porous, and low-density nature makes MMBs effective for acoustic insulation (Bonga et al., 2024). Regarding MMBs, higher-density materials exhibit better performance than non-pressed materials (Brito Guerrero de Escalante, 2023). Notably, MMBs have been shown to reduce noise by three-quarters at a frequency of 1000 Hz (Jones et al., 2020; Brito Guerrero de Escalante, 2023).

Figure 5.108 Acoustic insulation block developed using mycelium and sawdust

5.3.2.3 Basidiomata Fig. 5.109

Basidiomata (singular: basidioma) are the reproductive structures or fruiting bodies of fungi in the phylum Basidiomycota. They exhibit diverse shapes, sizes, and colours, including mushrooms, brackets, puffballs, stinkhorns, and jelly fungi. These fungi have significant ecological roles as saprobes, parasites, and ectomycorrhizae. Mushrooms are highly prized as a source of food, supplements, and medicine. Typically, basidiomata consist of a pileus or cap, gills or pores or teeth, and a stipe or stem. Basidia are specialised cells in basidiomata that produce and release basidiospores. Both the basidiospores and the context mycelium can be used for isolation to develop pure cultures. The pure culture is utilised in spawn preparation and inoculation of substrates to prepare mushroom mycelium-based biomaterials (Khyaju & Luangharn, 2024). Basidiomata are sometimes directly crushed and processed for biomaterial production (Bustillos et al., 2020; Porter & Naleway, 2022). Alternatively, researchers such as Müller et al. (2021) and Pylkkänen et al. (2023) cultivated basidiomata in moulds, allowing them to grow into predefined shapes and sizes of products to obtain biomaterials.



Source Redrawn from Pegler (1983a).

Figure 5.109 Basidiomata of *Lentinula edodes* show pileus, gills, and stipe

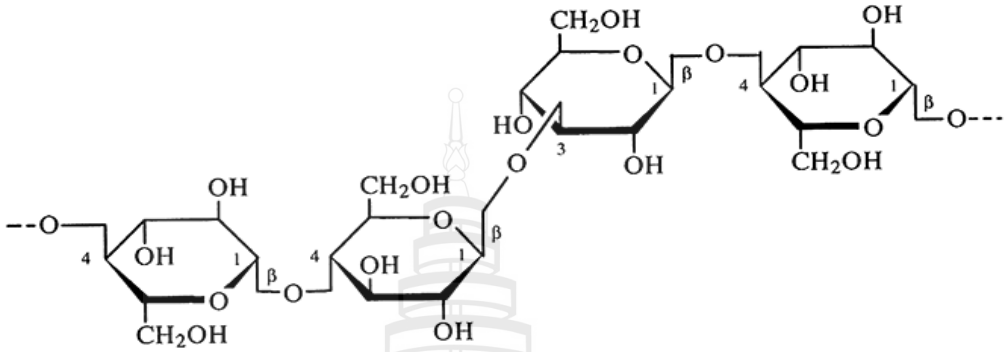
5.3.2.4 Beta-glucans Fig. 5.110

Beta-glucans (β-glucans) are naturally occurring soluble fibres or polysaccharides found in the cell wall of fungi, bacteria, yeast, and some cereals (Wasser & Weis, 1999; Rop et al., 2009; El Khoury et al., 2012; Thanasannubanant et al., 2025). These bioactive compounds are well known for their health-promoting effects, including the regulation of insulin resistance, hypertension, dyslipidemia, and obesity (El Khoury et al., 2012).

In mushrooms, beta-glucans are the most abundant structural polysaccharides, forming essential components of the fungal cell walls, in linear and branched form, consisting of *β*-1,3 and *β*-1,6 glycosidic linkages (Ruiz-Herrera & Ortiz-Castellanos, 2019). These molecular linkages form a micro-fibril structure that plays an important role in cell wall architecture, resistance, and mechanical strength (Rop et al., 2009; Ruiz-Herrera & Ortiz-Castellanos, 2019).

In the development of mushroom mycelium-based biomaterials (MMBs), β-glucans are instrumental in binding substrate particles together during mycelial colonisation (Ruiz-Herrera & Ortiz-Castellanos, 2019). Their adhesive properties support

the formation of a cohesive material matrix. Moreover, β-glucans are biodegradable, breaking down naturally into glucose, thereby contributing to the environmental sustainability and degradability of MMBs.



Source Rop et al. (2009)

Figure 5.110 Structure of *β*-glucans

5.3.2.5 Biochar

Biochar is a carbon-rich material produced through the pyrolysis of organic matter, including agricultural wastes, wood, and municipal solid waste (Lehmann & Joseph, 2009; Wang & Wang, 2019; Choi et al., 2023b). It possesses several beneficial properties, such as high carbon content, strong cation exchange capacity, a large surface area, and structural stability (Sepehri & Sarrafzadeh, 2018; Wang & Wang, 2019). In mushroom mycelium-based biomaterials (MMBs), fire testing has demonstrated the formation of a protective char layer on the surface, which effectively inhibits combustion and heat penetration (Choi et al., 2023b). Due to these higher char yields, MMBs exhibited superior fire resistance compared to conventional plastics (Jones et al., 2018b). Additionally, the pyrolysis process leads to shrinkage in mycelium diameter while preserving the fibrous structure, further enhancing the fire-retardant behaviour of materials (Jones et al., 2018b).

5.3.2.6 Biodegradability

The ability of a material to decompose naturally into simpler compounds like carbon dioxide, water, and organic matter is termed biodegradability. Microorganisms, such as bacteria and fungi, degrade complex materials, leading to a reduction in the

weight and volume of the material. The decomposition of organic matter affects the formation and functioning of soil in nature (Smagin et al., 2018).

The biodegradability of biomaterials is a key benefit over plastic-based or synthetic products. The rate of degradation is affected by environmental conditions, including temperature, moisture, and oxygen levels. Mushroom mycelium-based biomaterials exhibit high biodegradability, making them an eco-friendly product that aligns with the principles of the circular economy. For instance, mycelium-based biomaterials exhibited weight loss of 61 to 85 % in 90 days of soil burial (Aiduang et al., 2024).

The biodegradability of a material is tested by burying it in soil for a specific duration. The samples are retrieved at intervals of 15, 30, 45, 60, 75, and 90 days, cleaned to remove adherent soil, and dried at 60°C until reaching a stable weight. The initials and final weights are recorded, and the weight loss percentage is calculated using the following formula (Juanga-Labayen & Yuan, 2021; Aiduang et al., 2024);

$$WL\ (\%) = \frac{Wi - Wt}{Wi} \times 100\%$$

where,

WL = Weight loss (%), W_i = initial weight (g), W_t = weight after the given time (g)

5.3.2.7 Biomaterial packaging Fig. 5.111

The global challenge of environmental pollution is driven by plastic-based packaging products such as polystyrene or styrofoam (Abhijith et al., 2018). Biomaterial packaging refers to alternative solutions derived from renewable and biodegradable materials based on biological sources. Biomaterials are eco-friendly, sustainable, lightweight, energy-efficient, and have a lower carbon footprint. Among the various biomaterial packaging options, mushroom mycelium-based biomaterials (MMBs) are an innovative alternative to traditional plastic. The MMBs are developed using mushroom mycelium and lignocellulosic substrates (Abhijith et al., 2018; Vandelook et al., 2021). MMBs are fully biodegradable and renewable, making them an attractive and sustainable packaging option (Asore, 2021). Some companies, such as Dell, IKEA, and Ecovative Design, have already incorporated MMBs for packaging electronics, beverages,

cosmetics, and fragile items (Holt et al., 2012; Iordache et al., 2018; Vandelook et al., 2021).

Figure 5.111 Biomaterial packaging from mushroom mycelium-based biomaterials

5.3.2.8 Biopolymer

Biopolymers are natural polymers synthesised by living organisms, including plants, animals, and microorganisms. Common biopolymers include cellulose, chitin, starch, proteins, and nucleic acids, all of which are typically biodegradable and environmentally sustainable (Liu et al., 2023c). These polymers are formed from monomeric units such as sugars, amino acids, and nucleotides. For example, proteins are composed of long chains of amino acid residues, while lignin is an amorphous, cross-linked polymer derived from phenolic precursors. Lignin exhibits several beneficial properties, including antioxidant activity, high thermal stability, chemical reactivity, and adhesive characteristics (Naseem et al., 2016; Liu et al., 2023c). In certain applications, biopolymers are extracted from various mushroom species (Hassan et al., 2019; Benbelkacem et al., 2022). In the development of mushroom mycelium-based biomaterials (MMBs), the mycelium functions as a natural binder due to its rich biopolymer content. Key criteria for selecting biopolymers for their applications include biocompatibility, non-toxicity, and the ability to support favourable biological growth (Hassan et al., 2019).

5.3.2.9 Carbon footprint

A carbon footprint (CF), also known as greenhouse gas footprint, refers to the quantified amount of greenhouse gases (GHGs) emitted into the atmosphere. It measures the total amount of mainly carbon dioxide emissions, directly and indirectly, associated with an activity and accumulated throughout a product's lifecycle (Wiedmann & Minx, 2008). The CF of a product can vary significantly based on factors such as production, processing, transportation, and disposal. Carbon emissions are measured using three methods: input-output (IO) analysis, life cycle assessment (LCA), and IO-LCA (Gao et al., 2014). In 2006, the International Organization for Standardization (ISO) introduced the ISO14064 standard, which provides guidelines for measuring and managing GHG emissions (Gao et al., 2014).

The GHGs are major contributors to global warming and present a significant challenge for sustainability and humanity (Gao et al., 2014). To address this growing threat, several international agreements have been established, including the United Nations Framework Convention on Climate Change (1992), the Kyoto Protocol (1997), the Bali roadmap (2007), and the Copenhagen Agreement (2009) (Gao et al., 2014). These initiatives have encouraged the creation of eco-friendly, sustainable, and biodegradable products. Among these innovations, mushroom mycelium-based biomaterials (MMB) have emerged as a promising solution with a low carbon footprint. MMBs are developed using the vegetative part of mushrooms called mycelium and agricultural or forest byproducts (Khyaju & Luangharn, 2024). Both mycelium and these byproducts are renewable natural resources, and MMBs are increasingly used in various applications, including packaging, construction, architectural design, insulation, and textiles.

5.3.2.10 Carbon sequestration

Carbon sequestration is the process of capturing and storing atmospheric carbon dioxide (CO_2) in biological and geological reservoirs to reduce the concentration of CO_2 in the atmosphere (Lal, 2008). Globally, the major carbon pools include the biotic, pedologic (soil), atmospheric, oceanic, and fossil fuel (Lal, 2008). Reducing

atmospheric CO_2 through various carbon management techniques is a key strategy to combat global warming and climate change. Among these, carbon-neutral technologies play a central role (Lal, 2008). In mushroom mycelium-based biomaterials (MMB) production, lignocellulosic substrates are utilised along with mycelium, which otherwise might be burnt, releasing CO_2 into the atmosphere (Khyaju & Luangharn, 2024). Agricultural and forest byproducts are used as input resources for MBB production, thereby following the circular economy model (Khyaju & Luangharn, 2024). MMB production aligns with the principles of the circular economy, where waste materials are transformed into valuable and renewable resources. By substituting traditional petroleum-based plastics with biodegradable MMBs, this approach also reduces environmental pollution, particularly in oceans, air, and landfills. Notably, the life cycle assessment (LCAs) of MMB production using mushroom mycelium and agricultural byproducts results in a net carbon sink (Livne et al., 2022). In today's world, MMBs are applied in a wide range of sectors, including packaging, construction materials, thermal and acoustic insulation, textiles and furniture, eco-friendly design, and architecture. These applications not only replace conventional, high-emission materials but also contribute to active carbon sequestration, offering a scalable and sustainable solution for mitigating climate change (Livne et al., 2022; Khyaju & Luangharn, 2024).

5.3.2.11 Chemical characterisation

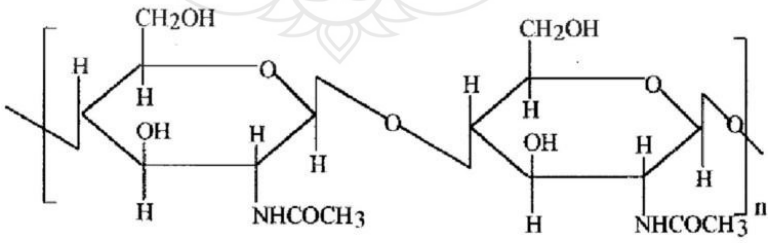
The evaluation of chemical characteristics in mushroom mycelium-based biomaterials (MMBs) mainly includes techniques such as Fourier Transform Infrared Spectroscopy (FTIR), Thermogravimetric Analysis (TGA), and measurements of pH, nitrogen content, organic matter content, and electrical conductivity (Aiduang et al., 2022c). MMBs are composed of mycelium that primarily consists of polysaccharides (chitin, glucans, chitosan), proteins (hydrophobins, enzymes), and lipids (fatty acids). The chemical composition of MMBs plays a critical role in determining their physical, mechanical, and biodegradability properties. For instance, the differences in chemical composition (cellulose) of MMBs result in differences in water absorption abilities (Aiduang et al., 2022c). Additionally, the pH of MMBs tends to decrease significantly

following a period of mycelial fermentation (Aiduang et al., 2022c). In terms of organic matter (OM) content, mycelium-grown MBBs exhibit reduced OM levels compared to the initial substrate (Aiduang et al., 2022c). Notably, due to their natural constituents, MBBs are fully biodegradable, offering a sustainable alternative to petroleum-based plastic and foam products (Alemu et al., 2022a).

5.3.2.12 Chitin Fig. 5.112

Chitin is a long-chain biopolymer composed of an amide derivative of glucose, N-acetylglucosamine, linked by β-(1→4) bonds (Kalutharage & Rathnasinghe, 2020). It is structurally similar to cellulose, except that the hydroxyl group in cellulose is substituted by acetyl amine (Alimi et al., 2023). The chitin synthesis mechanism is highly conserved and involves several enzymes, with chitin synthase being the principal enzyme (Merzendorfer, 2011). It is often cross-linked with glucans and proteins, giving flexibility to the cell wall. Fungal chitin exhibits crystalline micro-fibrils in three isomeric forms: α-chitin, β-chitin, and γ-chitin (Ru et al., 2019). Among these, α-chitin is the most abundant in fungi and is the strongest and most resistant isomer (Triunfo et al., 2021; Alimi et al., 2023). Chitin is a key structural component of fungal cell walls and septa, providing mechanical strength and rigidity.

The abundance of chitin, along with proteins and glucans, plays a significant role in the mechanical strength and structural integrity of mycelium-based biomaterials (Amobonye et al., 2023). In addition, the deacetylated derivative of chitin, known as chitosan or glucosamine, is applied to prepare different materials, such as membranes, sponges, gels, scaffolds, nanoparticles, and nanofibers (Duan et al., 2018).



Source Alimi et al. (2023)

Figure 5.112 Chemical structure of chitin.

5.3.2.13 Circular economy

Circular economy is an economic model that aims to produce goods and services by minimising resource consumption and waste (Meyer et al., 2020; Alemu et al., 2022a). In contrast to the linear economy model, which follows a make-use-dispose approach, the circular economy model transforms waste into valuable resources. The overexploitation of natural resources and improper waste disposal are major contributors to pollution, posing a serious risk to ecosystems and human health (Alemu et al., 2022a). Mushroom mycelium-based biomaterials (MMBs) offer a sustainable alternative, as they are fully biodegradable and produced from lignocellulosic organic substrates (such as agricultural and forest byproducts), combined with mushroom mycelium (Khyaju & Luangharn, 2024). These materials are promising candidates in transitioning a petroleum-based linear economy to a bio-based circular economy and reducing greenhouse gas emissions (Meyer et al., 2020). Notably, MMBs can be composted after use, which ultimately contributes to ecological balance and resource regeneration.

5.3.2.14 Compressive strength Fig. 5.113

Compressive strength (CS) is the maximum stress a material or structure can withstand under compression or loads before failure. It is a key factor in determining the suitability of materials for packaging, construction, and engineering various applications. CS of mushroom mycelium-based biomaterials depends on the substrate type and the type of mushrooms used (Chan et al., 2021; Mardijanti et al., 2021). For mycelium-based biomaterials, the CS typically ranges from 0.03 to 4.44 MPa (Aiduang et al., 2022b). The CS is determined using standardised protocols, such as ASTM D3501, on an Instron 5900R load bench with a 100 kN capacity and a 10 kN static load cell under ambient conditions (25°C and ~50% RH) (Aiduang et al., 2022b). The 10 kN load cell ensures precise results due to the expected low ultimate load values. The tests are conducted under displacement control at a rate of 5 mm/min. The resulting load-displacement data is then converted to a stress-strain curve, using the following formula to calculate compressive stress (σ) and strain (ε):

$$\sigma = \frac{F}{A}[MPa]$$

and,

$$\varepsilon = \frac{\Delta L}{Lo}[-]$$

where,

F = compressive force (N), A = original cross-section area of the specimen (mm^2), ΔL = displacement of the loading surfaces (mm), and L_o = original height of the test piece (mm).

Figure 5.113 Compression strength test of mycelium-based biomaterial test sample

5.3.2.15 Construction biomaterials Fig. 5.114

Construction biomaterials are innovative, sustainable, and eco-friendly materials derived from natural sources and designed for use in building and construction. They are increasingly popular due to their low environmental impact, biodegradability, and lower energy consumption and carbon emissions compared to traditional construction materials such as concrete, steel, and plastics. Biomaterials include a wide range of products, including mushroom mycelium-based biomaterials (MMBs), bamboo, hemp crates, and straw bales. They can be manufactured into bricks, blocks, and panels, primarily using natural lignocellulosic byproducts as the key components. Among these, MMBs, as construction products, exhibit lower brittleness and higher ductility than

products without mycelium (Sharma & Sumbria, 2022). Notably, they meet international standards for construction biomaterials, offering desirable properties such as physical and mechanical strength, thermal and acoustic insulation, and resistance to water and fire (Saez et al., 2021). However, these products require further research to enhance their strength and durability (Dessi-Olive, 2019; Özdemir et al., 2022).

Figure 5.114 Mushroom mycelium-based biomaterials as construction biomaterials

5.3.2.16 Denaturation Fig. 5.115

Denaturation refers to the structural alteration of living materials, particularly proteins and nucleic acids (Dill & Shortle, 1991). In mushroom mycelium-based biomaterials (MMBs), this treatment is done after mycelium has fully colonised the substrate, by exposing it to a higher temperature for a specific duration. The heating conditions can vary, such as 90°C for 90 min or 90°C for 30 min, 60°C for 48 hr (Ghazvinian et al., 2019; Ly & Jitjak, 2022; Oral et al., 2022). This post-harvest treatment effectively kills the mycelium without any adverse effects on users of the final products. The heat-press treatment of MMBs increases anastomosis among hyphae, resulting in greater bonding and strength. Notably, the higher temperature treatment removes almost all the moisture from the MMBs and makes them rigid with increased mechanical strength.

Figure 5.115 Denaturation of mushroom mycelium-based biomaterials

5.3.2.17 Dry density

Dry density is a fundamental physical property defined as the ratio of mass to volume. It is calculated using the formula: D = m/v, where "D" is the dry density (kg/m^3), "m" is the dry mass of materials (kg), and "v" is the volume of the sample (m^3) (Elsacker et al., 2019).

In the context of mushroom mycelium-based biomaterials (MMBs), density is a critical parameter that directly affects the material's mechanical performance, structural integrity, and potential applications. Density of MMBs ranged between 25–954 kg/m^3, comparable to synthetic materials that range between 11–920 kg/m^3 (Jones et al., 2020; Aiduang et al., 2024). Several factors influence the density of MMBs, including mushroom species used (e.g., *Ganoderma lucidum*, *Pleurotus ostreatus*, and *Trametes versicolor*), substrate type and substrate packing, growth conditions (e.g., relative humidity, temperature, moisture, and pH), post-processing techniques (e.g., pressing), and drying methods and conditions (Aiduang et al., 2024). These parameters can be fine-tuned to create mycelium materials with desired densities suited to specific applications such as packaging, acoustic insulation, composite panels, and eco-design products. Beyond their comparable densities, MMBs offer key sustainability advantages over synthetic alternatives. They are biodegradable, low-cost, energy-efficient, and derived

from renewable biological sources. This makes MMBs a promising candidate for replacing petroleum-based materials in various industries (Khyaju & Luangharn, 2024).

5.3.2.18 Ectomycorrhizal mushrooms Fig. 5.116

Ectomycorrhizal mushrooms are a group of fungi that form a mutualistic symbiotic association with the roots of primarily woody trees (Sharma, 2017). These fungi develop a fungal sheath around the host plant's root and form a Hartig net, a network of hyphae that penetrates between root cortical cells to exchange nutrients. Through this relationship, the fungus receives plant-derived carbohydrates (mainly glucose), while the plant gains enhanced access to water and essential mineral nutrients such as nitrogen and phosphorus. Notable genera of ectomycorrhizal fungi include both edible and toxic species, such as *Amanita* Pers., *Boletus* L., and *Cantharellus* Adans. ex Fr., *Lactarius* Pers., *Russula* Pers., and *Tuber* P. Micheli ex F.H. Wigg. (Yun & Hall, 2004).

While ectomycorrhizal fungi play vital ecological roles in forest ecosystems, they are less suitable for applications in mushroom mycelium-based biomaterial (MMBs). This is primarily because they depend on living host trees for growth and are not easily cultivated on common agricultural or forestry byproducts (Yun & Hall, 2004). In contrast, saprobic fungi, which decompose organic matter independently, are preferred for MMB development due to their ease of cultivation, substrate flexibility, and ability to form dense, cohesive mycelial networks (Sydor et al., 2022).

Figure 5.116 *Thelephora* species, an ectomycorrhizal mushroom

5.3.2.19 Elastic modulus

Elastic modulus, also known as modulus of elasticity, is a key mechanical property that measures the ability of a material to resist non-permanent (elastic) deformation under applied stress. It is defined as the slope of its stress-strain curve within the elastic deformation region. The elastic modulus is often determined by drawing a tangent to the steepest part of the force-displacement curve (Irbe et al., 2022). Based on its applications, mycelium is a biopolymer composed primarily of chitin microfibrils that play a central role in determining mechanical performance (Islam et al., 2017). The interconnected hyphal structure, formed through a process known as anastomosis (hyphal fusion), enhances the mechanical integrity and strength of the mycelium matrix (Glass et al., 2004).

In mushroom mycelium-based biomaterials, the elastic modulus is largely influenced by the filament elasticity, hyphal branching, and network density of the mycelium structure (Islam et al., 2017). Notably, the elastic modulus of mycelium is also affected by the variation in hyphal chemical composition of different fungal species (Haneef et al., 2017; Olivero et al., 2023).

5.3.2.20 Enzymatic degradation

Enzymatic degradation is the process in which enzymes break down complex molecules into simple forms. In nature, organic materials such as carbohydrates, proteins, and lipids are decomposed naturally by several decomposers, including bacteria, fungi, and soil organisms, and maintain the carbon cycle (Cragg et al., 2015). Among them, mushrooms release lignocellulolytic enzymes such as cellulases (endoglucanase, exoglucanase, glucosidase), hemicellulases (xylanase, mannanase, arabinase), and lignases (phenol oxidase, peroxidase) to degrade lignocellulosic substrates, followed by the utilisation of degraded materials to produce basidiomata (Kumla et al., 2020). The substrates are mainly composed of cellulose, lignin, and hemicellulose, which are degraded during solid-state fermentation by breaking glycosidic bonds (Sánchez, 2009; Andlar et al., 2018; Kumla et al., 2020). These hydrolytic and oxidative enzymes released by mushrooms act on these complex biopolymers, breaking them down (Kumla et al., 2020). In the mushroom mycelium-based biomaterial development process, enzymatic degradation of the lignocellulosic substrate is an essential step from mycelium inoculation into the substrate to final denaturation. The complex mycelial network binds substrate particles, forming a dense mycelial layer (Khyaju & Luangharn, 2024).

5.3.2.21 Fire resistance Fig. 5.117

Fire resistance is the ability of a material to withstand fire or high temperatures without igniting. Key factors influencing fire resistance include decomposition temperature, residual char formation, and the type of gases released during pyrolysis. Mushroom mycelium-based biomaterials (MMBs) have gained attention as promising candidates for fire-retardant applications, particularly in packaging and construction (Jones et al., 2018b). The thermal stability of mycelium is enhanced by the conversion of chitin into chitosan through deacetylation, as well as the presence of hydroxyl-terminated polysaccharides that promote char formation (Chulikavit et al., 2023). The resulting char acts as an insulating barrier, reducing heat transfer and limiting fire propagation (Chulikavit et al., 2023). For instance, MBBs have demonstrated that their fire resistance, compared to conventional thermoplastic polymers, is largely due to

their higher char yield (Jones et al., 2018b). However, a limitation of MMBs is that the organic constituent in MMBs releases heat, smoke, and gases during combustion, which can pose challenges in fire management (Mouritz & Gibson, 2006; Jones et al., 2018b). Nevertheless, incorporating fire-retardant materials, such as thermal protective coatings or sacrificial materials, can enhance fire resistance (Chulikavit et al., 2023). The elevated char yield signifies the potential of MMBs as effective fire-resistant materials.

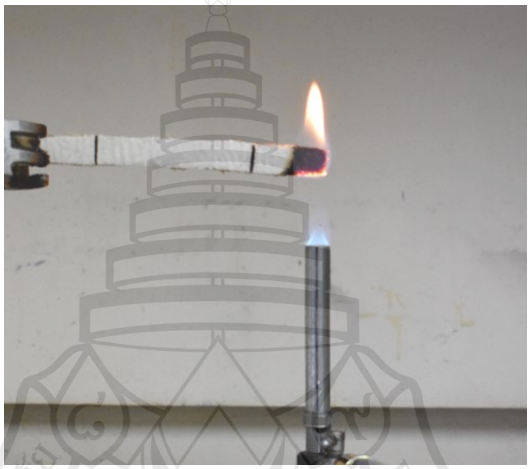


Figure 5.117 Fire resistance test showing char formation in the mushroom mycelium-based biomaterials

5.3.2.22 Flexural strength Fig. 5.118

The flexural strength (FS) test, also known as the three-point bending test, is used to determine a material's flexural or bending properties. Flexural strength is the ability of a material to resist deformation under bending (Yang et al., 2021). The FS test of mushroom mycelium-based biomaterials (MMBs) follows a standardised protocol, such as ASTM D7254, using a universal testing machine (UTM) equipped with a three-point fixture (Aiduang et al., 2022b). The apparatus has a cross-head speed of 2 mm/min and a clamp support distance of 100 mm. FS is a crucial parameter for evaluating the suitability of MMBs in applications such as packaging, construction, and insulation. FS values for MMBs typically range from 0.05 to 4.44 MPa (Aiduang et al., 2022b). FS of MMBs depends upon factors such as the type of hyphal system and the pressing method used (Appels et al., 2019).

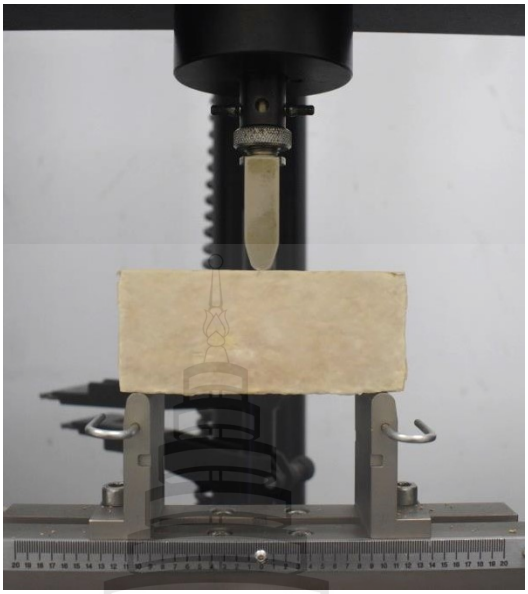
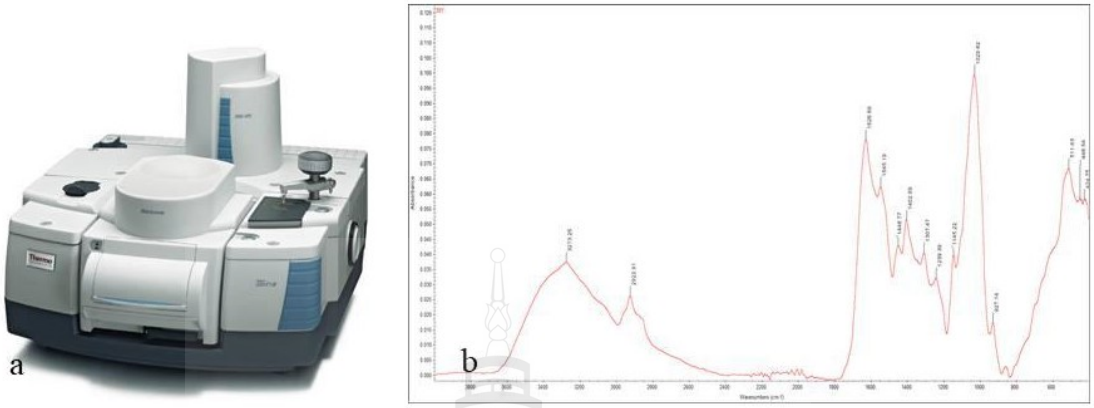


Figure 5.118 Flexural strength test of mycelium-based biomaterial

5.3.2.23 Fourier transform infrared spectroscopy Fig. 5.119

Fourier Transform Infrared Spectroscopy (FTIR) is an analytical technique used to obtain the infrared (IR) spectrum of absorption or emission of solid, liquid, or gas samples (Smith, 2011). FTIR analysis is typically performed using Attenuated Reflectance Spectroscopy (ATR) and Transmission spectroscopy. In the ATR method, IR radiation enters a crystal material at a 45° incident angle and interacts between the crystal and the sample. The radiation penetrates the sample to a depth of approximately one micrometre, where some is absorbed while the remaining radiation is reflected to a detector. In the transmission method, IR radiation passes directly through the sample, where a specific frequency of light is absorbed, and the unabsorbed radiation continues through the sample to a detector. In mushroom mycelium-based biomaterials, FTIR is used to analyse the mycelial chemical composition by scanning over a spectral range of 4000−400 cm^{-1} at a resolution of 1 cm^{-1} (Raman et al., 2022). The resulting FTIR spectra primarily reveal key functional groups, such as hydroxyl stretches, lipids, proteins, and polysaccharides.



Note a FTIR machine (Thermo Scientific Nicolet iS50 Ft-IR). b FTIR spectra.

Figure 5.119 FTIR spectroscopy

5.3.2.24 Genome editing

Genome editing, also known as gene editing, refers to a set of techniques used to modify the DNA of living organisms. These techniques enable the addition, deletion, or alteration of specific genes within a chromosome. One of the most popular tools is clustered regularly interspaced short palindromic repeats associated system 9 (CRISPR-Cas9), which has applications across food, agriculture, and biotechnology (Eş et al., 2019). In fungi, genome editing has been used in the development of mushroom mycelium-based biomaterials (MMBs). These biomaterials, valued for their sustainability and biodegradability, can now be enhanced at the genetic level to improve their physical and functional properties (Madusanka et al., 2024; Salichanh et al., 2025). Additionally, engineering *Ganoderma* species to express the β-1, 3-glucan synthases (BGS1 and BGS2) in *Ganoderma* led to a remarkable 135–165% increase in β-glucan, which is a key structural component of fungal cell walls (Vandelook et al., 2021; Madusanka et al., 2024; Salichanh et al., 2025). Furthermore, the deletion of the SC3 gene in *Schizophyllum commune* resulted in a significant increase in mycelium density, Young's modulus, and tensile strength compared to the wild type (Whabi et al., 2024). These genetic enhancements address some of the mechanical limitations traditionally associated with MMBs. Thus, genome editing continues to unlock new possibilities in fungal

biotechnology, paving the way for stronger, more functional, and more sustainable biomaterials.

5.3.2.25 Impact strength

The impact strength (IS) test is a method used to determine the impact resistance of materials. Impact strength refers to the ability of a material to withstand or resist sudden applied loads without breaking. During testing, samples are loaded in a testing machine and subjected to a known mass and length pendulum until fracture occurs. With this, the energy absorbed by a sample before breaking is measured. The two standard methods of IS testing are the Charpy and Izod impact methods. The IS test for mushroom mycelium-based biomaterials follows standardised protocols, such as ASTM D-256 for the Izod test method (Aiduang et al., 2022c). The IS value is essential in assessing the suitability of MMBs for applications such as packaging and construction. Impact strength is calculated using the formula;

$$IS = \frac{K}{A}$$

where,

IS = Impact strength (kJ/m^2), K = Energy required to fracture the sample (kJ), and A = Cross-sectional area (m^2)

5.3.2.26 Lignocellulosic substrate Fig. 5.120

Lignocellulosic substrates are plant-based materials primarily composed of cellulose, hemicellulose, and lignin. These materials are mainly sourced from agricultural residues and forest woody byproducts, such as sawdust, rice husk, rice straw, hemp fibre, sugarcane bagasse, corn stalks, corn husks, wheat straw, coffee residue, and sorghum stalks. After harvest, these residues become waste, contributing to environmental pollution. An innovative concept to mitigate this issue is to utilise them as input substrates to develop mushroom mycelium-based biomaterials (MMBs).

The selection of substrates is based on availability, nutritional content, degradability, cost, structural properties, and compatibility with mycelium (Etinosa, 2019; Alemu et al., 2022b). Nutrient supplements, such as rice bran, molasses, and yeast extract, are incorporated to improve fungal growth conditions. Additionally, lime

($CaCO_3$) and gypsum ($CaSO_4 \cdot 2H_2O$) regulate the pH, creating an optimal environment for mycelial growth. Mycelium breaks down cellulose into glucose, with cellulose-rich substrates providing robust MMBs. Substrate selection critically affects the physical and mechanical properties of the mycelium (Raman et al., 2022). The natural fibre within the substrate contributes to reinforcement, reducing shear failure risks in the final product (Yang et al., 2017a; Elsacker et al., 2020). Using the fibre-enriched substrates enhances the compression strength (570 kPa) and elastic modulus (60 MPa) of MMBs (Yang et al., 2017a).

Note a Sawdust. b Rice husk. c Rice straw. d Coconut coirs

Figure 5.120 Lignocellulosic substrates

5.3.2.27 Load-bearing capacity

Load-bearing capacity is defined as the maximum load a material can bear without failure. It is particularly related to the strength of the materials used in building and mechanical components, ensuring their safety and stability. It is influenced by key factors: density, strength, elasticity, shape, size, and environmental conditions. Mushroom mycelium-based biomaterials (MMB) are sustainable and biodegradable materials that have been increasingly utilised in several fields, including construction, textiles, packaging, and architectural works (Khyaju & Luangharn, 2024). MMBs are popular, innovative, and eco-friendly materials that fulfil material properties and are being utilised to overcome the issues inherent in plastic and foam-based products (Abhijith et al., 2018; Fairus et al., 2022). Previous studies have reported MMB properties as: density (25–954 kg/m^3), compressive strength (0.03–4.44 MPa), tensile strength (0.01–1.55 MPa), and flexural strength (0.05–4.40 MPa) (Aiduang et al., 2022b). MMB fulfils some of the properties of foam, plastic, and wood-based materials. Porter et

al. (2023) recommended mushrooms with trimitic hyphal structure for higher mechanical strength over mushrooms with monomitic or dimitic hyphal systems. However, for the construction of large structures, it holds limitations and requires reinforcement systems (Dessi-Olive, 2019; Özdemir et al., 2022). Research on improving the overall properties of MMB is increasing mainly through substrate selection, species exploration, and method improvement.

5.3.2.28 Moisture content

Moisture content refers to the amount of water present within a substance. Water content is an important factor in the development of mushroom mycelium-based biomaterial (MMBs), mainly in preparing cultures, spawn, and mycelium-substrate mixture. It provides turgor pressure to the hyphal tips, facilitating better penetration into substrates and promoting the elongation and extension of mycelia (Arijit et al., 2013; Nashiruddin et al., 2022). The ideal moisture content in the substrate ranges between 60–75%, and below 40% can result in slow and wispy mycelial growth (Stamets, 2011). In contrast, excessive moisture content can lead to oxygen deficiency and nutrient leaching (Nashiruddin et al., 2022). Additionally, excessive moisture content increases the risk of disease development (Ryu et al., 2015). Insufficient or excessive moisture in the substrates can cause poor mycelium growth and lead to failure in cultivation.

The moisture content in a material is measured using the oven drying method or a moisture analyser. It is calculated following ISO 16979:2003 using the formula below:

$$MC\ (\%) = \frac{Ww - Wd}{Wd} \times 100\%$$

where,

MC = moisture content (%), W_w = wet weight (g), W_d = oven dry weight (g)

5.3.2.29 Moulding Fig. 5.121

Moulding refers to the technique of shaping materials by placing them into hollow containers, known as moulds or formworks. In mushroom mycelium-based biomaterial (MMBs), this process involves breaking down a fully-grown mycelium-substrate mixture into fine particles under sterile conditions. Aseptic conditions are

maintained by 70% ethanol (Attias et al., 2019). The mycelium-substrate mix particles are then transferred into moulds, where the mycelium grows and binds the substrate into a cohesive form (Abhijith et al., 2018). Plastic moulds are commonly preferred due to their ease of handling, durability, and ability to provide a wide range of shapes and sizes (Attias et al., 2019). During mycelial growth, the mycelial network interconnects substrate particles in multiple dimensions, forming a solid structure as per the design of the mould (Manan et al., 2021). After a few days to weeks, they are unmoulded, and the material is allowed further mycelial growth on the surface of the material attached to the walls of moulds.

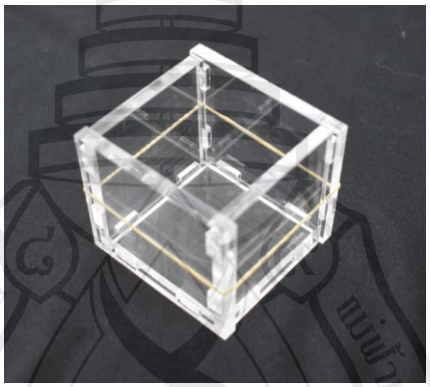


Figure 5.121 Acrylic cube mould used for test sample preparation

5.3.2.30 Mushroom mycelium Fig. 5.122

Mycelium is the vegetative part of mushrooms, consisting of a mass of branching, thread-like, hollow, and tubular hyphae (Alemu et al., 2022a). It plays a vital role in decomposing organic matter through enzymatic activity and absorbing nutrients from the substrate to support fungal growth and development. The innovative utilisation of mycelium in the creation of eco-friendly and biodegradable materials includes mushroom mycelium-based biomaterial (MMBs). In MMBs development, mycelium colonises a lignocellulosic (sawdust), forming a dense hyphal network that binds the particles of the substrate mixture. Once colonisation is complete, the material is dried or heated at high temperatures to stop further mycelium growth and enhance its mechanical strength (Khyaju & Luangharn, 2024). In addition to MMBs, pure mycelium mats or

mycelium leather can be produced by cultivating mycelium growth in liquid or solid media until the desired thickness and density are achieved, offering versatile applications in sustainable textiles and design.

Figure 5.122 Mushroom mycelium in agar media

5.3.2.31 Mushroom mycelium inoculation Fig. 5.123

Mushroom mycelium inoculation refers to the addition of mycelium, a vegetative part of a fungus, into a substrate, where it can grow and eventually produce basidiomata or fruiting bodies. The suitable substrates are autoclaved to eliminate alien fungi or bacteria. Pure culture is prepared by isolating (spore or tissue) from basidiomata and sub-culturing them, which is then inoculated into the substrates in the form of liquid or solid spawn. This process is done in sterile conditions, such as under laminar flow. The increased inoculation rate accelerates mycelial growth, reduces contamination, and significantly increases the yield (Stamets, 2011). In the development process of mushroom mycelium-based biomaterials, liquid culture or grain spawn is introduced into the substrate and allowed to grow until full maturity, and then the mycelium-substrate mix is broken down and transferred into predesigned moulds (Khyaju & Luangharn, 2024).

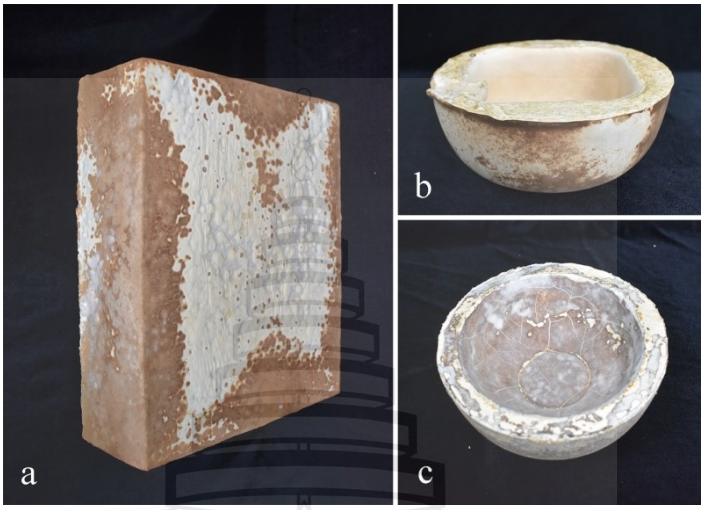
Figure 5.123 Sawdust cultivation bag after mycelial inoculation

5.3.2.32 Mushroom mycelium-based biomaterials Fig. 5.124

Mushroom mycelium-based biomaterials (MMBs), or mycelium-based bio-composites, are innovative, sustainable, eco-friendly, and biodegradable alternatives to plastics and synthetic products. It is developed from the combination of mushroom mycelium and lignocellulosic substrates. Among the mushrooms, species of *Ganoderma* P. Karst., *Trametes* Fr., and *Pleurotus* (Fr.) P. Kumm. are most widely utilised in the development of biomaterials (Aiduang et al., 2022c). Mycelium acts as a binder, holding substrates together under suitable conditions of temperature, moisture, and pH. Agricultural and forest byproducts are the main lignocellulosic substrates for biomaterial development.

The substrates are enriched with nutrient supplements, including rice bran, molasses, lime, and gypsum. The mixture is autoclaved, then inoculated with mycelium spawn. The mycelium of the species is isolated and sub-cultured to develop a pure culture (Aiduang et al., 2022c). Once the mycelium fully colonises the substrate and before pinning begins, it is dehydrated and treated to produce the final MMBs, which are applied

in packaging, construction, architectural designs, textiles, and insulation (Khyaju & Luangharn, 2024). Several leading companies, including Ecovative Design, Mycoworks Inc., and Mogu, are commercially producing MMBs.



Note a Construction block. b–c Container bowls

Figure 5.124 Mushroom mycelium-based biomaterials

5.3.2.33 Mushroom spawn Fig. 5.125

Spawn functions as a seed for transferring mycelium to a substrate for growing mushrooms. Spawns are typically prepared in the liquid, grain, or sawdust form for cultivating edible and medicinal mushrooms, such as *Agaricus bisporus*, *Lentinula edodes*, and *Pleurotus ostreatus*. The substrate is sterilised to kill the unwanted fungi and bacteria. A pure culture or mycelium, generally prepared in potato dextrose agar (PDA) media, is then inoculated into the sterilised substrates. The inoculated substrate is incubated for mycelial growth at room temperature (25–30ºC) in the dark. During this process, the fungal hyphae develop an interconnected network that binds the discrete particles (Cerimi et al., 2019).

Spawn inoculation percentage significantly influences the duration of colonisation and the timing of fruiting (Stamets, 2011). A higher inoculum proportion accelerates mycelium growth, thereby minimising the growth of fungal contaminants. Sydor et al. (2022) have recommended using the optimum inoculum density of spawn to

substrate to minimise the lag phase. It reduces overall mushroom cultivation time and production cost. In mushroom mycelium-based biomaterials, preparing spawn is a fundamental and critical step before preparing the mycelium-substrate mixture and the products.

Figure 5.125 Grain (sorghum) spawn of a mushroom

5.3.2.34 Mycelium anastomosis Fig. 5.126

Anastomosis refers to the random connection between two or more tubular or hollow structures within the same fungal species or between genetically similar species. In mushroom mycelium, the fusion of compatible hyphae results in a dense, fibrous vegetative structure known as mycelium (Islam et al., 2017; Patel & Sharma, 2023). This hyphae fusion enhances nutrient distribution and allows signal exchange across the network. This phenomenon enabled fungal-based applications, including pure mycelium leather, packaging, tissue engineering, and innovations in fashion and designs (Patel & Sharma, 2023). Additionally, the anastomosis technique has been utilised to develop new isolates or to improve the genetics of commercially cultivated edible mushroom species such as *Pleurotus florida* and *P. pulmonarius* (Samota & Sharma, 2008; Adebayo et al., 2013; Farimani & Farsi, 2023). During the production of mushroom mycelium-based biomaterial, anastomosis plays a key role in filling gaps between substrates and enhancing structural cohesion. This contributes to the formation of compact materials with improved physical strength, mechanical integrity, and durability (Patel & Sharma, 2023; Ruggeri et al., 2023).

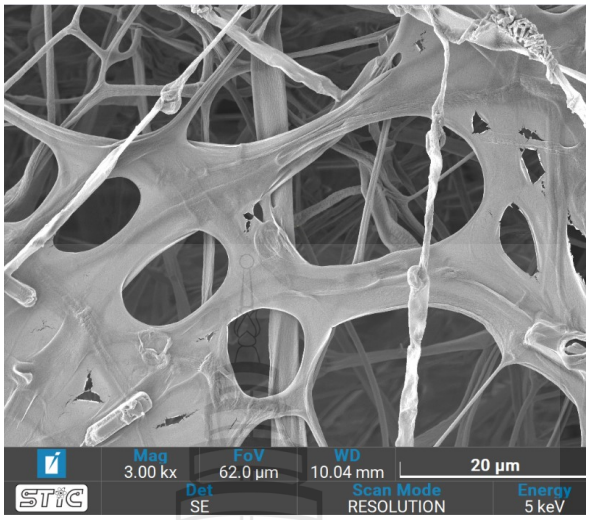


Figure 5.126 A representative SEM image of mycelium anastomosis of *Pleurotus ostreatus*

5.3.2.35 Mycelium biocompatibility

Mycelium biocompatibility refers to the response of mycelium to direct interaction with human skin, as assessed using dermal fibroblasts (Antinori et al., 2021). Mycelium, the vegetative part of fungi, is a self-growing, biodegradable, and cost-effective material. The mycelial application in biomedical engineering is an innovative technique that can mimic the extracellular matrix (ECM) of human tissues (Antinori et al., 2021). The function of the extracellular matrix is to provide physical support, communication pathways, and 3D organisation to the tissues (Frantz et al., 2010; Antinori et al., 2021). Mycelium secretes bioactive polysaccharides, such as chitin derivatives, which affect the growth of fibroblasts and keratinocytes (Antinori et al., 2021). Antinori et al. (2021) utilised edible and medicinal mushroom species, *Pleurotus ostreatus* and *Ganoderma lucidum*, in growing a self-growing mycelium mat. Using the standard test ISO10993-5, the cytotoxicity effect of mycelium extract was assessed on primary human dermal fibroblast cells (Kossyvaki et al., 2020; Antinori et al., 2021). Ruggeri et al. (2023) conducted in-vitro characterisation of these two mushrooms for tissue engineering and reported them as biocompatible, safe, and effective enhancers in repairing tissue.

5.3.2.36 Mycelium colonisation Fig. 5.127

Mycelium colonisation is a natural process in which mycelium colonises a substrate after inoculation. During mycelial growth, its hyphae break down complex organic materials into simpler compounds, which can be absorbed through the mycelial walls. Mycelium expands with a dense network of hyphae and spreads throughout the substrates. In artificial mushroom cultivation, this process occurs in two stages: during spawn preparation and after inoculation into substrates. Optimal conditions for mycelial growth include a suitable temperature (20–30°C), moisture content (55–65%), proper ventilation, and dark conditions. To develop mushroom mycelium-based biomaterials (MMBs), mushroom species with fast-growing, vigorous mycelium are preferred to reduce production time and costs. The mushroom hypha acts as a binding agent, integrating individual substrate particles to form a composite material that serves as the basis for MBB development (Jiang et al., 2016; Abhijith et al., 2018; Khyaju & Luangharn, 2024).

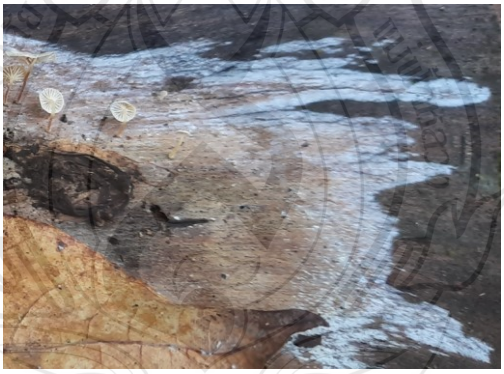


Figure 5.127 Mycelium colonisation by a mushroom species

5.3.2.37 Mycelium fermentation Fig. 5.128

Mycelium fermentation refers to the biotechnological process in which fungal mycelium breaks down and transforms organic substrates through metabolic activities under anaerobic conditions. There are four primary fermentation methods: liquid-state surface fermentation (LSSF), solid-state surface fermentation (SSSF), liquid-state

submerged fermentation (LSF), and blended spawn-based fermentation (Singh et al., 2025).

In liquid-state surface fermentation, mycelium grows across the surface of a liquid medium, forming a cohesive mat at the air-liquid interface (Vandelook et al., 2021; Salichanh et al., 2025). Once matured, the mycelium mats are harvested, rinsed with RO (reverse osmosis) water to remove residual broth, and dried at 60°C for 48 hours or until dried weight becomes stable (Kniep et al., 2024). In solid-state surface fermentation, mycelium colonises and forms a thick layer over solid substrates under carefully controlled environmental parameters, typically at 25–30°C, 40–99% relative humidity, and 50,000–70,000 ppm carbon dioxide (Vandelook et al., 2021; Salichanh et al., 2025).

Liquid-state fermentation (LSF), also known as submerged fermentation, involves cultivating mycelium in nutrient-rich liquid media (e.g., potato dextrose broth, yeast malt dextrose broth, and blackstrap molasses), resulting in slurry or pelletized biomass (Singh et al., 2025). Solid-state fermentation (SSF) is used to develop mushroom mycelium-based biomaterials (MMBs). In this method, lignocellulosic substrates such as agricultural waste are colonised by fungal mycelium, which binds the individual together into composite materials. SSF offers numerous advantages, including increased productivity, less energy and water consumption, lower contamination risk, and minimum water wastage (Singh et al., 2025).

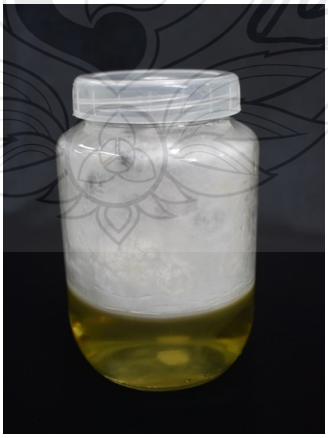


Figure 5.128 A representative image of liquid-state surface fermentation using mycelium of *Phlebiopsis friesii* in potato dextrose broth

5.3.2.38 Mycelium growth kinetics

Mycelium growth kinetics refers to the temporal dynamics of mycelial growth, quantified by parameters such as mycelial growth rate, substrate type, mycelial biomass production, and metabolite production. Mycelium growth comprises four stages: the lag phase, the exponential (log) phase, the stationary phase, and the decline or death phase. During the lag phase, there is no visible mycelial growth, but metabolic activity begins. Pollack et al. (2008) reported a finite lag time in starved mycelium; during this period, vacuolar degradation produces sufficient endogenous carbon to support survival and the restart of hyphal extension. This phase can be observed during substrate bag preparation, where the amount of inoculated spawn has a direct relationship with mycelial growth; the optimal amount of spawn inoculation mitigates the lag phase. The exponential phase exhibits rapid hyphal elongation and branching, and the highest growth rate. The mycelial growth rate is affected by several environmental factors, including substrate type, temperature, moisture, and pH (Zervakis et al., 2001). For example, the mycelium of *Phlebiopsis friesii* (Lév.) Spirin & Miettinen exhibited the fastest growth rate in corn meal agar, followed by yeast malt agar, and the least in oat meal agar (Khyaju et al., 2025). Similarly, in the substrate bag, the supplements boost the vigorous mycelial growth. With a decline in nutrients, mycelial growth becomes stationary. At the decline stage, mycelium starves as nutrients are depleted. In the development of mushroom mycelium-based biomaterials, mushrooms with fast mycelial growth rates and vigour are suitable for efficient production (Alemu et al., 2022a; Khyaju & Luangharn, 2024). Additionally, the breakdown of the mycelium-substrate mix during mould fabrication triggers mycelial branching.

5.3.2.39 Mycelium living architecture

Mycelium living architecture is an innovative approach that utilises mushroom mycelium as a structural and living building material. Mycelium is the vegetative part of fungi, composed of filamentous hyphae, and works as a natural binding agent (Khyaju & Luangharn, 2024). The versatile mycelium is allowed to grow on lignocellulosic substrates (such as sawdust, rice straw, corn stalk, cotton fibres, hemp

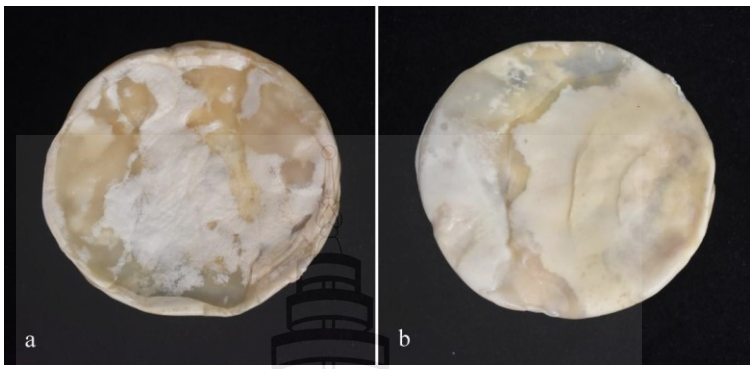
fibres, and coconut coir) and form a rigid composite, provided with a predesigned frame or mould. Several fungal genera utilised in this purpose include mainly *Ganoderma* P. Karst., *Trametes* Fr., and *Pleurotus* (Fr.) P. Kumm. (Aiduang et al., 2022c; Khyaju & Luangharn, 2024). The final material is composed of living mycelium, unlike traditional materials used in architecture. The individual blocks or materials are then joined to form a structure. Interestingly, the biomaterials are biodegradable materials and can be composted, thereby leaving no pollutants.

The concept of utilising mushroom mycelium-based biomaterial (MMB) in design and architectural works addresses environmental pollution, a critical concern associated with plastic and foam-based materials (Oral et al., 2022; Khyaju & Luangharn, 2024). The concept is successful as several projects have been built and exhibited using MMB, including the Growing pavilion, Hy-fi tower, Mycotree pavilion, Shell mycelium, Mycotectural alpha, My-co space, and EI Monolito (Almpani-Lekha et al., 2021; Modanloo et al., 2021; Khyaju & Luangharn, 2024). Currently, several fungal genera, substrates, and growth conditions are being investigated to produce superior-quality materials for MMB production. This indicates the expansion of MMBs in the construction and architectural design sectors due to their eco-friendly and sustainable aspects.

5.3.2.40 Mycelium-based leather Fig. 5.129

Mushroom mycelium-based leather (MML), also known as mycelium leather, is a sustainable, eco-friendly, and biodegradable alternative to animal or synthetic leather (Vandelook et al., 2021; Raman et al., 2022). It is produced by cultivating mycelium in lignocellulosic agricultural byproducts or synthetic nutrient media (Cartabia et al., 2021b). MML can be manufactured in a relatively small space and within a short time frame (weeks to months), emitting significantly fewer greenhouse gases than animal-based leather. Its production does not involve animal slaughter and requires fewer chemicals than conventional animal-based leather processing. Several commercial companies, such as Bolt Threads, MycoWorks, and Ecovative, are developing MML on an industrial scale. This innovative material has been applied in the fashion industry,

biomedical scaffolds, textiles, and electronic components (Khamrai et al., 2018; Vasquez & Vega, 2019a; Antinori et al., 2021; Gandia et al., 2021; Danninger et al., 2022).



Note a Top view. b Bottom view.

Figure 5.129 Representative mushroom mycelium-based leather

5.3.2.41 Porosity Fig. 5.130

Porosity is the percentage of voids within a material, expressed as the ratio of void volume to the total volume in a material. It is an important parameter in the hydrodynamic characterisation of a material. The porosity of mushroom mycelium-based biomaterials (MMBs) depends on several factors, such as fungal species, growth conditions, substrate type, and post-harvest treatments. In MMBs, porosity is estimated using scanning electron microscopy images by calculating the total pore area (Oliveira et al., 2023). Mercury intrusion porosimetry (MIP) is another technique used with pressure at 0.0136 MPa and increased up to 200 MPa at the rate of 6–14 MPa min^{-1} (Antinori et al., 2020).

The porosity of MMBs plays a significant role in determining material properties, including density, mechanical strength, water absorption, and sound absorption. This information provides guidance in the selection of MMBs for specific applications, including packaging, insulation, filtration, and biomedical uses. High porosity is directly correlated to increased water absorption capacity, while it is inversely related to material density and mechanical strength (Antinori et al., 2020). For instance, heat or cold pressing of harvested MMBs results in denser materials with low porosity

(Manan et al., 2021). Notably, porous materials are also valuable in biomedical applications, such as drug delivery and tissue engineering (Antinori et al., 2020).

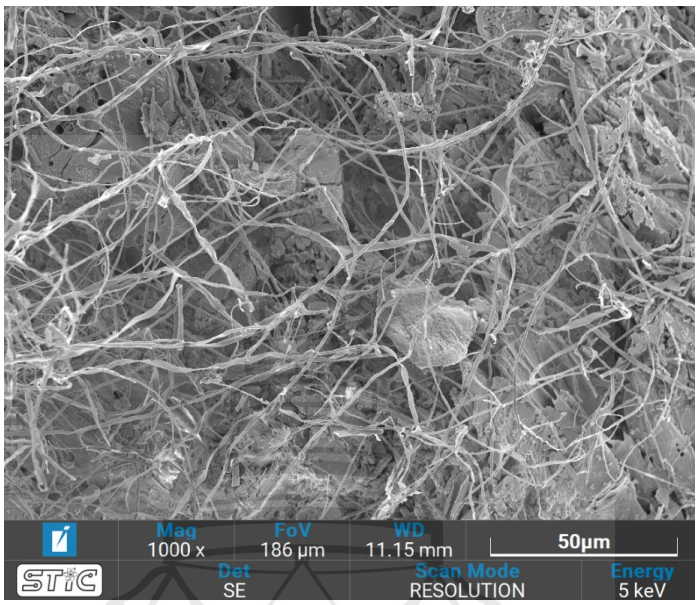


Figure 5.130 A representative SEM image of MMB developed from the mycelium of *Ganoderma tropicum* and sawdust, showing porous properties

5.3.2.42 Renewable materials

The term “renewable” refers to the resources that never end due to their replenishing nature, such as wood, wool, and solar energy. Mycelium, one among them, is a renewable root-like filamentous vegetative structure derived from mushrooms. It grows on a wide range of substrates and acts as a saprobe, pathogen, or ectomycorrhizal. Mycelium is the key component in mushroom mycelium-based biomaterial (MMBs) development that binds discrete substrates, especially lignocellulosic byproducts, to form a rigid composite (Fairus et al., 2022). Some commonly used renewable substrates in MMB are sawdust, coconut coir, hemp fibre, rice straw, corn stalk, and coffee wastes. MMB is an innovative and popular material due to its renewable, biodegradable, and environmentally safe characteristics (Khyaju & Luangharn, 2024). MMB materials align with the principles of the circular economy and are biodegradable, which can be composted, ultimately serving as fertilisers to plants. Additionally, they are low-cost and

low-energy-requiring materials that can be an alternative to the synthetic, non-renewable, and polluting petroleum-based plastic materials (Jiang et al., 2017; Fairus et al., 2022). Recently, these materials have been produced at an industrial scale and have a wide range of applications, including packaging, construction, leather, insulation, and architectural designs (Khyaju & Luangharn, 2024).

5.3.2.43 Saprophytic mushroom Fig. 5.131

Saprophytic mushrooms, or saprobes, are fungi that thrive on dead or decaying organic materials such as fallen trees, straws, sawdust, and leaf litter. Some popular saprobic mushroom genera are *Agaricus*, *Auricularia*, *Coprinus*, *Fomes*, *Ganoderma*, *Lentinus*, *Lentinula*, *Mycena*, *Panus*, *Pleurotus*, *Schizophyllum*, and *Trametes*. These fungi release enzymes that break down complex organic materials, primarily lignin, cellulose, or hemicellulose, into a simple soluble form that can be absorbed (Raman et al., 2022). These mushrooms play a significant role in maintaining ecological balance and supporting nutrient cycling, especially for key elements like nitrogen and carbon. In the natural habitat, these mushrooms exist in a vegetative form known as mycelium, producing a reproductive form as basidiomata (Raman et al., 2022). In developing mushroom mycelium-based biomaterial (MMBs), only saprophytic mushrooms are utilised due to their capacity to grow under artificial conditions (Sydor et al., 2022). Among the various saprophytic species, *Ganoderma*, *Trametes*, and *Pleurotus* are most commonly used in MMBs production (Khyaju & Luangharn, 2024). Additionally, pure mycelium leather has been successfully produced by cultivating saprophytic mushroom mycelium in nutrient broths, paste, or solid substrates, providing optimal environmental conditions (Amobonye et al., 2023).

Figure 5.131 *Trametes polyzona*, a saprophytic mushroom, growing on a dead tree stump

5.3.2.44 Scaling up

Scaling up refers to capacity expansion in any field, such as research, technology, and business. Currently, the research and development of mushroom mycelium-based biomaterials (MMBs) are in their early stages, with a limited number of products being commercially produced (Bitting et al., 2022). This slow progress might be attributed to their relatively low mechanical properties, the absence of standard production methods, and insufficient characterisation (Bitting et al., 2022). However, the MMBs have been applied in several fields, including packaging, construction, architectural design, insulation, and textiles (Khyaju & Luangharn, 2024). MMBs are sustainable, eco-friendly, and biodegradable materials that align with the principles of the circular economy. The awareness of people about environmentally safer materials is increasing steadily. Consequently, the demand for MMBs, as alternatives to expanded polystyrene (EPS) and foam products, is growing (Almpani-Lekka et al., 2021; Dessi-Olive, 2022a). Several companies, including Ecovative, Mycoworks, Mycotech, Bolt Threads, Adidas, Hermes, Lululemon, and Stella McCartney, have already introduced MMB products to the market (Vandelook et al., 2021). Notably, significant research is needed to adapt MMB production technologies for industrial use.

5.3.2.45 Scanning electron microscopy Fig. 5.132

Scanning Electron Microscopy (SEM) is a highly effective imaging technique used to study the surface topography and composition of materials at high resolution, with a range of 1 μm to 1 nm (Vernon-Parry, 2000). SEM is a popular tool used across several fields, such as material science, biology, and geology. The first SEM was developed based on the work of two physicians, Ruska and Knoll. In 1937, a high-resolution SEM was invented by Manfred von Ardenne (von Ardenne, 1939; Mohammed & Abdullah, 2018). SEM produces detailed images of a sample by scanning its surface with a focused electron beam of energy 2–40 keV (Vernon-Parry, 2000). The electrons interact with atoms in the samples, producing various signals related to the topography of the sample surface. Currently, three types of SEM are popular: conventional SEM, environmental SEM, and low vacuum SEM (Mohammed & Abdullah, 2018). The key components of SEM are an electron gun, a column, a deflection system with scan coils, detectors for backscattered and secondary electrons, a sample chamber, and a computer system to control the instrument and observe scanned images (Mohammed & Abdullah, 2018).

In the study of mushroom mycelium-based biomaterials (MMBs), a small sample piece is cut and mounted onto a stub adapter using double-sided carbon tape, and coated with gold for 2 min under high vacuum mode (Aiduang et al., 2022c). The sample is then photographed using an SEM microscope at an accelerating voltage of 5 kV to analyse the arrangements of hyphae, voids, and substrate on the sample.

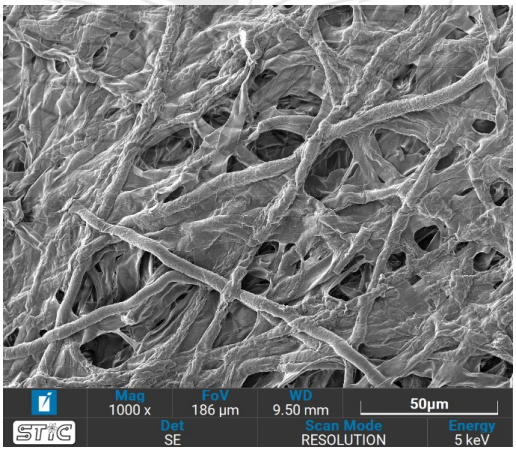


Figure 5.132 Scanning Electron Microscopy image of a pure mycelium mat

5.3.2.46 Soil enrichment Fig. 5.133

Soil enrichment is defined as the process of enhancing soil quality by adjusting soil fertility, pH, organic content, and beneficial microorganism composition. In the mushroom mycelium-based biomaterials (MMB) sector, the end product, such as packaging materials, after utilisation, can be broken down and composted. MMBs represent highly biodegradable alternatives to plastic and foam-based materials (Aiduang et al., 2022b; Fairus et al., 2022; Khyaju & Luangharn, 2024). Compost works as a fertiliser or soil supplement to improve soil porosity, organic matter, and nutrient content. The final MMB products are in a partially fermented state, where the complex components continue the decomposition phase (Ghazvinian & Gursoy, 2022a). Upon incorporation into soil, these materials interact with soil microorganisms to enhance the soil porosity. Also, they are rich in nutrients, providing beneficial materials for plants. Previous studies have reported nitrogen content and pH of the final MMB as 0.5–1.6% and 4.3–6.5, respectively (Aiduang et al., 2022b). Aiduang et al. (2022b) reported the water absorption potential of final MMB as 24.45–560%. This potentiality has a positive impact on the retention of moisture in the soil, thereby favouring the rhizosphere environment.

Figure 5.133 Biodegradation process of MMBs into soil enrichment supplements

5.3.2.47 Sterilisation Fig. 5.134

Sterilisation refers to the process of removing or killing microorganisms (fungi, bacteria, and viruses) from materials or media. Disinfection of a material can be done by several methods, such as using moist heat sterilisation (autoclaving), dry heat sterilisation (hot air oven), chemical sterilisation, and irradiation sterilisation (UV)

(Harrington et al., 2020). However, the sterilisation technique can influence the intrinsic properties of materials such as 3D printing inks (Shyam & Palaniappan, 2023). Effectiveness of sterilisation is affected by several factors, including material cleanliness, nature and extent of initial bio-burden, design of device, material chemical reactivity, and internal porosity (Harrington et al., 2020).

In mushroom mycelium-based biomaterials (MMBs), the absence of microorganisms, from mycelium culture to final product, allows successful development of biomaterials. Sterile conditions are a fundamental requirement in mycelium culture, spawn, mycelium inoculated bags, mould fabrication, and final mycelium growth. For example, PDA media is sterilised at 121°C for 15 min in an autoclave. Sorghum grains for spawn are sterilised by autoclaving at 121°C for 30 min before mycelium inoculation. Lignocellulosic substrates (sawdust, rice straw, corn stalk, and hemp fibre) are autoclaved at 121°C for 60 min before inoculation of mycelium.

Figure 5.134 An autoclaving machine used to sterilise substrate bags in mushroom cultivation

5.3.2.48 Sustainability

The concept of “sustainability” was first introduced by a German forester, Hans Carl von Carlowitz, in 1712 in his work *Sylvicultura Oeconomica*, where he outlined methods for managing forests to ensure their long-term viability (Scoones, 2007). This concept focuses on the importance of collective efforts to conserve natural resources for future generations while balancing developmental activities. The World Commission on Environment and Development (WCED, 1987) later defined sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. Sustainable materials generate minimal pollution and waste throughout their lifecycle, including production, use, transportation, and disposal (Alemu et al., 2022a).

Plastics, traditionally derived from non-renewable petroleum-based resources, are widely used but pose significant environmental challenges due to their non-degradable nature and persistent pollution. Numerous initiatives have been introduced at both national and international levels to address this issue. Mushroom mycelium-based biomaterials (MMBs) have emerged as a promising alternative. These materials are eco-friendly, biodegradable, cost-effective, and energy-efficient, aligning with the principles of the circular economy (Jones et al., 2020; Alemu et al., 2022a). Mycelium, the root-like structure of fungi, can be cultivated on a large scale in the laboratory and used as inoculum in agricultural and forest-based substrates. The MMBs have been developed for diverse applications, including packaging, construction, insulation, textiles, and architectural designs, offering a sustainable alternative to conventional plastics.

5.3.2.49 Tensile strength Fig. 5.135

Tensile strength (TS) is a mechanical property that measures the maximum stress a material can withstand while being stretched before failure. In testing, standard samples are clamped within a universal testing machine (UTM) and subjected to uniaxial tension at a controlled strain rate. The resulting stress-strain relationship is plotted as a graph. These results provide information on structural integrity, elastic behaviour, and suitability for application. It is important to confirm the results to meet international

standards such as the International Organization for Standardisation (ISO) and the American Society for Testing and Materials (ASTM) standards. For mushroom mycelium-based biomaterials (MMBs), TS evaluation is determined by an established standard protocol, such as ASTM D 638-14, with an elongation rate of 2 mm min^{-1} and a maximum load capacity of 1 kN under controlled temperature and humidity conditions (Appels et al., 2019). The main factors influencing TS in MMBs include mycelium strain, substrate composition, hyphal network density, and post-harvest processing treatments. Recent studies, such as Aiduang et al. (2022b), reported the TS values for MMBs ranging from 0.01 to 1.55 MPa.

Figure 5.135 Tensile strength testing of mushroom mycelium-based biomaterial

5.3.2.50 Thermal insulation

Thermal insulation refers to the process of reducing heat transfer between the environment and objects, thereby minimising energy consumption (Al-Qahtani et al., 2023). This technology is widely applied in buildings, clothing, vehicles, and electrical appliances to enhance energy efficiency. Conventional insulation materials, such as polystyrene foams, are commonly used due to their high insulating performance (Sulong et al., 2019; Tsao, 2020). However, upon disposal, it poses significant environmental and

health risks, including pollution and harming wildlife and humans. As a sustainable alternative, mushroom mycelium-based biomaterials (MMBs) have emerged as innovative, lightweight, porous, and eco-friendly materials that exhibit satisfactory thermal insulation properties (Elsacker et al., 2021; Alemu et al., 2022a; Al-Qahtani et al., 2023; Khyaju & Luangharn, 2024). MMBs exhibit a thermal conductivity ranging from 0.04–0.13 $W.m^{-1}.K^{-1}$, which is comparable to that of conventional foams with 0.03 0.04($W.m^{-1}.K^{-1}$) (Tsao, 2020). This inherent insulation capability makes MBBs suitable for various applications, particularly in the development of fire-retardant construction products, such as Greensulate (Abhijith et al., 2018).

5.3.2.51 Thermal pressingFig. 5.136

Thermal pressing is a fabrication technique conducted at room or elevated temperatures to produce dense, homogenised materials in desired shapes (Appels, 2020). This method is applied to various materials, including plastics, polymers, ceramics, metals, wood products, electronics, and composite materials. In mushroom mycelium-based biomaterials (MMBs), once the substrates are fully colonised by mycelium, they are harvested and dried to halt mycelial growth and remove moisture. The dried material is placed between heated plates or moulds and subjected to a hydraulic press at varying pressure and temperature conditions. For instance, this process is carried out at 150°C for 20 min under a pressure below 30 kN (Appels et al., 2019, 2020). The material can cool down under pressure to maintain the new shape. Hot-pressing MMBs increases their density and compressive strength by 2–3 times more than cold-pressing (Appels et al., 2019). It also improves mechanical properties such as tensile strength, flexural strength, stiffness, and elasticity (Appels, 2020; Shakir et al., 2020). Additionally, the heat-compressed materials develop a brownish appearance, which might be due to the Maillard reaction, caramelisation, and pyrolysis of organic material (Powrie et al., 1986; Appels et al., 2019). The final products are utilised in several fields, including packaging, insulation, and construction.

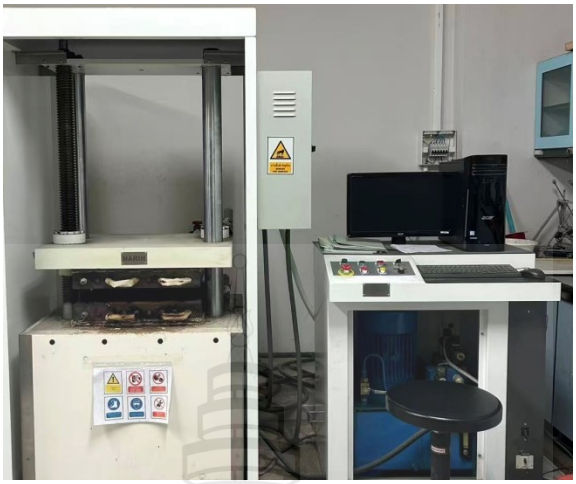


Figure 5.136 Thermal pressing machine set-up

5.3.2.52 Thermogravimetric analysis Fig. 5.137

Thermogravimetric analysis (TGA) is a technique to measure the mass change of a substance as it is exposed to controlled temperature and atmospheric conditions. It is an essential tool used to investigate thermal stability and compositional properties. When testing mushroom mycelium-based biomaterials (MMBs), a sample weighing 5–10 mg is heated from 25°C to 900°C at a scanning rate of 20°C min^{-1} with a nitrogen flow of 25 ml min^{-1} (Cartabia et al., 2021b). The resulting TGA curves reveal the distinct mass loss stages corresponding to its main components, such as chitin and beta-glucan content. Additionally, the first derivatives of these curves (DTGA) are used to identify the decomposition temperature of the peaks as well as the start and end of the decomposition process (Carbatia et al., 2021b).

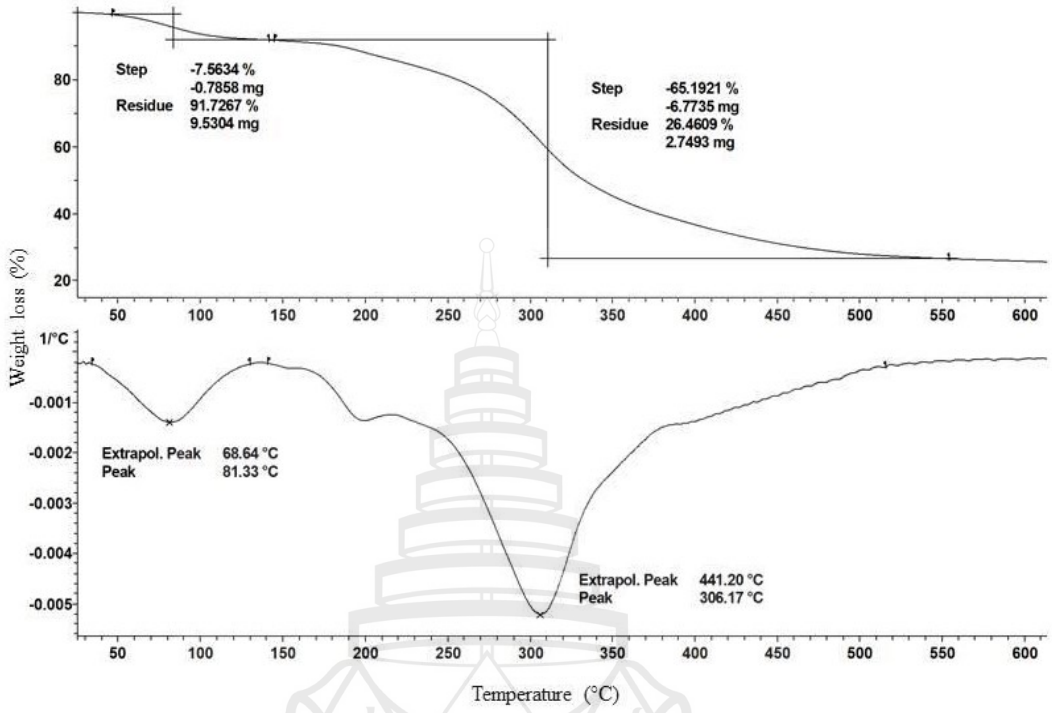


Figure 5.137 Thermogravimetric analyses (TGA and DTGA curves) of a mushroom mycelium-based biomaterial

5.3.2.53 Waste valorisation

Waste valorisation refers to the transformation of waste materials into valuable products for economic and environmental benefits. In the production of mushroom mycelium-based biomaterials (MMBs), a variety of agricultural, forestry, and industrial residues such as sawdust, straw, husks, and fibres are utilised as substrates. Conventionally, such lignocellulosic byproducts are incinerated or discarded, contributing to greenhouse gases, particularly carbon dioxide, and causing global environmental pollution (Peydayesh, 2024). These materials, which are rich in cellulose, hemicellulose, lignin, and chitin, serve as nutrients for the growth of mushroom mycelium (Aiduang et al., 2022a). MMBs have emerged as innovative and sustainable materials with diverse applications in packaging, architectural designs, building insulation, and textiles (Khyaju & Luangharn, 2024). In this approach, mushroom specimens harvested from the forest are isolated to prepare a pure culture, and

subsequently inoculated into the sterilised substrates. *Ganoderma*, *Pleurotus*, and *Trametes* are widely used mushroom genera (Khyaju & Luangharn, 2024). This approach to waste valorisation through MBBs follows the principles of the circular economy model, providing multiple benefits, including reducing lignocellulosic waste, promoting the utilisation of mushroom mycelium, reducing production cost, and developing economically valued products (Peydayesh, 2024).

5.3.2.54 Water absorption rate

Water absorption is defined as the movement of water into porous media without any external pressure. This test is performed by measuring the increment in the mass of a sample resulting from water absorption as a function of time when only one surface of the sample is exposed to water following ASTM C1585. It depends on the key factors, including surface energy, surface tension, capillarity, and material absorptivity (Nolan, 1997). The rate of water absorption is measured by applying the ASTM C1585–04 standard for Hydraulic-Cement Concretes to partially submerged samples of mycelium-based biomaterials. The tests are conducted at room temperature (25°C, RH = 50%). Mushroom mycelium-based biomaterials (MMB) are hygroscopic materials that exhibit higher water absorption capability, ranging from 24.45–560% (Jones et al., 2020; Aiduang et al., 2022b). The water absorption is affected by the density of MMB, with lower absorption in higher-density materials due to reduced voids or pores (Tacer-Caba et al., 2020; Aiduang et al., 2022b). Additionally, it is influenced by the cellulose component of the materials, which is composed of hydroxyl groups that characterise either hydrophobic or hydrophilic behaviour (Aiduang et al., 2022b).

For MMB samples, the water absorption is determined from the weight difference from the initial weight using the following formula;

$$m = \frac{M_t}{a \times d}$$

where,

m = water absorption (mm), M_t = changed weight of the sample (g), a = the exposed cross section area (mm^2), d = the density of the water (g/mm^3).

5.3.2.55 Water contact angle Fig. 5.138

The water contact angle (WCA) is a parameter to assess the wettability of solid surfaces by water (Antinori et al., 2021). It is defined as the angle between the tangent to a water droplet at the point of contact and the solid surface. A contact angle goniometer measures the WCA of test samples under static conditions at room temperature. During this process, a 5 µl droplet of de-ionised water is placed on the sample surface, and side-view images of the droplet are captured after 10 or 60 seconds. Surfaces with WCA less than 90º are classified as hydrophilic, those with a WCA greater than 90º as hydrophobic, and those exceeding 150º as super-hydrophobic. The hydrophobicity is related to specific proteins (hydrophobins and mannoproteins) in the outer cell wall of mycelium (Nussbaumer et al., 2023). Surface treatments or coatings, such as those applied to mushroom mycelium-based biomaterials using glycerol, tannic acid, or hot-pressed, can enhance the WCA and increase hydrophobicity. A higher WCA is generally desirable for materials, as it often correlates with a longer product shelf life. The relationship between the contact angle and surface energy is described by Young's equation as;

$$\gamma^{sv} = \gamma^{sl} + \gamma^{lv} Cos\theta$$

where,

γ^{sv} = surface tension of the solid-vapour interface

γ^{sl} = surface tension of the solid-liquid interface

γ^{lv} = surface tension of the liquid-vapour interface

θ = contact angle

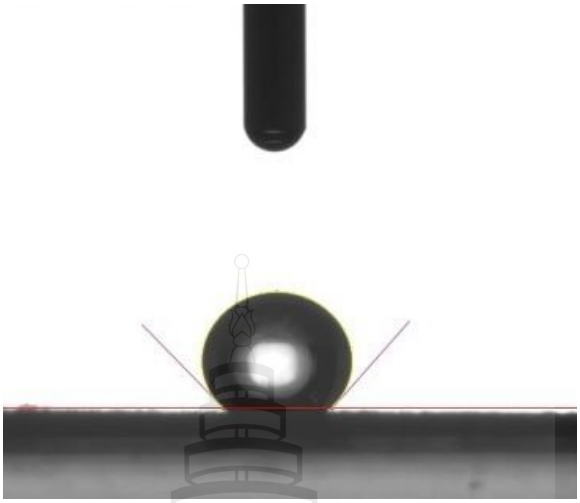


Figure 5.138 Water contact angle measurement of mushroom mycelium-based biomaterials

5.4 Significance of Fungalpedia in Mushroom Mycelium-Based Biomaterials

Scientific identification of fungal species is a crucial factor before their application in MMBs. The notes on the above-mentioned fungal genera provide important information for MMB work. Some key factors of fungal species that affects in MMB development are listed below (Sydor et al., 2022):

5.4.1 The hyphal system type has a significant effect on the mechanical and overall properties of the final MMB materials. Fungal species with trimitic or dimitic hyphal system types provide enhanced mechanical strength and other material properties, compared to monomitic.

5.4.2 Fungal species featured with medicinal properties are a top priority in MMB development, regarding safety to users from the end products. Additionally, the fungal species that are poisonous or toxic are screened out from being used in the MMB sector.

5.4.3 The white-rot decay fungi are preferred as they efficiently degrade lignin of plants, a property that is lacking in brown-rot fungi.

5.4.4 Saprophytic fungal species are suitable for culture preparation and growing in lignocellulosic substrates or byproducts, which is a fundamental step in MMB development.

The detailed note on terms is the first compilation related to MMBs, easing understanding and encouraging systematic research and development. Additionally, this study supports the selection criteria of fungal species in MMB research and development.

5.5 Limitations and Challenges in Fungalpedia

The preparation of Fungalpedia entries faced some major limitations and challenges, including the unavailability of published papers, limited information, illustration issues, taxonomic and nomenclatural changes, and uncertain placements.

5.5.1 Unavailability of published papers: The compilation of information on fungal taxa faced the unavailability of published articles due to their availability restricted to printed form or a lack of a digital copy. Additionally, some articles available in digital form were requiring subscription or payment to access.

5.5.2 Limited information: Fungal genera established with insufficient details on macro- and micro-morphological characteristics pose a major issue in delineating them from other genera. The provided information might overlap with closely related genera but lacks distinct features.

5.5.3 Illustration issues: Basidiomata pictures and morphological drawings are lacking in either the old or the small group of taxa that corresponds to the limited studies. Some taxa lack scale bars in the photo plate, limiting the necessary information on morphology. Additionally, some publications contain incomplete morphological drawings or figures.

5.5.4 Taxonomic and nomenclatural changes: Identification of fungal genera solely based on morphology and lacking molecular studies could lead to wrong identification. The recurrent changes in taxonomic position and naming are caused mainly by the incorporation of molecular phylogenetic evidence, uncertain placement,

and cryptic species. Molecular information of fungal samples has provided significant support in scientific identification, leading to the renaming of previously established fungal taxa. This data also contributes to distinguishing cryptic species. Regarding taxonomic placement of some fungal taxa, updates among major online databases such as Index Fungorum, GenBank, and MycoBank lack uniformity.

5.5.5 Uncertain placement (*incertae sedis*): Although scientific investigations have been conducted on fungal taxa, their taxonomic placement might remain unclear. This could be due to differences in the perspectives of researchers on its placement and a lack of consensus. Lacking molecular data results in unclear evolutionary relationships among fungal species. Some fungi might exhibit ambiguous traits, posing a problem to fit to respective taxonomic level.

CHAPTER 6

ADDITIONAL WORK: MORPHOLOGICAL AND PHYLOGENETIC ANALYSIS OF FUNGAL SAMPLES FROM THAILAND

6.1 Introduction

Fungi play an important ecological role in nature, including organic matter decomposition, nutrient cycling, and forming symbiotic associations with plants (Hongsanan et al. 2025). Besides this, a large number of fungi have benefitted human through the production of food, medicine, supplements, antibiotics, and biotechnological applications (Niego et al. 2023). In today's world, the identification of fungal species based on a combination of morphological characteristics and molecular phylogenetic analyses is more reliable. The genetic makeup of one species is different from another and is reflected in differences in their applications, such as in metabolites, medicinal effects, and biomaterial properties. Therefore, exploration of fungal samples and their scientific identification of fungal species are crucial to avoid misleading practices.

Thailand is a hotspot of fungal diversity in tropical regions, with 96% of fungi are estimated to be novel (Hyde et al. 2018). The trend of the discovery of new species from this region is increasing, with the addition of above 500 novel fungal species in the last decade (Hyde et al. 2018). However, a significant gap remains due to huge underexplored fungal species, and requires rigorous investigation. In this study, 365 fungal samples (mushrooms) were collected in Chiang Rai, Chiang Mai, Lampang, Phayao, Phrae, Chanthaburi, and Narathiwat provinces in Thailand during 2022–2025. This study contributes to expanding the knowledge of fungal species, both in terms of novelty and the new geographical distribution of fungal species in Thailand.

6.2 Fungal Sample Collections

All the collected fungal samples are presented in Appendix A1 and A2. Based on fungal classification, the collected fungal species are divided into 3 subclasses, 10 orders, 40 families, and 90 genera, excluding *incertae sedis* and unidentified samples (Figure 6.1, Table 6.1). Among the collected fungal samples, the order Polyporales represents the largest number of fungal strains (67.7%), followed by Agaricales (17.8%) and Hymenochaetales (4.7%). In Polyporales, the family Polyporaceae occupied the majority of fungal samples (207) (Figure 6.2). In Agaricales, the largest number of samples is in Mycenaceae (10), followed by Schizophyllaceae (9), Omphalotaceae (8), and Psathyrellaceae (7) (Figure 6.3). Cultures of 187 fungal strains were successfully extracted from the basidiomata using either the tissue or spore isolation method.

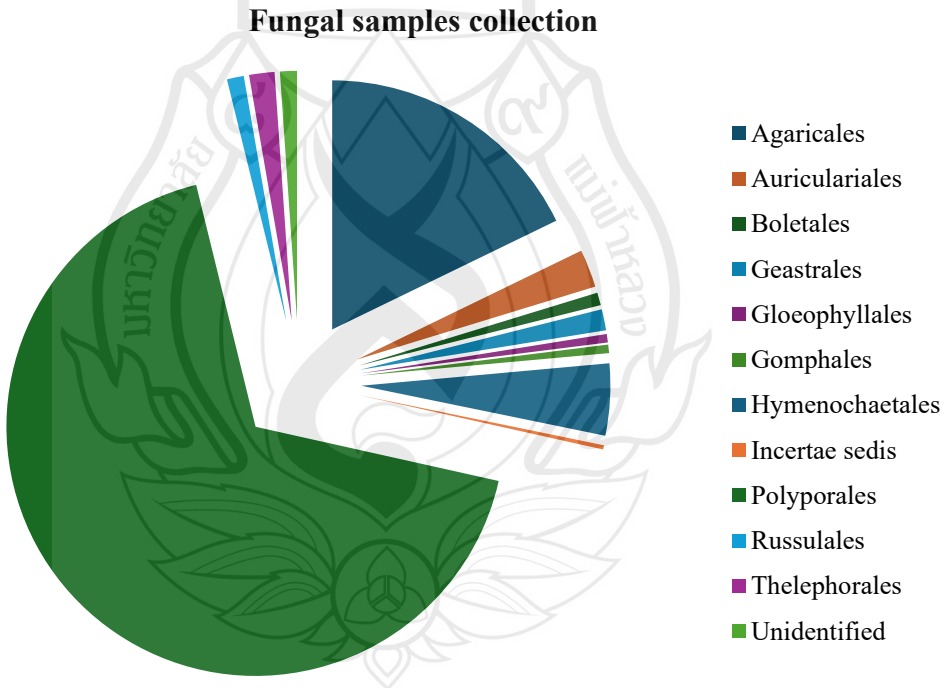


Figure 6.1 Pie chart showing the distribution of collected fungal species at the order level

Table 6.1 Classification of collected fungal strains in subclass, order, family, and genus

Subclass	Order	Family	Genus	Strains	Percentage (%)
Agaricomycetidae	Agaricales	17	33	65	17.8
	Boletales	3	3	3	0.8
	Hymenochaetales	2	7	17	4.7
Auriculariomycetidae	Auriculariales	1	2	9	2.5
Phallomycetidae	Geastrales	1	1	5	1.4
	Gomphales	1	1	2	0.5
Incertae sedis	Gloeophyllales	1	1	2	0.5
	Polyporales	10	37	247	67.7
	Russulales	2	3	4	1.1
	Thelephorales	2	2	6	1.6
	Incertae sedis	1	1	1	0.3
Unidentified				4	1.1
Total		41	91	365	100

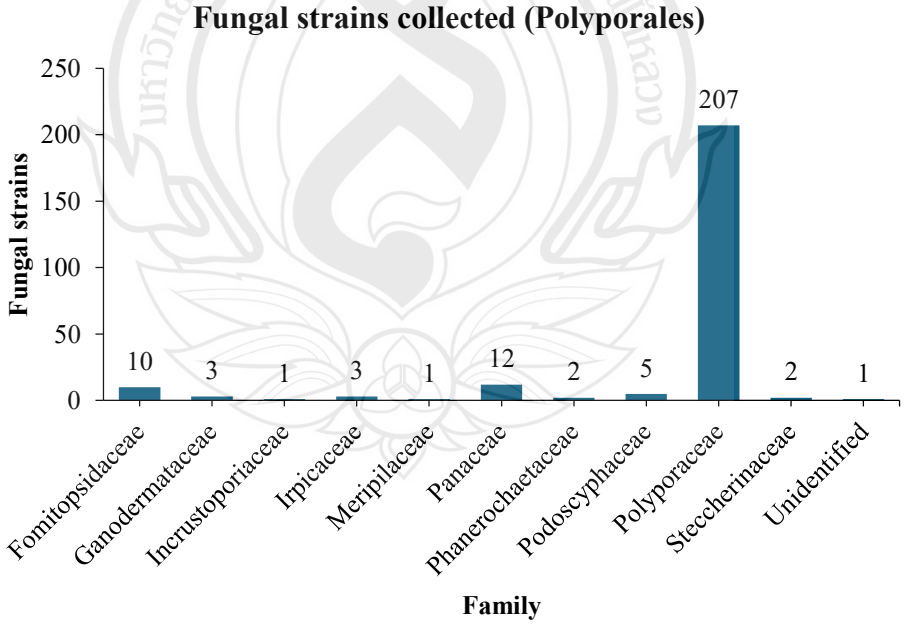


Figure 6.2 Bar diagram showing the distribution of collected fungal species at the family level (Polyporales)

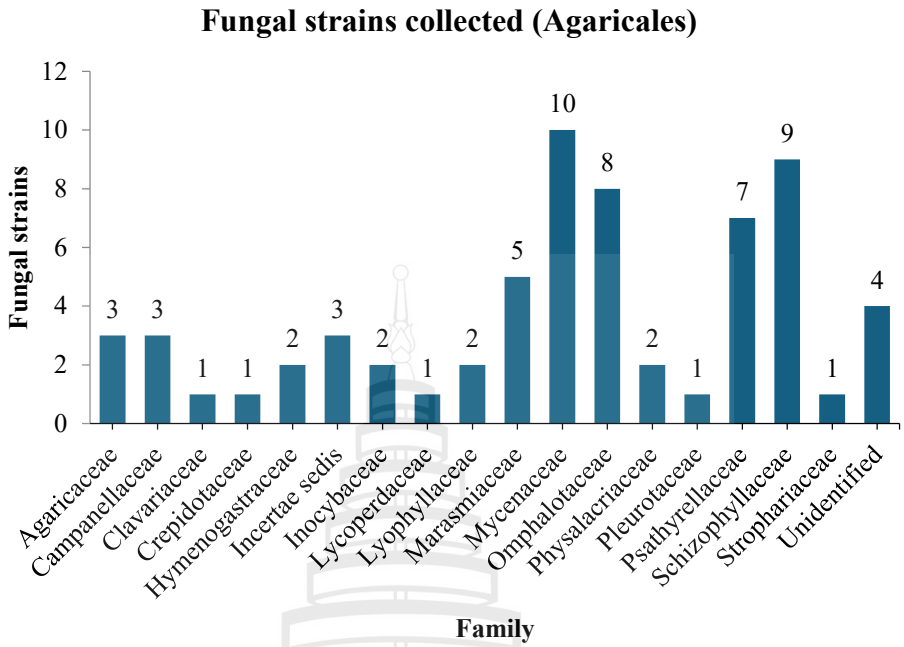


Figure 6.3 Bar diagram showing the distribution of collected fungal species at the family level (Agaricales)

6.3 Morphological and Phylogenetic Analyses of Fungal Samples from Thailand

Among the collected fungal samples (Appendix A1, A2), morphological and phylogenetic analyses of some fungal samples were carried out. As a result, this chapter reports three new species, namely *Echinochaete thailandica*, *Phanerochaete brunneohyha*, and *Thelephora chiangmaiensis,* and three new geographical records, namely *Favolaschia variistipitata*, *Podoscypha gillessi*, and *Trullella yunnanensis*.

6.3.1 *Echinochaete thailandica* S. Khyaju, T. Luangharn, I. Bera & K.D. Hyde, in Phytotaxa 718(1): 6, Figures. 6.4, 6.5

Index Fungorum number: IF903907; *Facesoffungi number*: FoF 17780

Etymology: The specific epithet “thailandica” refers to the type location, Thailand.

Holotype: THAILAND, Chiang Mai Province, Mae Taeng District, elev. 890 m, N 19°7'5", E 98°43'57", 04 April 2023, *S. Khyaju*, SK134 (MFLU25-0193, holotype).

Diagnosis: The small basidiomata, lanceolate to cylindrical, longer, setoid elements bearing lateral spines on the pileus and hymenium surface, and larger and broader basidiospores. It differs from *Echinochaete russiceps* by the presence of larger basidiospores (10.5–14.5 × 4.1–6.8 μm).

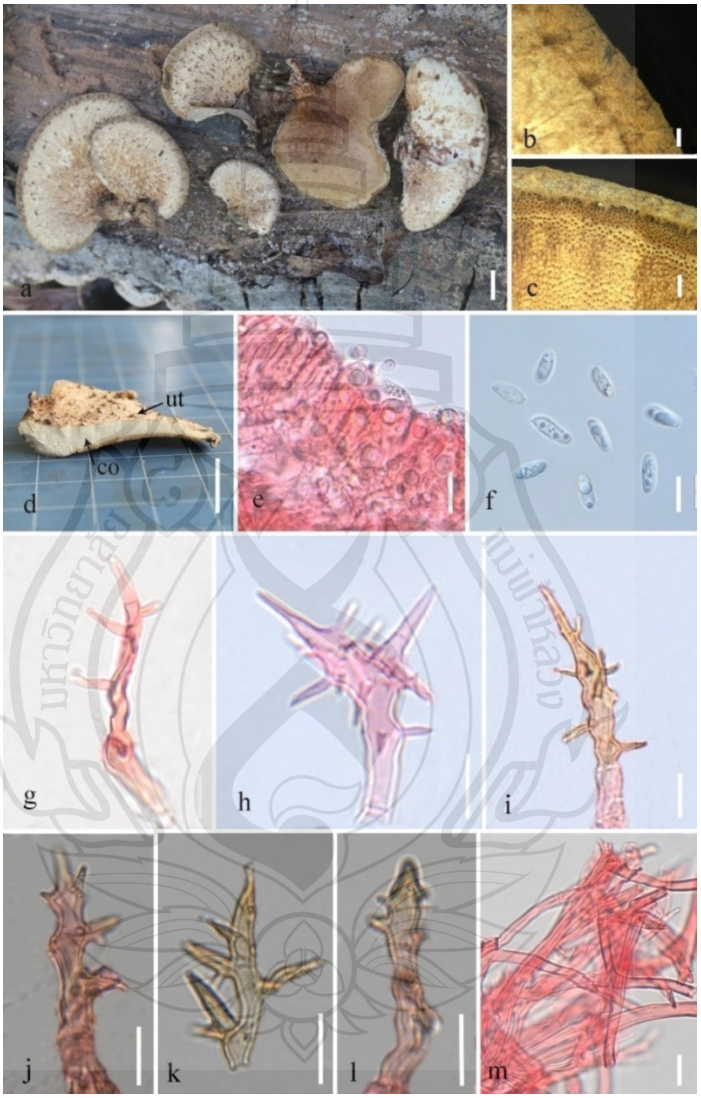
Basidiomata annual, substipitate to laterally stipitate, occurring gregariously. *Pileus* up to 60 mm in diam., and up to 5 mm thick, flabelliform, ranging from flat to convex. *Pileus surface* uplifted tomentose, dry; light brown (5D4) at the base, combination of yellowish white (1A1) to pale yellow (1A2–3) with light brown (5D4) at the center, and greyish orange (5B4) at the margin, partially covered with a light brown (5D6–7) to yellowish brown (5D8) cuticle. *Margin* incurved, hairy, and zonate. *Stipe* 5–8 × 5–13 mm, short, cylindrical. *Stipe surface* rough, soot brown (5F5), non-bruising. *Context* up to 5 mm thick, fleshy-leathery when young, becoming leathery to brittle when dried, yellowish white (4A2), non-bruising. *Pore* 4–6 per mm, round to angular, dissepiments thin, greyish yellow (4B3–5), brown (6E6) with age. *Tube surface* up to 2 mm deep, greyish yellow (1B3). *Odour and taste* not distinct.

Basidiospores 10.5–14.5 × 4.1–6.8 μm, avL × avW = 12.3 × 5.2 μm, Q = 2.13–2.54, Qav = 2.35 (50/2), cylindrical, hyaline, thin-walled, non-dextrinoid, and greyish white in spore deposit. *Basidia* 21.7–27.1 × 6.9–10.5 μm, broadly clavate with large vacuoles, 4-spored; sterigmata up to 5.2 μm long. *Setoid elements* 37–103 × 6–9 μm, abundant on the pileus surface, thick-walled, lanceolate to cylindrical, bearing pointed lateral spines, yellowish brown to brown in 5% KOH, lateral spines up to 15 μm long. In the hymenium, setoid elements on the pore edge, 26–52 × 3–10 μm, thick-walled, subulate to lanceolate or ventricose with pointed lateral spines, yellowish brown to brown in 5% KOH; lateral spines 2–12 μm long. *Hyphal system* dimitic, composed of generative and skeleton-binding hyphae. *Contextual generative hyphae* 3–5 μm wide, thin-walled, hyaline, non-dextrinoid, with clamp connections. *Contextual skeleton-binding hyphae* 4–10 μm wide, thick-walled, frequently branched, non-dextrinoid. *Tramal generative hyphae* 3–4 μm wide, thin-walled,

hyaline, non-dextrinoid, with clamp connections. *Tramal skeleton-binding hyphae* 2–6 µm wide, thick-walled, frequently branched, non-dextrinoid.

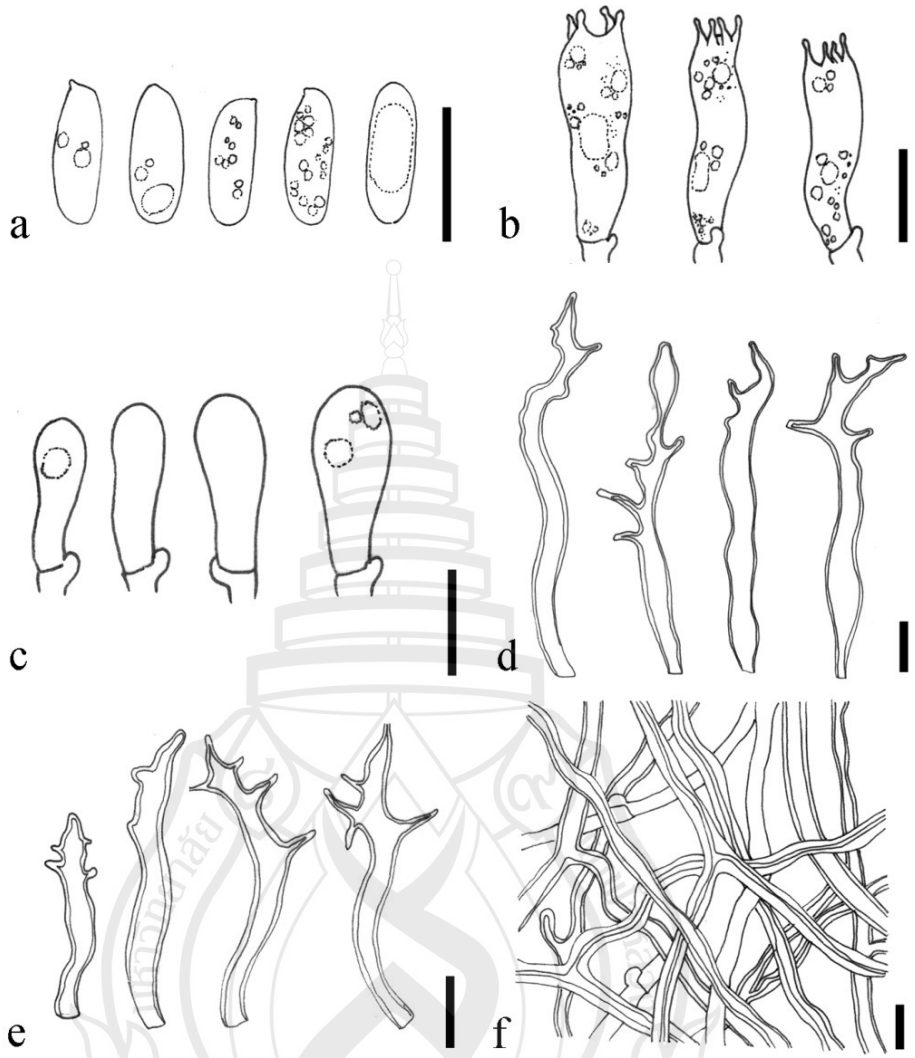
Habitat: on a decaying log of an angiosperm tree.

Additional specimen examined: THAILAND, Chiang Mai Province, Mae Taeng District, elev. 911 m, N 19° 7' 10", E 98° 44' 3", 03 April 2023, *S. Khyaju*, SK126 (MFLU25-0194, paratype).



Note a Fresh basidiomata in habitat. b Pileus tomentose surface. c Pore surface. d Basidiomata showing context (co) and uplifted tomentose (ut) surface. e Basidia and basidioles. f Basidiospores in Melzer's reagent. g–i Setoid elements on the pileus surface. j–l Setoid elements on the hymenium surface. m Hypha of context. Scale bars: a, d = 1 cm, b–c = 1 mm, e–m 10 µm.

Figure 6.4 *Echinochaete thailandica* (MFLU25-0193, holotype)



Note a Basidiospores. b Basidia. c Basidioles. d Setoid elements on the pileus surface. e Setoid elements on the hymenium surface. f Hyphae from context. Scale bars: a–f = 10 μm.

Figure 6.5 *Echinochaete thailandica* (MFLU25-0193, holotype), line drawing

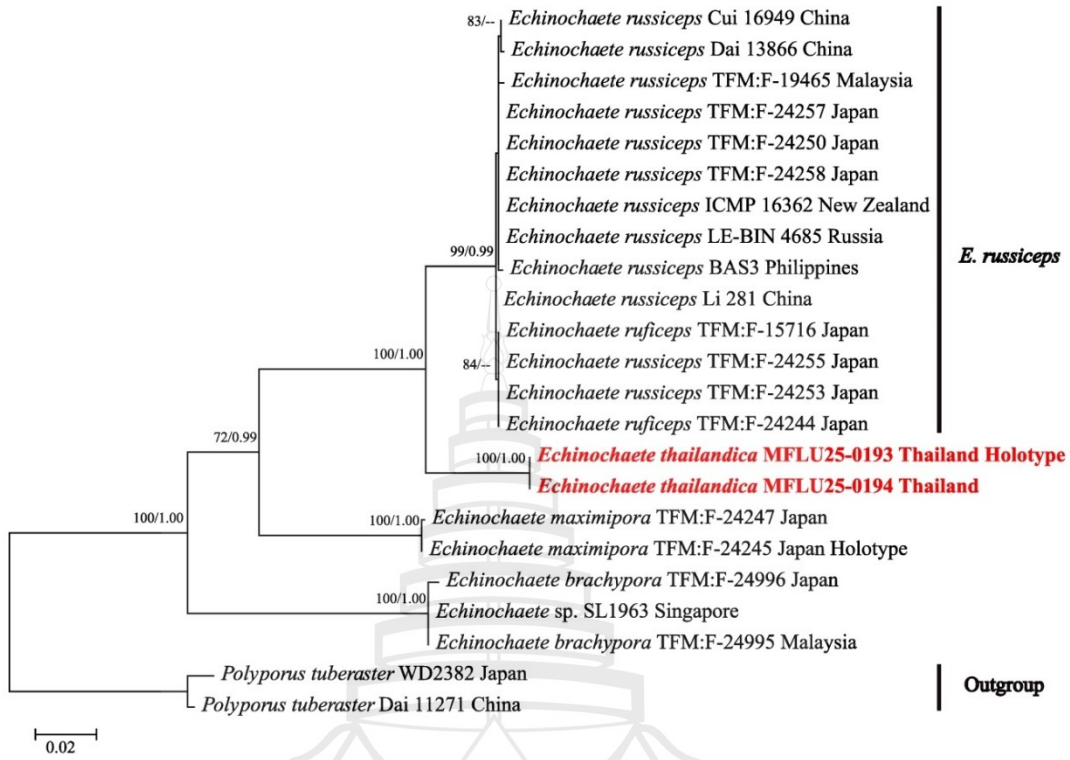
Phylogenetic analyses were inferred from the combined ITS and LSU sequences, comprising 23 taxa, including the two outgroup species. The final dataset comprised 1,194 total characters, including gaps: 453 characters for ITS and 741 characters for LSU. The best-scoring of the combined ML and BI tree is shown in Figure 6.6, with an optimal log-likelihood value of -3148.039205. The proportion of gaps and completely undetermined characters in the alignment was 11.17 %. Estimated base frequencies were A = 0.249698, C = 0.202835, G = 0.273935, T =

0.273532; substitution rates AC = 0.798668, AG = 2.524972, AT = 1.072623, CG = 0.594639, CT = 5.158352, GT = 1.000000; and the gamma distribution shape parameter α = 0.095613. Phylogenetic analysis indicates our *Echinochaete thailandica* (MFLU25-0193, MFLU25-0194) forms a separate clade with 100% ML and 1.00 BI support.

The BLAST result of the ITS sequence (MFLU25-0193) retrieved from our specimens shows the top result as *E. russiceps* (98.48% similarity) (voucher number SWFU WYJ169). However, since the specimen is incorrectly labelled, the second-ranked result has been considered (Table 6.2).

Table 6.2 The BLAST results of *Echinochaete thailandica* (voucher number MFLU25-0193) in NCBI

Species name	**Genes used**	**Voucher name**	**% of similarity**	**% query coverage**
Echinochaete russiceps	ITS	BAS3	92.24%	94%
E. russiceps	LSU	Dai 13866	97.66%	100%



Note Phylogram generated from the maximum likelihood (ML) and Bayesian Inference (BI) based on combined ITS and LSU datasets. The tree is rooted with *Polyporus tuberaster* (WD2382) and *P. tuberaster* (Dai 11271). Maximum Likelihood bootstrap support values (≥70%) and BI posterior probabilities (≥95%) are denoted on the nodes. Newly generated sequences are indicated in red bold.

Figure 6.6 Phylogenetic tree of *Echinochaete*

Notes: The identification of our studied species as a member of the genus *Echinochaete* is supported by a unique combination of morphological characteristics: laterally stipitate basidiomata, a dimitic hyphal system comprising skeleton-binding hyphae and clamped generative hyphae, the presence of spinulose setoid elements on both the pileus and hymenial surfaces, and cylindrical basidiospores (Reid, 1963a; Núñez & Ryvarden, 2001; Sotome et al., 2009). Among the Asian *Echinochaete* species, *E. brachypora*, *E. ruficeps*, *E. russiceps*, and *E. maximipora*, our species shares several morphological features, particularly in the shape and size of setoid elements. In contrast, the only known African species, *E. cinnamomeosquamulosa*,

exhibits clavate to ovoid setoid elements bearing short, irregular spines on the pileus surface (Ryvarden & Johansen, 1980; Núñez & Ryvarden, 1995, 2001; Sotome et al., 2009). However, these species can be distinguished based on the shape and size of their setoid elements (Ryvarden & Johansen, 1980; Corner, 1984; Núñez & Ryvarden, 1995, 2001; Sotome et al., 2009).

Our species differs from *E. brachypora* in lacking reddish-brown spots on the pileus surface and a reddish-brown hymenium. Additionally, it possesses smaller pores (4–6 per mm), compared to the larger pores (0.5–2 per mm) observed in *E. brachypora*, which also exhibits more intense reddish-brown colouration (Coelho et al., 2014). While *E. russiceps* is characterised by lanceolate setoid elements with relatively short lateral spines (up to 10 μm) (Sotome et al., 2009), our species exhibits lanceolate to cylindrical setoid elements with distinctly longer lateral spines (up to 15 μm) on the pileus surface. Although Reid (1963a) reported similar basidiospore sizes across *Echinochaete* species, our species is distinguished by its notably larger and broader basidiospores (10.5–14.5 × 4.1–6.8 μm).

In our phylogenetic analyses (Figure 6.6), sequences of our specimen formed a sister clade with an undescribed sequence from China named *Echinochaete russiceps*. They showed a close relationship with the clade representing the actual *E. russiceps*. Morphologically, the Thai specimen most closely resembles *E. russiceps*, which can be distinguished by several key features, such as a gregarious growth habit and smaller, rounded to angular pores (4–6 per mm). Thus, based on morphological and phylogenetic evidence, the Thai specimens represent a distinct species within the genus *Echinochaete*.

Table 6.3 Morphological comparison among the descriptions of holotype specimens of *Echinochaete*

Character	***E. brachypora***	***E. cinnamomeo-squamulosa***	***E. maximipora***	***E. ruficeps***	***E. russiceps***	***E. thailandica***
Pileus width	5 cm	5–9 cm	1–4.8 cm	Up to 2.2 cm	7.5 cm or more	Up to 6 cm
Pileus shape	Sub-half, sub-flabellate	Conchato sub-reniform	Dimidiate, flat to convex	Dimidiate to nephroid	–	Flabelliform, flat to convex
Pileus colour	Brown	Cinnamon	Grey orange to brownish yellow	Light brown	Bright brown	Yellowish brown
Cuticle on the pileus surface	–	Velvety-scaly, with fading darker scales	Absent	Absent	Present, almost fully covering the pileus surface	Present
Pores shape	Angular	Round	Radially elongated	Elongated, partly angular	Angular	Round to angular
Pore size (per mm)	3–5/mm	–	(1)2–4 × (0.5)1–2 mm	(0.5)1–2 × 0.5–1 mm	(3)4–5/mm	4–6/mm

Table 6.3 (continued)

Character	*E. brachypora*	*E. cinnamomeo-squamulosa*	*E. maximipora*	*E. ruficeps*	*E. russiceps*	*E. thailandica*
Basidiospore size (µm)	–	–	8–11 × 2.5–4 µm (10.2 × 3.1 µm)	9–11 × 3.5–4 µm (10 × 3.4 µm)	–	10.5–14.5 × 4.1–6.8 µm (12.3 × 5.2 µm)
Q-value	–	–	3.2 (88/2)	2.9 (6/1)	–	2.35 (50/2)
Setoid elements on the pileus	–	Present, brown, forked setae	Present, cylindrical to cylindro-clavate with pointed apex, yellowish brown to brown, thick–walled, with short lateral spines near the apex	Present, lanceolate with branched and pointed hyphal ends	Present, aculeate to lanceolate with branched and pointed hyphal ends	Present, lanceolate to cylindrical with pointed lateral spines, thick-walled, yellowish brown to brown

Table 6.3 (continued)

Character	***E. brachypora***	***E. cinnamomeo-squamulosa***	***E. maximipora***	***E. ruficeps***	***E. russiceps***	***E. thailandica***
Setoid elements on hymenium surface	–	Present, brown, forked setae	Present, subulate to lanceolate, thick-walled, pale to dark brown, with sharp spines and hyphal pegs	Present, lanceolate with branched and pointed hyphal ends	Present, aculeate to lanceolate with branched and pointed hyphal ends	Present, lanceolate to cylindrical, thick-walled, with pointed lateral spines, yellowish brown to brown
References	Montagne (1854)	Hennings (1901)	Sotome et al. (2009)	Berkeley and Broome (1873)	Berkeley and Broome (1873)	**This study**

Note "–" = not mentioned

Notes: Based on detailed morphological characterisation and phylogenetic analyses, using ITS and LSU sequence data, our study identifies a distinct species within the genus *Echinochaete* and reports it as a new species. Members of *Echinochaete* are mainly distributed in tropical and subtropical regions, with reports from parts of Asia, Africa, and South America (Reid, 1963a; Núñez & Ryvarden, 1995, 2001; Sotome et al., 2009). The discovery of this new species in tropical Thailand extends the known distribution of *Echinochaete* and represents the first confirmed record of the genus in the country.

The taxonomy of *Echinochaete* has undergone several revisions. All of the currently accepted species in this genus, except *E. maximipora*, have been introduced as recombinations and were previously classified under the two genera: *Favolus* Fr. (*F. ruficeps* Berk. & Broome) and *Polyporus* P. Micheli ex Adans. (*P. brachyporus* Mont., *P. cinnamomeosquamulosus* Henn., and *P. russiceps* Berk. & Broome) (Montagne, 1854; Berkeley & Broome, 1873; Hennings, 1901). This taxonomic ambiguity persisted until Sotome et al. (2009) conducted comprehensive phylogenetic analyses supported by detailed morphological comparisons, which led to the recognition of *Echinochaete* as a distinct genus within Polyporales. Morphologically, although pileus coloration among known species tends to range from brown to reddish-brown, key characteristics used in species delimitation include pore morphology (shape and size), as well as the shape, size, position, and abundance of setoid elements (Reid, 1963a; Ryvarden & Johansen, 1980; Núñez & Ryvarden, 1995, 2001; Sotome et al., 2009).

In our study, the new species shares morphological similarities with *E. russiceps*, particularly in the overall characteristics of the basidiomata and hyphal structure. However, several distinct features support the recognition of our Thai specimen as a separate species. In *E. russiceps*, the setoid elements on the pileus surface are described as aculeate to lanceolate with shorter lateral spines (Sotome et al., 2009), whereas in our species, they are lanceolate to cylindrical with longer lateral spines. Additionally, our species displays smaller pores with distinct shape differences. A detailed comparative analysis is provided in Table 6.3.

In conclusion, this study expands the known diversity of the genus *Echinochaete*. It provides a base for further biogeographic and phylogenetic analyses,

which are necessary for a comprehensive understanding of the evolutionary relationships and ecological roles of *Echinochaete* species across their global distribution.

Key to *Echinochaete* species

1.a. Pores radially elongated, large (2–4 × 1–2 mm) ..... *E. maximipora*

1.b. Pores round, angular or elongated, smaller in size ……...…….2

2.a. Setoid elements absent on pileus surface; hyphal ends cylindrical, thick-walled, unbranched, septate, up to 225 µm long..... ..... *E. brachypora*

2.b. Setoid elements present on the pileus surface or terminal hyphae pointed/branched 3

3.a. Setoid elements ovate to clavarioid with lateral spines; pileus cinnamon-coloured, surface velvety-scaly..... .....*E. cinnamomeo-squamulosa*

3.b. Setoid elements lanceolate, aculeate, or cylindrical with spines; pileus in shades of brown, surface smooth or slightly covered with cuticle..... 4

4.a. Basidiospores large (10.5–14.5 × 4.1–6.8 µm); pileus yellowish brown; pores round to angular (4–6/mm) .....*E. thailandica*

4.b. Basidiospores smaller (9–11 × 3.5–4 µm); pileus light brown or bright brown; pores elongated, partly angular or angular……..... 5

5.a. Basidiomata distinctly or indistinctly stipitate; pileus up to 2.2 cm, light brown; pores elongated, partly angular, (0.5)1–2 × 0.5–1 mm..... *E. ruficeps*

5.b. Basidiomata usually indistinctly stipitate; pileus 7.5 cm or more, bright brown; pores angular, (3)4–5/mm…….....*E. russiceps*

6.3.2 *Phanerochaete brunneohypha* S. Khyaju, I. Bera, & K.D. Hyde *sp. nov.*

Index Fungorum number: IF904456; *Facesoffungi number*: FoF ***; Figure 6.7

Etymology: referring to the brown pigmented hyphae.

Holotype: MFLU**

Basidiomata up to 225 mm × 42 mm, 0.4 mm thick; annual, resupinate, adnate, effused, loosely attached to the substrate, forming a continuous crust, membranous, non-cracking, coriaceous on drying. *Hymenium* surface smooth to slightly tuberculate or uneven, tobacco brown (5E6), exuding amber to honey coloured guttation droplets when alive, coriaceous upon drying; margin thin, irregular, slightly fibrillose, white to

cream. *Hyphal system* monomitic, generative hyphae interwoven, simple-septate; subiculum hyphae 2.1–6.2 µm diam., thick-walled (0.6–0.8 µm thick), loosely interwoven, irregular orientation, branched, brown; subhymenium hyphae 2–5.5 µm, thick-walled (0.6–0.7 µm thick), dense and compact, brown, some densely covered by crystals; IKI–, CB–, unchanged in KOH. *Cystidia* absent. *Basidia* 21–30.8 × 4–6.7 µm, narrowly clavate, simple-septate, thin-walled, brown, 4-sterigmate, sterigmata 2.7–3.8 µm long. *Basidiospores* 4.4–*5.1*–6 × 2.5–*2.7*–2.9 µm [n = 30, Q = 1.62–*1.82*–2.04], cylindrical, adaxially flattened, thin-walled, smooth, hyaline, inamyloid, nondextrinoid, acyanophilous.

Culture characteristics: colonies on PDA reaching 90 mm diam. at 25°C after 12 days, white, flat, non-fluffy, thin, margin irregular; not producing pigmentation in the culture.

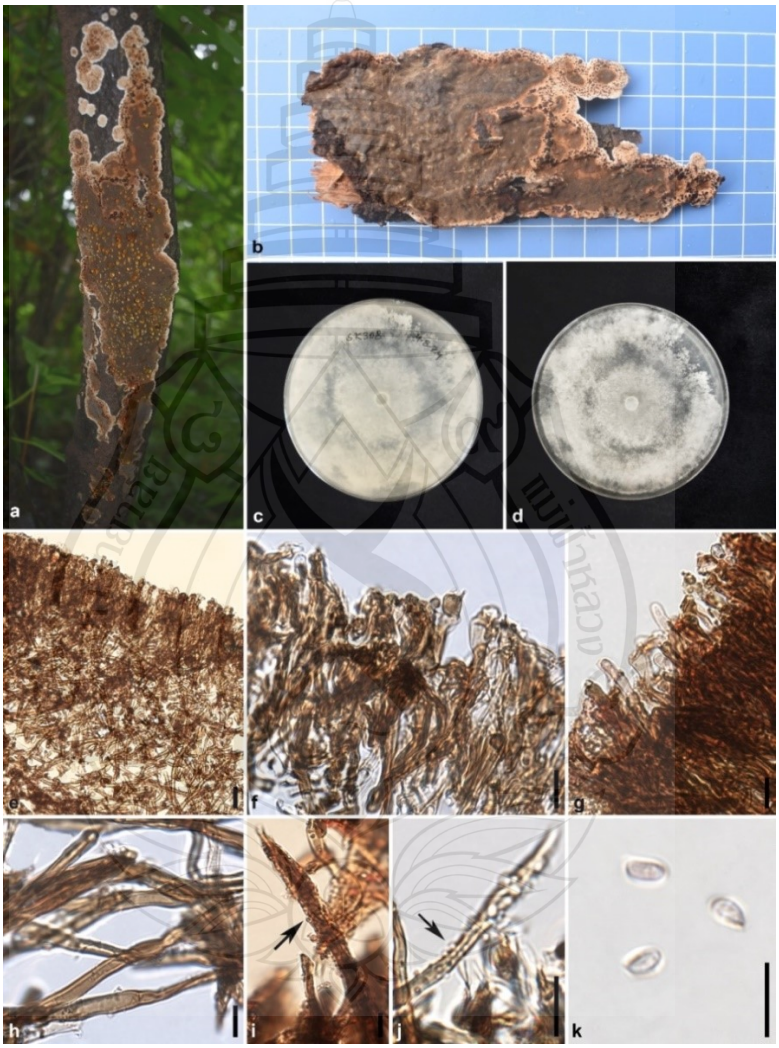
Material examined: Thailand, Phrae Province, Long district, on decaying angiosperm tree branch in a subtropical forest, 3 August 2024, S. Khyaju SK308 (MFLU, holotype**); ex-type living culture, MFLUCC; Chiang Mai Province, on decaying angiosperm tree branch in a subtropical forest, 12 September 2024, S. Khyaju SK312 (MFLU**).

GenBank accession numbers: ITS: PX457265 (holotype), PX457266; LSU: PX457263 (holotype), PX457264.

Notes: *Phanerochaete brunneohypha* is characterised by brown, simple-septate, thick-walled generative hyphae and the absence of cystidia. Only a few species in the genus share this combination of characters. Morphologically, it resembles *P. porostereoides* S.L. Liu & S.H. He from China in having a brown hymenophore, simple-septate brown generative hyphae, absence of cystidia, and similar basidiospores (Liu & He, 2016). However, *P. porostereoides* lacks evidence of any subhymenial hyphae encrusted with crystals, and the two species are not phylogenetically closely related. *Phanerochaete canobrunnea* Sheng H. Wu, C.C. Chen & C.L. Wei from China and *P. thailandica* Kout & Sádlíková from Thailand also possess brown subicular generative hyphae and lack cystidia, but both differ by the presence of brown skeletal hyphae (Sádlíková & Kout, 2017; Wu et al., 2018). Another morphologically comparable taxon, *P. aurantiobadia* Ghobad-Nejhad, S.L. Liu & E. Langer, also lacks cystidia but differs by the distinctive coccine-red colour change of the basidiomata in

KOH (Ghobad-Nejhad et al., 2015). *Phanerochaete fusca* Sheng H. Wu, C.C. Chen & C.L. Wei likewise has a smooth to tuberculate dark brown hymenium and a monomitic hyphal system, but can be distinguished by the presence of leptocystidia (Wu et al., 2018).

Phylogenetically, *P. brunneohypha* forms an independent lineage showing close affinity to the *P. porostereoides* clade, although the two species are morphologically distinct (Figure 6.8).



Note a, b Basidiomata. c, d Colony on PDA (front and below). e Transverse section showing hymenium and subiculum. f, g Transverse section through hymenium. h Generative hyphae. i Hyphae of subhymenium covered with crystals. k Basidiospores. Scale bars: e = 50 µm, f–k = 10 µm.

Figure 6.7 *Phanerochaete brunneohypha* (holotype)

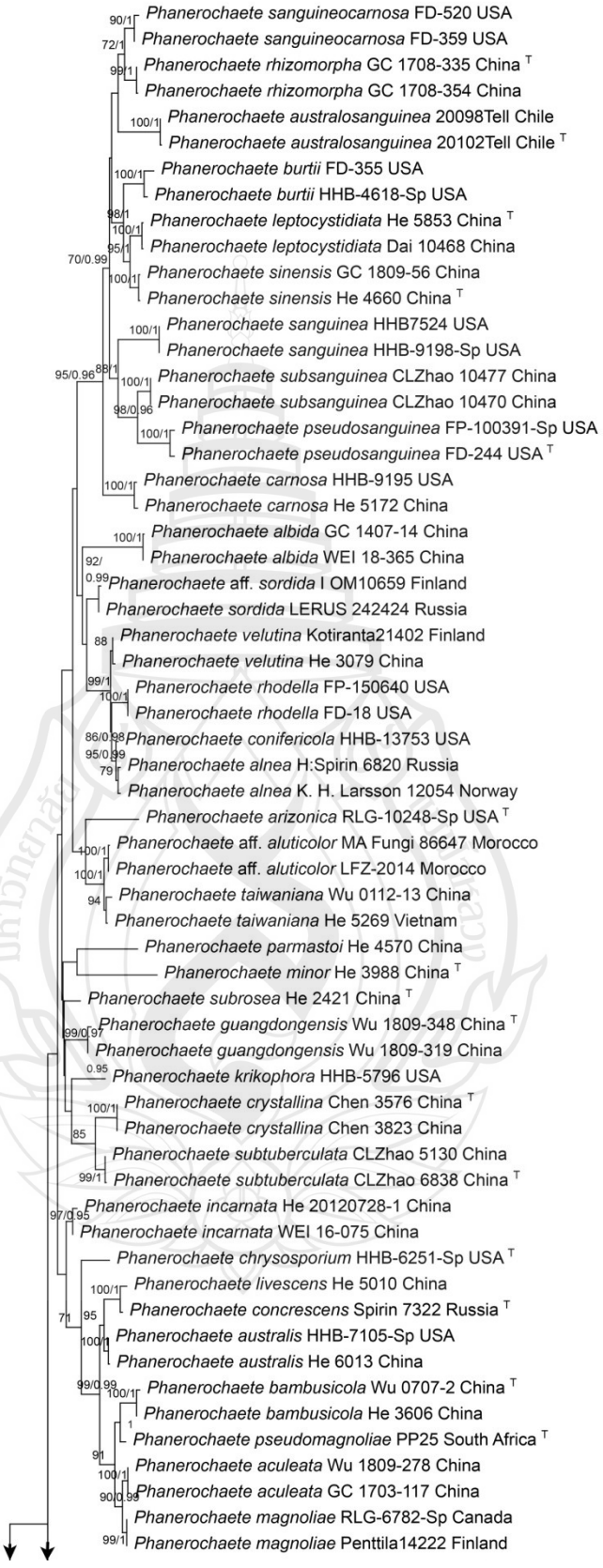
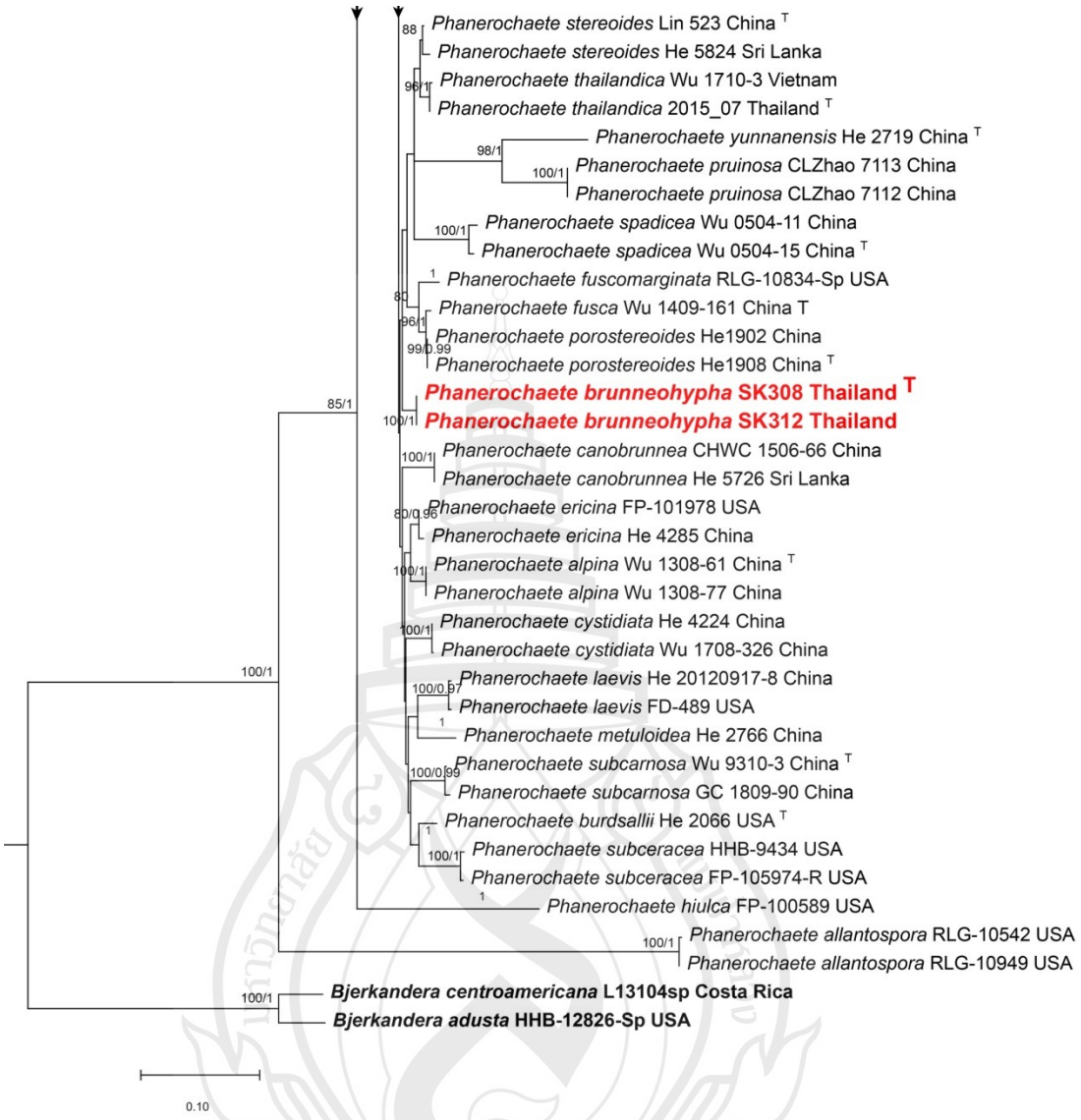


Figure 6.8 Phylogenetic tree of *Phanerochaete*



Note Phylogenetic analyses based on Maximum likelihood and Bayesian analysis from the combined ITS and LSU sequence alignments. Bootstrap support values for maximum likelihood (ML, first value) equal to or greater than 70 and Bayesian posterior probabilities (BYPP, second value) equal to or greater than 0.95 are given above the nodes. The scale bar indicates expected changes per site. The tree is rooted to *Bjerkandera centroamericana and B. adusta,* indicated in bold. Ex-type strains are indicated with "T". The newly generated sequences are indicated in red and bold.

Figure 6.8 (continued)

6.3.3 *Thelephora chiangmaiensis* S. Khyaju, K.D. Hyde & T. Luangharn *sp. nov.*

Index Fungorum number: IF903936; *Facesoffungi number*: FoF 17779; Figures 6.9, 6.10

Etymology: the name "*chiangmaiensis*" indicates the holotype specimen collected from Chiang Mai Province, Thailand.

Holotype: MFLU20-0205

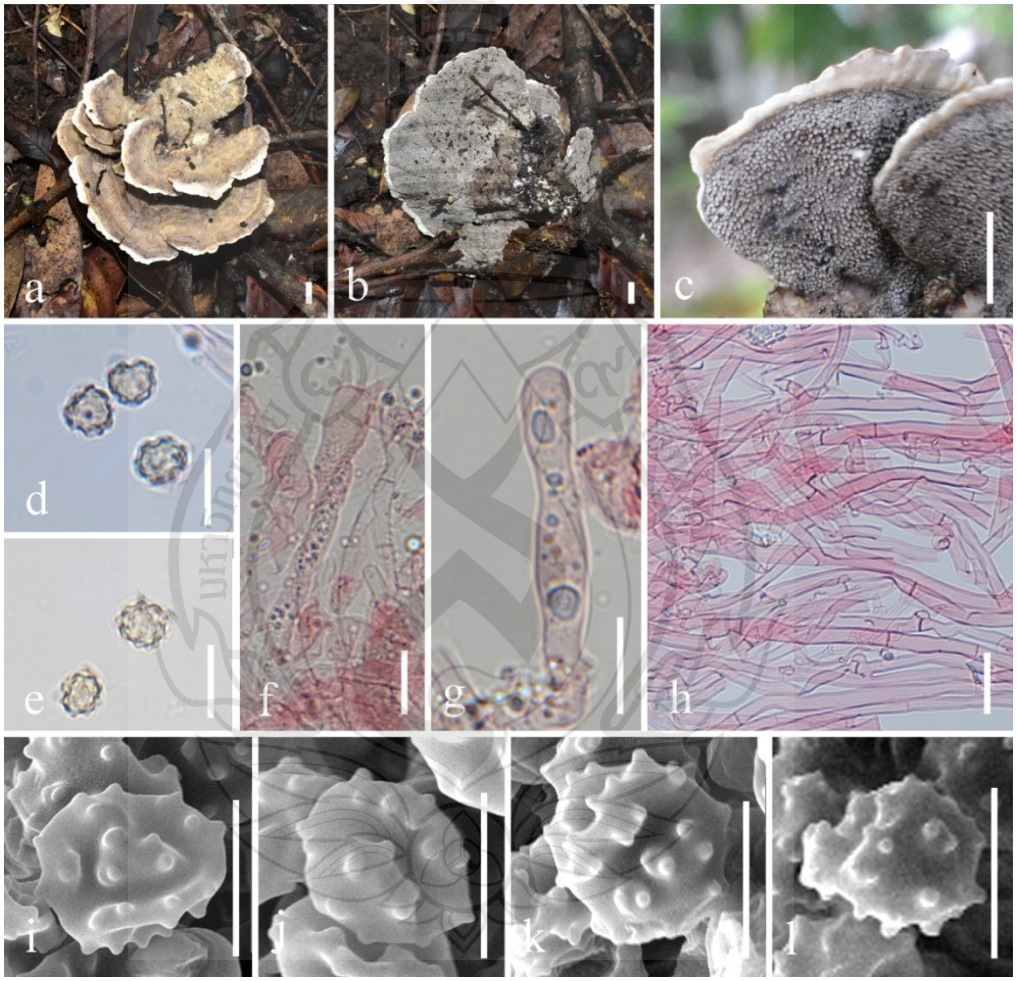
Basidiomata up to 8 cm high, annual, eccentrically stipitate, rosette-shaped, concrescent, thin, humid and leathery when fresh, becoming brittle when drying; branches arise from a common stipe. *Pileus* up to 10.5 cm wide, up to 5.5 cm long, 0.4 cm thick at the centre, circular to irregular, imbricated, merging laterally. *Pileus surface* moist, spongy, undulated, light brown to greyish or yellowish brown (5D3–5, 5E5–6), zonate with alternate light and dark, with scattered dark stains, white (1A1) margin. *Context* up to 0.2 cm thick, thinning out towards the margin, white to yellowish white (1A1–2, 2A1–2) upon drying, tissue turned blue-green in KOH. *Hymenophores* granulose, gray-brown (7F3–5), white at margin when fresh; *hymenium* warts up to 27.9 µm in length, up to 15.3 µm in diam. *Margin* 0.1–0.2 cm thick, white to yellowish or orange white (4A2, 5A2), wavy, sterile. *Stipe* irregularly cylindrical, surface grey brown, short, up to 1 cm long, 0.8 cm in diam., broadened at base; *stipe surface* cylindrical, downy, concolourous to hymenium. *Odour* mild. Taste not distinct.

Basidiospores 5.8–8.1 × 4.5–6.8 µm (not including ornamentation), avL = 6.92 µm, avW = 5.61 µm, Q = 1.19–1.29 (n = 75/3), globose to irregularly elliptical, warted, brownish; echinulis 0.4–0.8 µm high, subconical, yellowish brown to brownish in Melzer's reagent, inamyloid. *Basidia* 21.6–57.2 × 7–10.4 µm, clavate, 4-spored; sterigmata 3.4–7.1 µm long. Basidioles similar to basidia in shape. *Cystidia* and *cystidioles* absent. *Hyphal system* monomitic; *contextual generative hyphae* 3.8–7.1 µm in diam., mostly with simple septa, frequently with clamp connections, hyaline, slightly thick-walled, regularly arranged, occasionally branched, inamyloid; *stipe generative hyphae* 3.1–7 µm in diam., simple septa, frequently with clamp connections, hyaline, slightly thick-walled, branched, inamyloid.

Material examined: THAILAND, Chiang Mai Province, on leaf litter in soil, 19° 7' 5" N, 98° 43' 58" E, alt. 915 m, 22 July 2023, S. Khyaju, SK207 (MFLU20-0205, holotype).

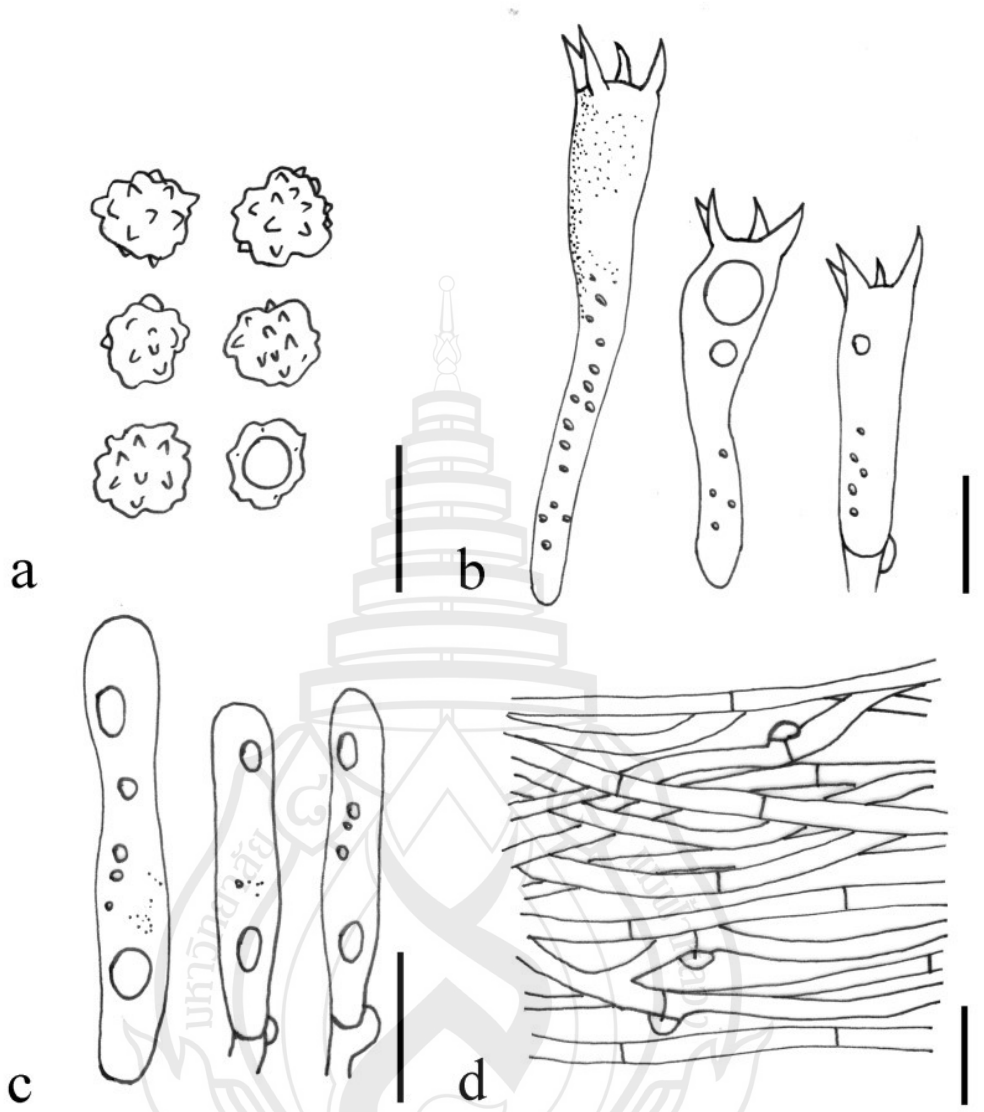
GenBank accession numbers: MFLU20-0205 (ITS: PV765348, LSU: PV765353), MFLU20-0206 (ITS: PV765349, LSU: PV765354)

Additional specimen examined: THAILAND, Chiang Mai Province, among leaf litter in soil, 19° 7' 53" N, 98° 43' 49" E, alt. 915 m, 23 July 2023, S. Khyaju, SK216 (MFLU20-0206, paratype).



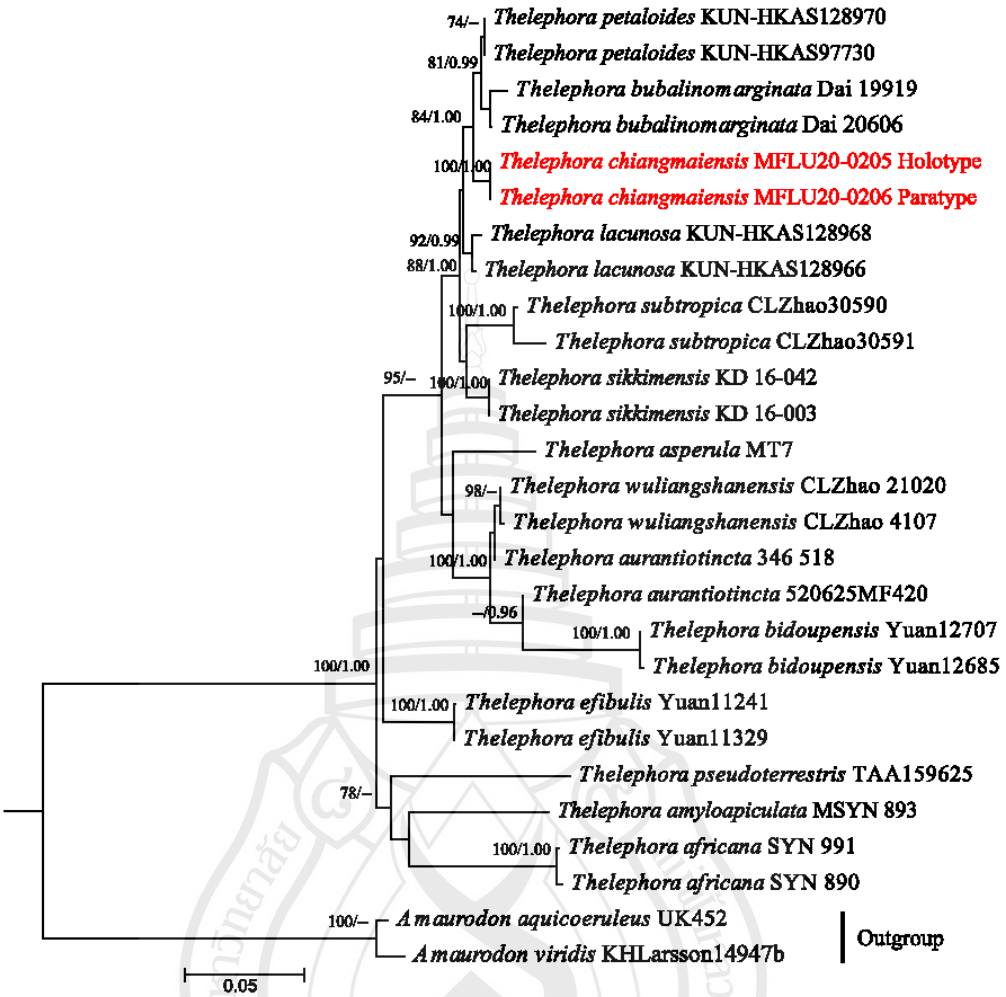
Note a–b Basidiomata in the field. c Hymenium showing granulated surface. d–e Basidiospores. f Basidia. g Basidiole. h Hyphae from context. i–l = SEM of basidiospores. Scale bars: a–c = 1 cm, d–g = 10 µm, h = 20 µm, i–l = 5 µm.

Figure 6.9 *Thelephora chiangmaiensis* (MFLU20-0205, holotype)



Note a Basidiospores. b Basidia. c Basidioles. d Hyphae from context. Scale bars: a–c = 10 μm, d = 20 μm.

Figure 6.10 *Thelephora chiangmaiensis* (MFLU20-0205, holotype), line drawing



Note Maximum likelihood consensus tree inferred from the combined ITS and LSU multiple sequence alignments. Bootstrap support values for maximum likelihood (ML, first value) equal to or greater than 70% and Bayesian posterior probabilities from MCMC analyses (BPP, second value) equal to or greater than 0.95 are given above the nodes. The scale bar indicates expected changes per site. The tree is rooted to *Amaurodon aquicoeruleus* (UK452) and *A. viridis* (KHLarsson14947b). The newly generated sequences are indicated in red.

Figure 6.11 Phylogenetic tree of *Thelephora*

Notes – Thelephora chiangmaiensis is nested in the core clade of *Thelephora*, forming a close clade to *T. petaloides* Yan C. Li & Zhu L. Yang, and *T. bubalinomarginata* B.K. Cui, Y.F. Sun and C.G. Song, which exhibits strong phylogenetic support (ML = 1, BPP =1.00) (Figure 6.11). *Thelephora chiangmaiensis*

aligns with the generic description of *Thelephora* in key morphological characteristics, including tissue turning blue-green in KOH, monomitic hyphal system, and warted and inamyloid basidiospores. Our species has larger basidiomata (up to 10.5 cm width) and brownish basidiospores as compared to *T. bubalinomarginata* having smaller basidiomata (up to 6.8 cm width) and hyaline to light yellow or light brown basidiospores (Song et al., 2025). Additionally, our species is unique from *T. bubalinomarginata* due to its smooth hymenophores (Song et al., 2025). Our species exhibits smaller basidia (21.6–57.2 × 7–10.4 μm) compared to *T. petaloides* with larger basidia (53–92 × 9–12 μm) (Tian et al., 2024).

6.3.4 *Favolaschia variistipitata* W.H. Lu, Tibpromma & Karun., Phytotaxa 694(2): 148 Figure 6.12

Index Fungorum number: IF856190; *Facesoffungi number*: FoF17246

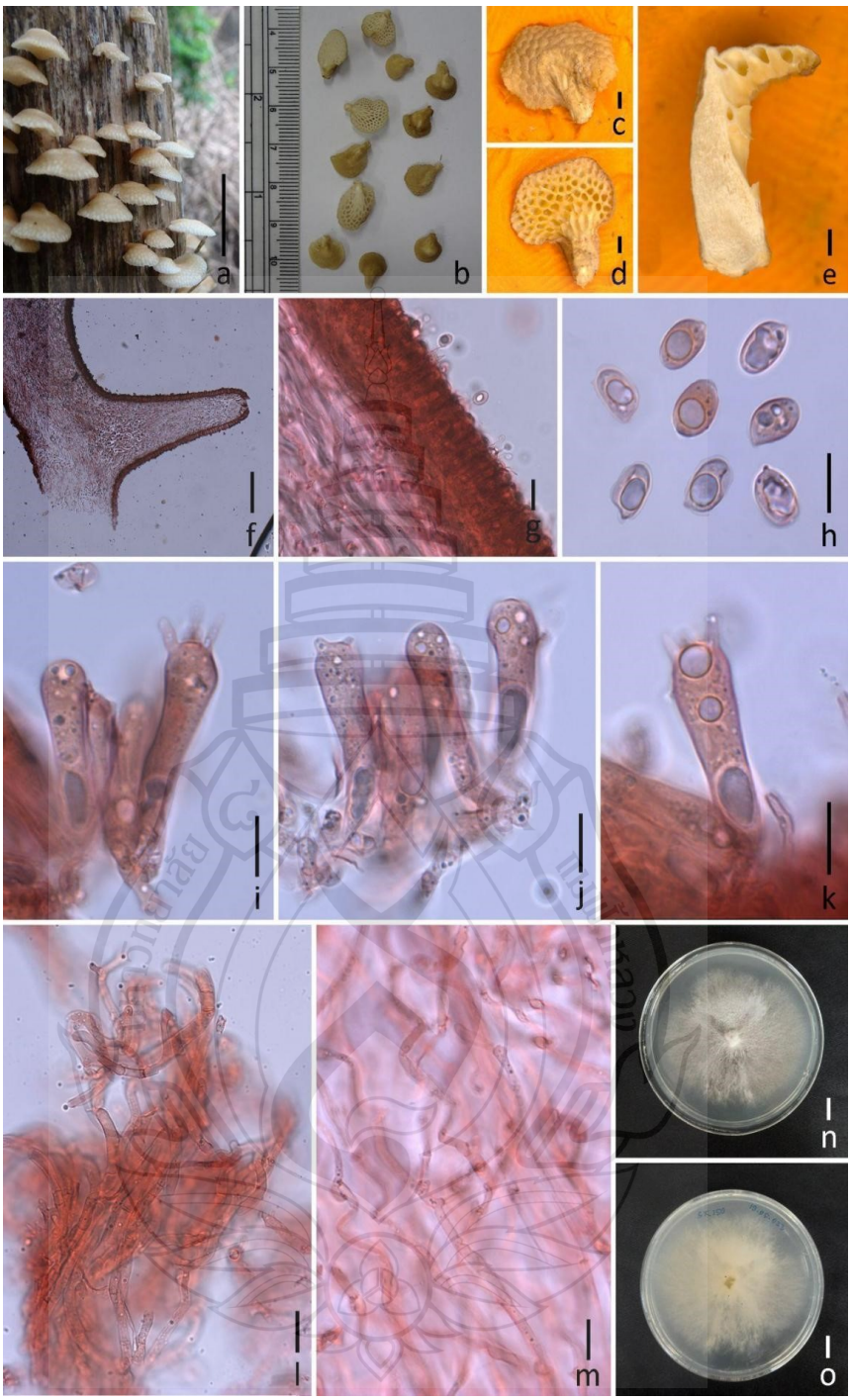
Basidiomata annual, gregarious, and gelatinous when fresh, becoming dry. *Pilei* 5−8 × 3.5−8 mm, pileal surface whitish then greyish (3B3) when fresh, turning greyish (4C4) to dirty brownish (5D4) upon drying, convex, reticulate pattern distinct, matching the pores below, glabrous; margin straight, crenulated; context up to 32.1 μm, with translucent. *Hymenophore* concolourous with pileal surface, poroid, 60−125 pores per basidiomata; mature pores 0.5−0.9 mm diam., polygonal, size varies irregularly, larger near the base and smaller near the edge, the margin pores often incomplete; tubes up to 1.4 mm long. *Stipe* 1.7−3 × 1−2.2 mm, concolourous with pilei, surface gelatinous. *Basidiospores* 7.8−12.5 × 5.1−8.4 μm, L = 10.63 μm, W = 6.75 μm, Q = 1.49−1.54 (n = 50/3), broadly ellipsoid to subglobose, hyaline, thin-walled, smooth, with one or two guttules. *Basidia* 40−52 × 10−13 μm, narrowly clavate with some guttles, tapered towards the base, apex broadly rounded, 2 or 4-spored, sterigmata 3.6−8 × 2.1−2.9 μm long; basidioles similar in shape to the basidia, but slightly smaller. *Acanthocystidia* and *gloeocystidia* absent. *Cheilocystidia* 13−20 × 4−5 μm, thin-walled, present at the dissepiment edge, irregular with small diverticulate projections on the side of the apex. *Pileipellis* hyphae interwoven, occasionally with some small diverticulate projections, smooth, thin-walled, 2.4−4.8 μm diam. *Tramal hyphae* 2.3−5.4 μm diam., thin-walled, interwoven, widely spaced in a thick gelatinous matrix, frequently branched. *Stipe hyphae* 2−6 μm, subparallel along the stipe, and some parts swollen. *Clamp connections* present in all tissues.

Culture characteristics: Colonies on PDA occurred after incubation for 5 days, reaching 7.5 cm diam., after incubating at 25°C for 20 days, from above, white radiating outwards, thin, irregular, flattened with smooth surface; reverse white.

Material examined: Thailand, Chiang Rai Province, Muang, 400 m, 19°56' 27" N, 99°40'23" E, 12 May 2023, on decaying bamboo in a mixed deciduous forest, S. Khyaju, SK150 (MFLU25-0024), living culture MFLUCC 25-0026.

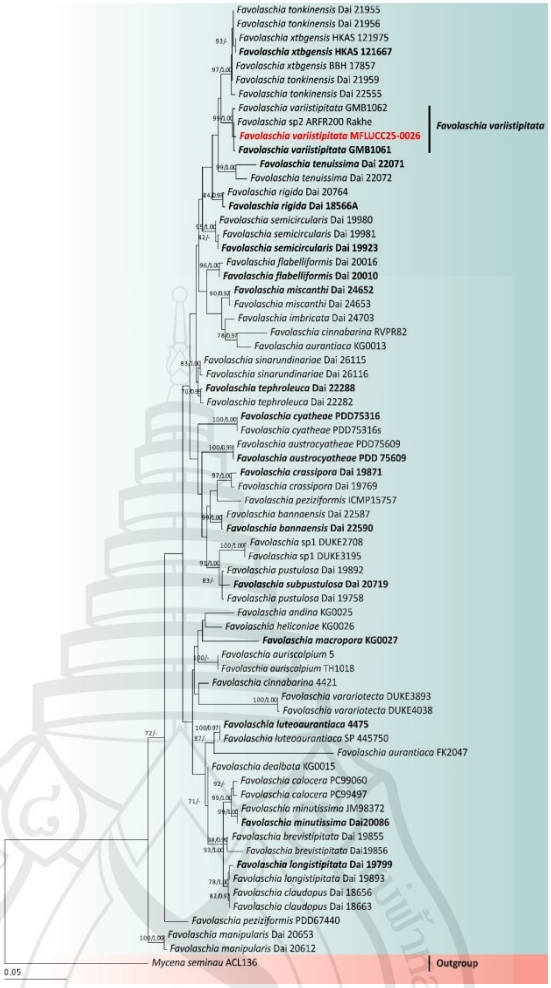
GenBank numbers: ITS = PQ897959, LSU = PQ899253.

Notes: Phylogenetically, our sample (MFLUCC 25-0026) forms a lineage within the *Favolaschia variistipitata* clade (GMB1061, GMB1062, and ARFR200 Rakhe), with a strong support (99% ML, 1.00 BYPP, Figure 6.13). Morphologically, our sample shares common macro- and micro-characteristics with the holotype of *F. variistipitata* (GMB1061) (Lu et al., 2025). However, the basidiospore of our sample is slightly larger (7.8−12.5 × 5.1−8.4 μm) compared to the holotype (5–8.7 × 3.5–6.5 μm). Similarly, the basidia are also larger (40−52 × 10−13 μm) than those of the holotype (21–29 × 7–9.5 μm). Our sample exhibited 2- or 4-spored basidia, differing from the holotypic, which described only 2-spored basidia. Notably, the gloeocystidia are absent in our studied sample, which is described in the holotype. Based on phylogenetic analyses and overlapping morphological characteristics, we identified our sample as *F. variistipitata.* This represents a new geographical record for Thailand.



Note a–d Basidiomata. e Longitudinal section of basidiomata. f Vertical-section of pileus. g Vertical section of hymenium layer. h Basidiospores. i–k Basidia and basidioles. l Hyphae of pileipellis. m Hyphae of trama. n, o Culture characteristics. Scale bars: a, n, o = 1 cm, c–e = 1 mm, f = 200 μm, g–m = 10 μm.

Figure 6.12 *Favolaschia variistipitata* (MFLU25-0024)



Note Phylogram generated from maximum likelihood analysis based on combined ITS and LSU sequence data from 69 taxa, comprising 1,508 characters (ITS = 599, LSU = 909). The best-scoring RAxML tree with a final likelihood value of -6668.926 is presented. The matrix contained 476 distinct alignment patterns, with 26.77% of the characters being undetermined or gaps. Estimated base frequencies were as follows: A = 0.243, C = 0.208, G = 0.266, T = 0.282; substitution rates: AC = 1.191, AG = 2.959, AT = 1.551, CG = 0.731, CT = 5.570, GT = 1.0; gamma distribution shape parameter α = 0.219. Bootstrap support values for maximum likelihood (ML) equal to or greater than 70% and clade credibility values greater than 0.90 (rounded to two decimal places) from Bayesian inference analysis are labelled at each node. The newly generated sequence is in red bold. The tree is rooted to *Mycena seminau* (ACL136) (Zhang et al., 2024c).

Figure 6.13 Phylogenetic tree of *Favolaschia*

6.3.5 *Podoscypha gillesii* Boidin & Lanq., Persoonia 7(2): 145, Figure 6.14

Index Fungorum number: IF320789; *Facesoffungi number*: FoF 18007

Basidiomata annual, leathery, sessile or short, flattened stipe, gregarious. *Pileus* up to 8 cm wide, 5.5 cm long, 326–413 µm thick, flabelliform to subinfundibuliform, minutely tomentose, often with lobed margins, fused along adjacent margins, not cracking when dry. *Pileal surface* brown except at the margin, with distinct concentric zones in varying shades, orange white (5A2), pale orange (5A3), light brown (6D5–6), brown (7E5–7), and dark brown (7F5–7), no reaction to KOH. *Margin* white, wavy, sterile, thinning out, and lacking hairs. *Hymenial surface* smooth, whitish when young, becoming pale to brown with age, no reaction to KOH; in section, hymenium hyaline, surface brown with dark hairs. *Odour* and *taste* not distinctive.

Hyphal structure dimitic, inamyloid, tissue unchanged in KOH. *Generative hyphae* common in the pileus context, with clamp connections and simple septa, hyaline, thin-walled, usually branched, 2.7–6.4 µm in diam. *Skeletal hyphae* 3.7–7.2 µm in diam, thick-walled (wall thickness 1.3–2.6 µm), with narrow lumen, simple-septate, unbranched, inamyloid. *Gloeocystidia* common, 31.1–47.6 × 7.7–14.5 µm, hyaline, thick-walled (1.21–2.47 µm), long and undulating with 1–2 swollen sections, narrow towards apex, arising from the sub-hymenium, with the upper part often filled with highly refractive contents. *Basidia* 12.7–20.5 × 1.7–5.4 µm, clavate to cylindrical, with 4 sterigmata and a basal clamp. *Basidioles* dominant, similar in shape to basidia but slightly smaller. *Basidiospores* 2.2–3.6 × 1.5–2.4 µm (n = 30/3), L = 2.94 µm, W = 2.0 µm, Q = 1.48–1.49, subglobose to globose, hyaline, thin-walled, smooth, and inamyloid.

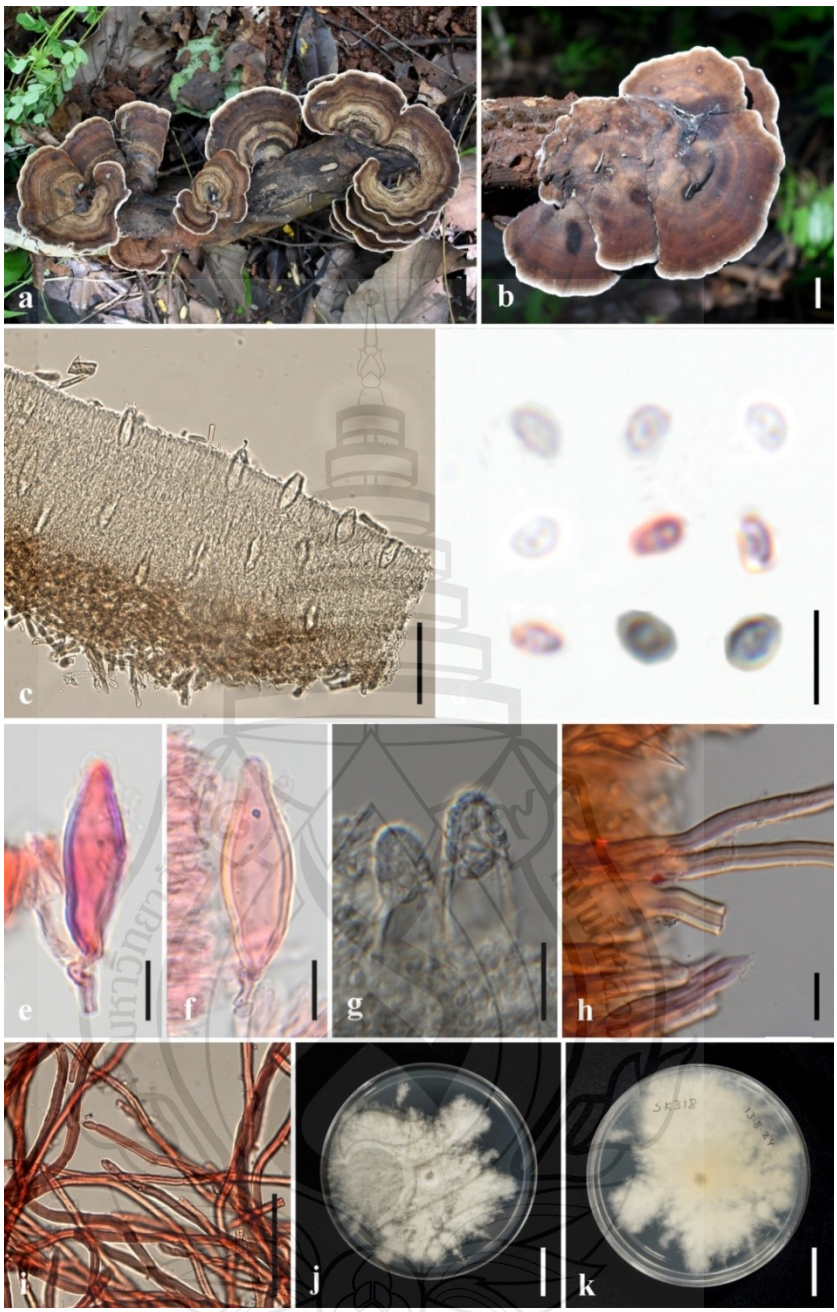
Culture characteristics: Basidiospores germinate on PDA after incubating for 24 hr at 25°C, colonies grow to 9 cm in diam after 20 days, with irregular margins surface downy, white, and dense. Generative hyphae with clamp connections, thin-walled, hyaline, and frequently branched.

Material examined: Thailand, Chiang Rai Province, Muang Chiang Rai District, growing on fallen angiosperm tree branch, 10 August 2024, S. Khyaju, SK318, 470 masl, N 20°2'47", E 99°53'47" (MFLUCC 25-0238, MFLU 25-0226)

Known distribution (based on molecular data): China (Huang et al. 2024), Germany (GenBank), India (GenBank), Malaysia (GenBank), Thailand (this study).

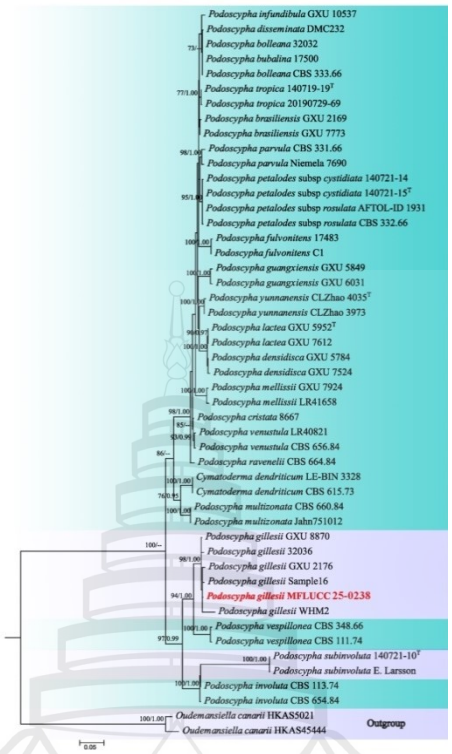
GenBank Accession Numbers – ITS: PV954759; LSU: PV946030.

Notes: In the phylogenetic analyses, our strain (MFLU 25-0226) is grouped with the other specimens of *Podoscypha gillesii* (GXU 8870, 32036, GXU 2176, Sample 16, WHM2) by forming a separate clade, with 98% ML and 1.00 BYPP support (Figure 6.15). The morphological characters of our specimen align well with those of the holotype (voucher LY6698) collected in Gabon, Africa, as described by Boidin and Lanquetin (1973). *Podoscypha gillesii* is distinguished by several key characteristics, including flabelliform to subinfundibuliform, sessile basidiomata with a densely brown-hairy surface, a white sterile margin, distinct concentric zoning, hyaline hymenium in section, brown pileus surface with brown hairs, dimitic hyphal system, presence of gloeocystidia, and inamyloid, sub-globose to globose basidiospores (Boidin & Lanquetin, 1973; Drechsler-Santos et al., 2007; Huang et al., 2024). Boidin and Lanquetin (1973) have reported similarities in microscopic characteristics between *P. gillesii* and the closely related species *P. vespillonea*. However, our specimen is distinguishable by the absence of bright-colored basidiomata and the presence of a brown upper surface with a white margin (Boidin & Lanquetin, 1973). Additionally, our specimen is thin (0.5 mm), leathery in texture, and does not crack upon drying. Based on morphological characteristics and phylogenetic evidence, we conclude our specimen is *Podoscypha gillesii* and it is a new geographical record in Thailand.



Note a–b Basidiomata in habitat. c Section of basidiomata. d Basidiospores. e–g Gloeocystidia. h Skeletal hyphae. i Hyphal hairs on the pileus surface. j Culture (top view). k Culture (bottom view). Scale bars: a–b, j–k = 2 cm, c, i = 20 µm, d = 5 µm, e–h = 10 µm.

Figure 6.14 *Podoscypha gillessi* (MFLUCC 25-0238)



Note Phylogram generated from maximum likelihood (ML) analysis based on a combined ITS and LSU sequence. Forty-nine taxa were included in the analyses, which comprised 1384 characters with gaps (ITS = 438, LSU = 944). Single-gene analyses were also performed, and the resulting topologies and clade stability were compared with those from the combined dataset. The best-scoring RAxML tree, with a final likelihood value of -5819.807334 is presented. The matrix contained 469 distinct alignment patterns, with 28.35% of characters being undermined or gaps. Estimated base frequencies were as follows: A = 0.258061, C = 0.199321, G = 0.275267, T = 0.267352; substitution rates: AC = 1.142699, AG = 2.770921, AT = 1.201185, CG = 0.824953, CT = 5.431885, GT = 1.0; gamma distribution shape parameter α = 0.279021. Bootstrap support values from ML equal to or greater than 70% and clade credibility values equal to or greater than 0.95 (rounded to two decimal places) from Bayesian inference analysis are labelled above each node. The newly generated sequence is in red bold, and the type strains are indicated with "^{T}". *Oudemansiella canarii* (HKAS5021) and *O. canarii* (HKAS45444) were used as outgroup taxa.

Figure 6.15 Phylogenetic tree of *Podoscypha*

6.3.6 *Trullella yunnanensis* C.L. Zhao, in He, Dong & Zhao, Kew Bull. 78(1): 216, Figures 6.16, 6.17

Index Fungorum number: IF843170, *Facesoffungi number*: FoF 16637

Basidiomata annual, solitary, laterally stipitate. *Pileus* 1.5−6 cm wide, up to 1 mm thick, reniform to semi-circular, applanate, smooth, zonate, radially striate, cream to yellowish when young, light brown upon maturity on the upper surface. *Margin* entire, acute. *Pores* 7−8 per mm, small and round, dissepiments thin, entire, white to cream when young, light brown upon maturity. *Stipe* up to 4 cm long, up to 6 mm diam., with a cylindrical shape. *Corky* up to 0.2 mm thick, creamy, and leathery in dried condition. *Tubes* up to mm 0.3 mm long, concolourous with hymenium surface, with corky.

Basidiospores (3.4–)3.7–5.6(– 5.7) × 1.6–2.4 µm, L = 4.9 µm, W = 2 µm, Q = 2.15–2.33, Q_m = 2.42 (n = 30), cylindrical and curved, thin-walled, smooth, colourless. *Basidia*. 7−12 × 5−7.5 µm, clavate to barrel-shaped, with four sterigmata clamped at base. *Basidioles* dominant, pear-shaped, and slightly smaller than basidia. *Hyphal structure* dimitic hyphal system and clamped generative hyphae, all tissues unchanged in KOH. *Context* 3−5 µm in diam., generative hyphae dominant, colourless, thin-walled, and branched; skeletal hyphae 4−5.5 µm in diam., colourless, thick-walled, with unbranched. *Tubes*: hyphal pegs common 25−40 × 15−30 µm. *Cystidia and cystidioles* absent. *Culture characteristics* greyish white, non-fluffy. *Odour* and *Taste* Undetermined.

Habitat: on decaying log, mixed coniferous forests.

Material examined: Thailand, Chiang Rai Province, Mae Fah Luang District, 20 October 2023, S. Khyaju, MFLU24-0322.

GenBank accession numbers: ITS: PQ452693.

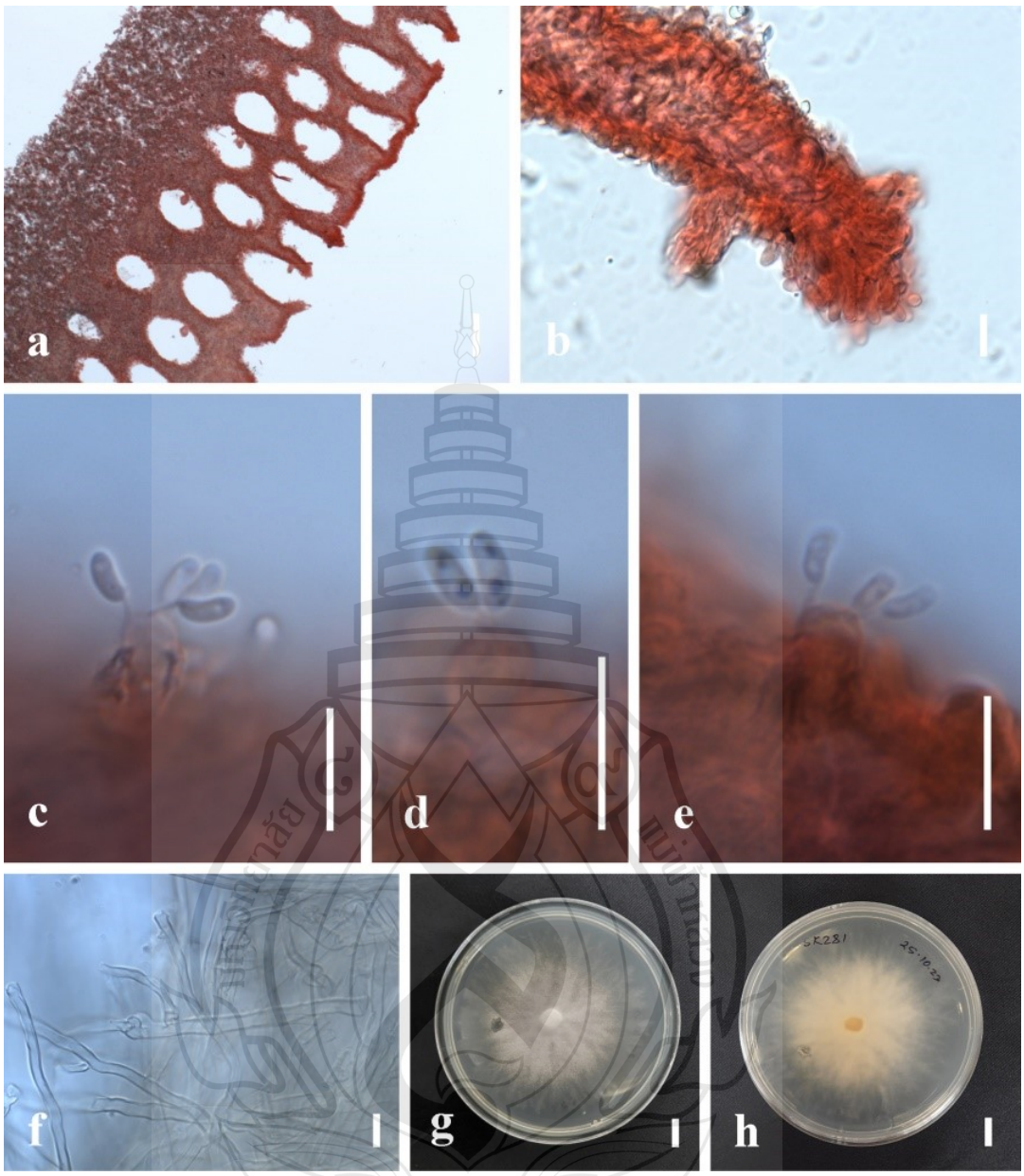
Known distribution: China (Cao et al. 2021, He et al. 2023), Thailand (this study).

Notes: The newly recorded species, *Trullella yunnanensis* is described based on morphological characters and phylogenetic (ITS) analyses. In the present study, our strain is nested in the *T. yunnanensis* clade and forms a sister clade with *T. conifericola* (Figure 6.18). However, the former taxa have 7−8 pores per mm, whereas the latter have 10–12 pores per mm. This study supports the prediction of He et al.

(2023) that this species could be found in East Asia. Additionally, with further investigations, new taxa and records are possible to be found in this region.

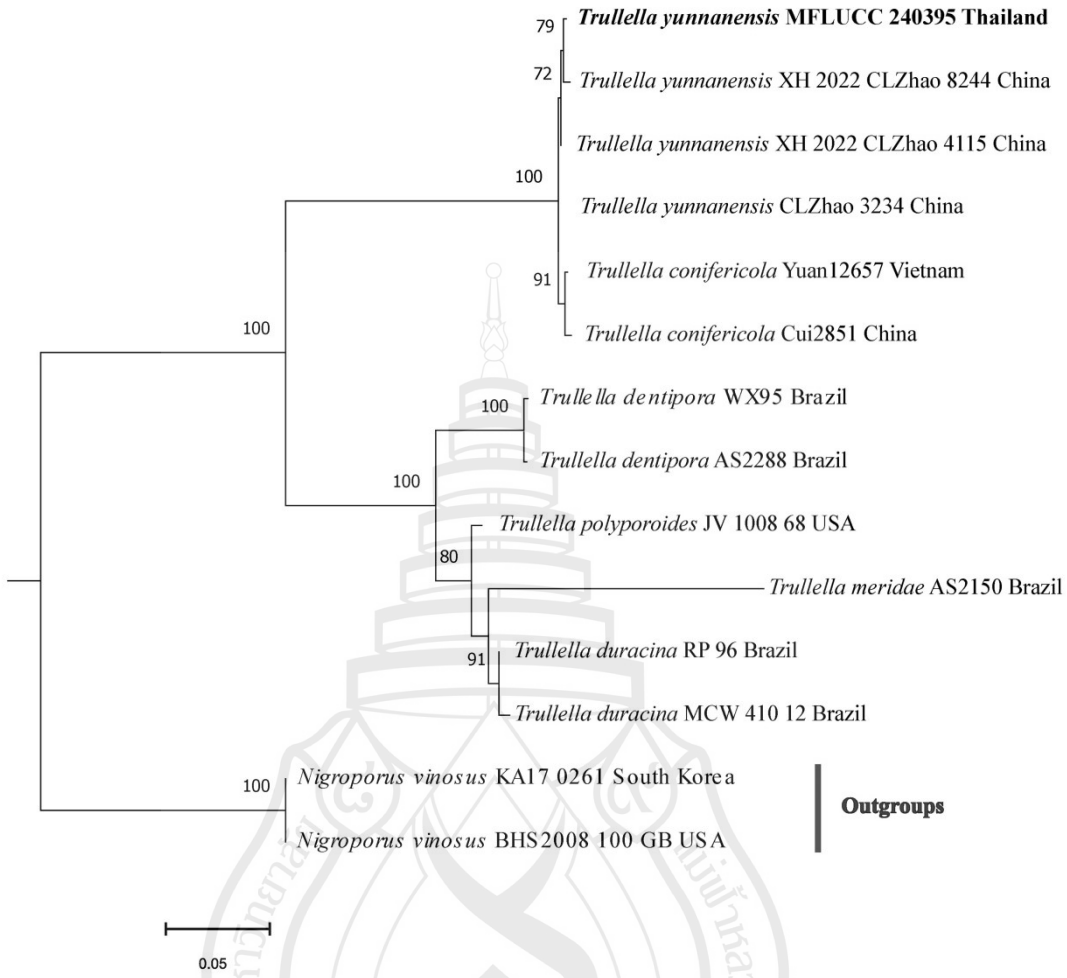
Note a–c Basidiomata. d Pore surface. Scale bars: a, b = 2 cm, d = 1 mm.

Figure 6.16 Macro-morphology of *Trullella yunnanensis* (MFLU 24-0322)



Note a Section of hymenium and hyphal pegs in it. b A hyphal peg in the wall of the hymenium pore. c−e Basidia & basidiospores. f Hyphae from context. g Culture in PDA (top view). h Culture in PDA (bottom view). Scale bars: a = 100 µm, b−f = 10 µm, g, h = 1 cm.

Figure 6.17 Micro-morphology of *Trullella yunnanensis* (MFLU 24-0322)



Note Phylogenetic tree (RAxML) obtained from the DNA sequence data of the nrITS dataset. Phylogenetic analyses were inferred from the ITS sequences, comprising 14 taxa, including 12 *Trullella* species and two outgroup species, *Nigroporus vinosus* BHS2008 and *Nigroporus vinosus* KA170261. The final dataset comprised 647 total characters, including gaps after alignment. Our specimen grouped with the strains of *T. yunnanensis*, and forms a sister clade with *T. conifericola*. Bootstrap values (BS) from maximum likelihood (ML) greater than 70% are indicated above the nodes. The tree is rooted with *Nigroporus vinosus* BHS2008 and *Nigroporus vinosus* KA170261. Newly recorded species from Thailand are indicated in black bold.

Figure 6.18 Phylogenetic tree of *Trullella*

CHAPTER 7

CONCLUSIONS

7.1 Overall Conclusions

7.1.1 Development and Characterization of Mycelium-Based Biomaterials

7.1.1.1 Study on pure mycelium mats developed from *Phlebiopsis friesii*

In this study, a wild mushroom specimen collected in Chiang Mai, Thailand, was identified as *Phlebiopsis friesii* based on morphology and phylogeny analysis. The mycelium mats were successfully developed using commercial nutrient broths and liquid-state surface fermentation techniques. Comparative studies of treated and untreated mycelium mats provided valuable insights into their potential as leather substitutes. Key characteristics of the mycelium mats, including mycelium biomass, TGA, FTIR, SEM, and WCA, were evaluated and reported. Notably, this is the first in-depth investigation of this genus regarding pure mycelium mats. However, limitations in the final products highlight the need for further research to optimize processing techniques and enhance the quality of mycelium mats for leather applications.

7.1.1.2 Study on mycelium-based biomaterials developed from *Panus ciliatus* and *P. subfasciatus*

In this study, two wild fungal species, *Panus ciliatus* and *P. subfasciatus*, collected in Chiang Rai, Thailand, were identified based on a combination of morphological features and phylogenetic molecular analyses (ITS), the former species being a new geographical record in Thailand (ML = 80%, BPP = 0.92). Mycelial growth in both agar media and sawdust indicates that these fungal species are suitable for MMB production. MMB developed from these species exhibited suitable physical and mechanical properties, supporting previous studies and matching synthetic foams. However, the low mechanical properties exist as a challenge for materials, requiring greater strength. Notably, the lower shrinkage (around 8%) of MMB material supports construction. The water contact angle above 100 degrees with the samples reflects the hydrophobicity of the mycelium of these species. However, the higher water absorption

of composite samples due to the inherent properties of sawdust suggests their use in dry conditions for packaging and indoor applications. Thermal behaviour analysis and flammability testing showed greater thermal stability due to the properties of mycelium in forming char and resisting heat transmission into the inner area. Changes in the chemical properties of MMBs were the result of the enzymatic digestion process of mycelium in lignocellulosic substrates in suitable environments. The higher weight loss percentage (above 60%) in 90 days indicates that MMB is a biodegradable and eco-friendly material, which results from microbial activity and biochemical reactions. Both chemical changes and biodegradability showed that composting MMB contributes to ecological balance through both nutrient cycling and soil enrichment. Additionally, viability maintenance of the two *Panus* species was successfully conducted through basidiomata production, providing a solution for culture degeneration issues. The fabrication of prototypic MMB materials has provided insights for the commercial-scale production potential of these two mushrooms, including construction, packaging, household uses, and insulation products.

7.1.1.3 Study on mycelium-based biomaterials developed from twelve fungal strains

In this study, ten wild mushrooms and two commercial edible fungal strains were used to develop MMB test samples. The mycelial growth performance in agar media (PDA and MEA) and sawdust could be referred to as preliminary criteria for understanding culture characteristics. Pure mycelium mats were successfully developed in broth media (PDB and MEB), thereby providing a basis for further exploration to strengthen them. The MMB test samples exhibited suitable physical and mechanical behavior comparable to synthetic foams, suggesting it as an alternative material. The fungal strains showed thermal stability, leaving more than 30% of residue at around 300°C. Additionally, mycelium showed higher hydrophobicity, above 125° and 120° at 10 and 60 s, respectively. All fungal strains showed a higher percentage (above 60%) of weight loss around 90 days of soil burial, providing insights into their sustainability and biodegradability. The prototypic MMBs indicate the scope of scale-up, focusing on packaging, insulation, and the non-load-bearing construction sector.

7.1.2 Global Checklist of Fungi in MMBs

This study reveals that for the development of mushroom mycelium-based biomaterials (MMBs), only a limited number of mushroom species are used, distributed

in the orders *Polyporales* (67 species) and *Agaricales* (20 species), and a few in the orders *Hymenochaetales* (six species), *Auriculariales* (two species), *Russulales* (two species), and *Gleophyllales* (one species). Regarding direct use of mushroom basidiomata to develop mushroom-based biomaterials (MBs), only seven fungal species have been studied. Research and development on MMBs are growing worldwide, with major efforts in Asia, Europe, and North America. The study indicates a huge gap between the total described fungal species and the selectively used fungal species in MMBs. Additionally, the challenges inherent in this field, including misleading science, substrate concerns, culture contamination issues, material properties, scale-up, and marketing regulations, unveil the requirement for intensive exploration in research and development.

7.1.3 Fungalpedia – Basidiomycota Genera and Notes on Mushroom Mycelium-Based Biomaterials

This study is divided into two parts: (a) notes on Basidiomycota genera and (b) notes on terminologies related to mushroom mycelium-based biomaterials. The first part provides notes of 229 genera distributed in 60 families, 15 orders, and 3 sub-classes under the class Agaricomycetes. Redrawn illustrations of fungal species are provided based on publications to ease the understanding of their morphological characters. The photos of original basidiomata are provided with the permission of the authors. The second part of this section is notes on 55 terminologies commonly used in the field of mushroom mycelium-based biomaterials (MMBs). Photos of related terms are provided for clarity.

7.1.4 Additional work: Morphological and Phylogenetic Analysis of Fungal Samples from Thailand

Among the collected fungal samples in this study, the order Polyporales represents the largest number of fungal strains (67.7%), followed by Agaricales (17.8%) and Hymenochaetales (4.7%). In Agaricales, the largest number of samples is in Mycenaceae (10), followed by Schizophyllaceae (9), Omphalotaceae (8), and Psathyrellaceae (7). Regarding culture, 187 fungal strains were successfully isolated from the basidiomata using either the tissue or spore isolation method. Among the collected fungal samples, some were studied morphologically and phylogenetically. This section reports three new species, namely *Echinochaete thailandica*, *Phanerochaete brunneohyha*, and *Thelephora chiangmaiensis*, and three new geographical records, namely *Favolaschia variistipitata*, *Podoscypha gillessi*, and *Trullella yunnanensis*.

7.2 Research Highlights

7.2.1 The first worldwide checklist of fungi used in mushroom mycelium-based biomaterials (MMBs) until 2024 was provided.

7.2.2 A review on a wide range of applications of MMBs, mainly packaging, building, insulation, architectural designs, and textiles, was conducted.

7.2.3 A total of 15 fungal strains were used in the development of MMBs test samples, their characterization (physical, mechanical, hydrodynamic, and chemical properties), and prototypic product development. Additionally, four new species and four new geographical records were reported.

7.2.4 Fungalpedia entries on basidiomycota genera, including 60 families and 229 genera, were provided. The first compilation of notes on terms related to MMBs was also provided.

7.3 Research Advantages

7.3.1 The first checklist of fungal species used in MMBs: Scientific identification of fungal species poses prime importance before its application, for reliability and reproducibility. The combination of morphological characteristics and phylogenetic analyses provides confidence in fungal identification. All the fungal taxa that were used in MMB studies, both at experimental and commercial scales, are compiled for easy referencing for expanding research and development.

7.3.2 A review on diverse applications of MMBs: Despite the innovative field, the trend of MMB application has surged to a wide range of applications. Demand for pure mycelium mats has increased not only as an alternative to animal hide-based leather, but also to medical appliances such as wound healing tape. MMB has been used in non-load-bearing constructions, insulation, and architectural designs. Their cushioning effects make it an option to replace synthetic foams, especially in packaging and furniture.

7.3.3 Comprehensive characterisation of MMBs: MMBs need to deliver complete information on their biological, chemical, and material properties before

scale-up. This study provided comprehensive details on 15 fungal strains, which has never been done before. The criteria for characterizing MMBs will be easier to understand by referencing these methods and results presented here. Additionally, the successful prototypic development will lead to its industrial-level production.

7.3.4 Compilation of illustrated notes on fungal genera: Many fungal genera established a long time ago are mostly deficient in information. The described fungal genera solely based on taxonomy require an update on the latest molecular phylogeny, habit and habitat, geographical distribution, closely related taxa, and applications. This study has fulfilled the gap by providing comprehensive information, along with hand-drawn photo plates.

7.3.5 Compilation of notes on terms related to MMBs: This compilation of notes on terminologies generally used in the MMB sector will ease understanding. Scientific investigation on MMB would be easier allowing consistency and uniformity in the literature. Additionally, public awareness of using renewable and sustainable materials will be boosted.

7.3.6 Fungal strain resource: A total of 365 fungal strains were collected and preserved, with 187 pure cultures. The cultures will be an accessible resource for extensive study on suitable fungal candidates in MMBs.

7.4 Future Work

7.4.1 Further collection of suitable fungal candidates: The number of Basidiomycota fungal species accounts for approximately 40,000, leaving a high chance of finding highly suitable fungal candidates for the MMB sector. Undiscovered fungal species require scientific identification using the widely accepted approach of combining morphological characteristics with molecular phylogenetic analyses. Pure cultures extraction from them will be another essential task to begin preliminary culture studies.

7.4.2 Experimental study on other isolated fungal species: Only a portion of fungal species have been studied during this research, due to time limitations. Many other fungal genera need thorough investigation, at least the tests and analyses performed for the above-mentioned fungal species.

7.4.3 Establishing and patenting methods/ protocols: Suitable methods for developing MMBs can be properly described and established through a multidisciplinary approach. Successful techniques can be patented to provide the right direction of research and development in MMBs.

7.4.4 Enhancing overall mechanical properties: In this study, Ashby's chart of the test samples developed using mycelium and sawdust substrates showed similar mechanical strength compared to synthetic foams. However, the strength can be enhanced by applying techniques such as heat-pressing and boosting mycelial density. Treatments with different plasticisers and hyphae-linking binder chemicals could enhance the flexural and tensile strength of MMBs. Additionally, genetically modified fungal mycelium of some fungal species has exhibited enhanced mechanical strength of MMBs.

7.4.5 Medical application: Pure mycelial mats derived from some of the medicinal fungal species have been successfully used as wound dressing materials at the research level. Biocompatibility of mycelium with human tissue provides insights for in-depth studies.

7.4.6 Collaboration among mycologists, environmentalists, engineers, and medical personnel: A well-organised conservation effort for fungal species relies on scientific identification of the fungal species. Environmental protectionists and mycologists should work together in order to conserve the fungal species in their natural habitat. MMBs are an interdisciplinary approach, including engineering prospects to deal with materialistic behavior. Mycologists also need to collaborate with medical experts to use pure mycelium for health care purposes without issues.

7.5 Publications

First Author Publications

Khyaju, S., & Luangharn, T. (2024). Diverse use of mushroom mycelium-based biomaterial products: A mini review. *Fungal Biotec, 4*(1), 56–67. https://doi.org/10.5943/FunBiotec/4/1/4

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Khyaju, S., Salichanh, T., Khongphinitbunjong, K., Duangphet, S., Hyde, K. D., & Luangharn, T. (2025). *Phlebiopsis friesii* (Phanerochaetaceae, Polyporales), a new record in Thailand and the first preliminary characterization of its potential in mycelium mats. *Mycobiology, 53*(4), 480–494. https://doi.org/10.1080/12298093.2025.2518801

Co-author Publications

Bera, I., Sysouphanthong, P., Khyaju, S., Hyde, K. D., & Thongklang, N. (2024). Insights into the genus *Xeromphalina*, *X. tenuipes* (Schwein.) AH Sm. complex and discovery of a novel species, *X. pseudotenuipes*, from Thailand. *Phytotaxa, 666*(3), 169–187. https://phytotaxa.mapress.com/pt/article/view/phytotaxa.666.3.1

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APPENDIX A

DETAILS OF FUNGAL SAMPLES

Table A1 Detail Classification of Collected Fungal Samples

Subclass	Order	Family	Genus	Scientific name	Sample Code
Agaricomycetidae	Agaricales	Agaricaceae	*Agaricus*	*Agaricus leptocaulis*	SK30
Agaricomycetidae	Agaricales	Agaricaceae	*Coprinus*	*Coprinus* sp.	SK79
Agaricomycetidae	Agaricales	Agaricaceae	*Leucoagaricus*	*Leucoagaricus* sp.	SK273
Agaricomycetidae	Agaricales	Campanellaceae	*Campanella*	*Campanella buettneri*	SK154
Agaricomycetidae	Agaricales	Campanellaceae	*Campanella*	*Campanella* sp.	SK335
Agaricomycetidae	Agaricales	Campanellaceae	*Campanella*	*Campanella* sp.	SK336
Agaricomycetidae	Agaricales	Clavariaceae	*Ramariopsis*	*Ramariopsis* sp.	SK52
Agaricomycetidae	Agaricales	Crepidotaceae	*Crepidotus*	*Crepidotus* sp.	SK17
Agaricomycetidae	Agaricales	Hymenogastraceae	*Galerina*	*Galerina* sp.	SK348
Agaricomycetidae	Agaricales	Hymenogastraceae	*Gymnopilus*	*Gymnopilus* sp.	SK64
Agaricomycetidae	Agaricales	Incertae sedis	*Lactocollybia*	*Lactocollybia epia*	SK85
Agaricomycetidae	Agaricales	Incertae sedis	*Trogia*	*Trogia* sp.	SK284
Agaricomycetidae	Agaricales	Inocybaceae	*Inocybe*	*Inocybe hopeae*	SK345

Table A1 (continued)

Subclass	Order	Family	Genus	Scientific name	Sample Code
Agaricomycetidae	Agaricales	Inocybaceae	*Inocybe*	*Inocybe virosa*	SK354
Agaricomycetidae	Agaricales	Incertae sedis	*Trogia*	*Trogia* sp.	SK183
Agaricomycetidae	Agaricales	Lycoperdaceae	*Lycoperdon*	*Lycoperdon* sp.	SK362
Agaricomycetidae	Agaricales	Lyophyllaceae	*Termitomyces*	*Termitomyces* sp.	SK170
Agaricomycetidae	Agaricales	Lyophyllaceae	*Termitomyces*	*Termitomyces* sp.	SK302
Agaricomycetidae	Agaricales	Marasmiaceae	*Crinipellis*	*Crinipellis rhizomaticola*	SK155
Agaricomycetidae	Agaricales	Marasmiaceae	*Marasmius*	*Marasmius* sp.	SK169
Agaricomycetidae	Agaricales	Marasmiaceae	*Marasmius*	*Marasmius* sp.	SK98
Agaricomycetidae	Agaricales	Marasmiaceae	*Marasmius*	*Marasmius trichotus*	SK160
Agaricomycetidae	Agaricales	Marasmiaceae	*Marasmius*	*Marasmius xestocephalus*	SK163
Agaricomycetidae	Agaricales	Mycenaceae	*Favolaschia*	*Favolaschia calocera*	SK204
Agaricomycetidae	Agaricales	Mycenaceae	*Favolaschia*	*Favolaschia manipularis*	SK353
Agaricomycetidae	Agaricales	Mycenaceae	*Favolaschia*	*Favolaschia* sp.	SK150
Agaricomycetidae	Agaricales	Mycenaceae	*Favolaschia*	*Favolaschia* sp.	SK164
Agaricomycetidae	Agaricales	Mycenaceae	*Favolaschia*	*Favolaschia* sp.	SK188
Agaricomycetidae	Agaricales	Mycenaceae	*Favolaschia*	*Favolaschia* sp.	SK208
Agaricomycetidae	Agaricales	Mycenaceae	*Favolaschia*	*Favolaschia* sp.	SK289

Table A1 (continued)

Subclass	Order	Family	Genus	Scientific name	Sample Code
Agaricomycetidae	Agaricales	Mycenaceae	*Filoboletus*	*Filoboletus manipularis*	SK338
Agaricomycetidae	Agaricales	Mycenaceae	*Mycena*	*Mycena* sp.	SK153
Agaricomycetidae	Agaricales	Mycenaceae	*Panellus*	*Panellus luxfilamentus*	SK159
Agaricomycetidae	Agaricales	Omphalotaceae	*Collybiopsis*	*Collybiopsis* sp.	SK102
Agaricomycetidae	Agaricales	Omphalotaceae	*Gymnopus*	*Gymnopus* sp.	SK165
Agaricomycetidae	Agaricales	Omphalotaceae	*Gymnopus*	*Gymnopus* sp.	SK22
Agaricomycetidae	Agaricales	Omphalotaceae	*Lentinula*	*Lentinula edodes*	SK27
Agaricomycetidae	Agaricales	Omphalotaceae	*Lentinula*	*Lentinula edodes*	SK6
Agaricomycetidae	Agaricales	Omphalotaceae	*Marasmiellus*	*Marasmiellus* sp.	SK152
Agaricomycetidae	Agaricales	Omphalotaceae	*Marasmiellus*	*Marasmiellus* sp.	SK67
Agaricomycetidae	Agaricales	Omphalotaceae	*Neonothopanus*	*Neonothopanus nambi*	SK352
Agaricomycetidae	Agaricales	Physalacriaceae	*Armillaria*	*Armillaria tabesens*	SK349
Agaricomycetidae	Agaricales	Physalacriaceae	*Oudemansiella*	*Oudemansiella canarii*	SK327
Agaricomycetidae	Agaricales	Pleurotaceae	*Pleurotus*	*Pleurotus ostreatus*	SK7
Agaricomycetidae	Agaricales	Psathyrellaceae	*Candolleomyces*	*Candolleomyces candolleanus*	SK56
Agaricomycetidae	Agaricales	Psathyrellaceae	*Coprinellus*	*Coprinellus* sp.	SK57

Table A1 (continued)

Subclass	Order	Family	Genus	Scientific name	Sample Code
Agaricomycetidae	Agaricales	Psathyrellaceae	*Coprinellus*	*Coprinellus* sp.	SK38
Agaricomycetidae	Agaricales	Psathyrellaceae	*Coprinellus*	*Coprinellus* sp.	SK66
Agaricomycetidae	Agaricales	Psathyrellaceae	*Parasola*	*Parasola* sp.	SK29
Agaricomycetidae	Agaricales	Psathyrellaceae	*Psathyrella*	*Psathyrella cacao*	SK317
Agaricomycetidae	Agaricales	Psathyrellaceae	*Psathyrella*	*Psathyrella* sp.	SK358
Agaricomycetidae	Agaricales	Schizophyllaceae	*Schizophyllum*	*Schizophyllum* sp.	SK101
Agaricomycetidae	Agaricales	Schizophyllaceae	*Schizophyllum*	*Schizophyllum* sp.	SK120
Agaricomycetidae	Agaricales	Schizophyllaceae	*Schizophyllum*	*Schizophyllum* sp.	SK131
Agaricomycetidae	Agaricales	Schizophyllaceae	*Schizophyllum*	*Schizophyllum* sp.	SK282
Agaricomycetidae	Agaricales	Schizophyllaceae	*Schizophyllum*	*Schizophyllum* sp.	SK42
Agaricomycetidae	Agaricales	Schizophyllaceae	*Schizophyllum*	*Schizophyllum* sp.	SK50
Agaricomycetidae	Agaricales	Schizophyllaceae	*Schizophyllum*	*Schizophyllum* sp.	SK58
Agaricomycetidae	Agaricales	Schizophyllaceae	*Schizophyllum*	*Schizophyllum* sp.	SK68
Agaricomycetidae	Agaricales	Schizophyllaceae	*Schizophyllum*	*Schizophyllum* sp.	SK72
Agaricomycetidae	Agaricales	Strophariaceae	*Agrocybe*	*Agrocybe flexuosipes*	SK112
Agaricomycetidae	Agaricales	Unidentified	Unidentified	Unidentified	SK330
Agaricomycetidae	Agaricales	Unidentified	Unidentified	Unidentified	SK346

Table A1 (continued)

Subclass	Order	Family	Genus	Scientific name	Sample Code
Agaricomycetidae	Agaricales	Unidentified	Unidentified	Unidentified	SK71
Agaricomycetidae	Agaricales	Unidentified	Unidentified	Unidentified	SK78
Agaricomycetidae	Boletales	Boletaceae	*Boletus*	*Boletus* sp.	SK70
Agaricomycetidae	Boletales	Boletinellaceae	*Phlebopus*	*Phlebopus* sp.	SK148
Agaricomycetidae	Boletales	Serpulaceae	*Serpula*	*Serpula* sp.	SK294
Agaricomycetidae	Hymenochaetales	Hymenochaetaceae	*Fulvifomes*	*Fulvifomes fastuosus*	SK303
Agaricomycetidae	Hymenochaetales	Hymenochaetaceae	*Fuscoporia*	*Fuscoporia gilva*	SK86
Agaricomycetidae	Hymenochaetales	Hymenochaetaceae	*Fuscoporia*	*Fuscoporia gilvoides*	SK189
Agaricomycetidae	Hymenochaetales	Hymenochaetaceae	*Fuscoporia*	*Fuscoporia* sp.	SK291
Agaricomycetidae	Hymenochaetales	Hymenochaetaceae	*Hymenochaete*	*Hymenochaete conchata*	SK295
Agaricomycetidae	Hymenochaetales	Hymenochaetaceae	*Hymenochaete*	*Hymenochaete* sp.	SK180
Agaricomycetidae	Hymenochaetales	Hymenochaetaceae	*Hymenochaete*	*Hymenochaete* sp.	SK306
Agaricomycetidae	Hymenochaetales	Hymenochaetaceae	*Phellinus*	*Phellinus* sp.	SK177
Agaricomycetidae	Hymenochaetales	Hymenochaetaceae	*Phellinus*	*Phellinus* sp.	SK209
Agaricomycetidae	Hymenochaetales	Hymenochaetaceae	*Phellinus*	*Phellinus* sp.	SK235
Agaricomycetidae	Hymenochaetales	Hymenochaetaceae	*Phellinus*	*Phellinus* sp.	SK293
Agaricomycetidae	Hymenochaetales	Hymenochaetaceae	*Phellinus*	*Phellinus* sp.	SK298

Table A1 (continued)

Subclass	Order	Family	Genus	Scientific name	Sample Code
Agaricomycetidae	Hymenochaetales	Hymenochaetaceae	*Phylloporia*	*Phylloporia clausenae*	SK106
Agaricomycetidae	Hymenochaetales	Hymenochaetaceae	*Phylloporia*	*Phylloporia pulla*	SK322
Agaricomycetidae	Hymenochaetales	Hymenochaetaceae	*Porodaedalea*	*Porodaedalea* sp.	SK217
Agaricomycetidae	Hymenochaetales	Hymenochaetaceae	*Porodaedalea*	*Porodaedalea* sp.	SK266
Agaricomycetidae	Hymenochaetales	Incertae sedis	*Trichaptum*	*Trichaptum byssogenum*	SK182
Auriculariomycetidae	Auriculariales	Auriculariaceae	*Auricularia*	*Auricularia asiatica*	SK292
Auriculariomycetidae	Auriculariales	Auriculariaceae	*Auricularia*	*Auricularia asiatica*	SK301
Auriculariomycetidae	Auriculariales	Auriculariaceae	*Auricularia*	*Auricularia* sp.	SK18
Auriculariomycetidae	Auriculariales	Auriculariaceae	*Auricularia*	*Auricularia* sp.	SK20
Auriculariomycetidae	Auriculariales	Auriculariaceae	*Auricularia*	*Auricularia* sp.	SK26
Auriculariomycetidae	Auriculariales	Auriculariaceae	*Auricularia*	*Auricularia* sp.	SK34
Auriculariomycetidae	Auriculariales	Auriculariaceae	*Auricularia*	*Auricularia* sp.	SK45
Auriculariomycetidae	Auriculariales	Auriculariaceae	*Auricularia*	*Auricularia* sp.	SK93
Auriculariomycetidae	Auriculariales	Auriculariaceae	*Elmerina*	*Elmerina sclerodontia*	SK337
Incertae sedis	Gloeophyllales	Gloeophyllaceae	*Gloeophyllum*	*Gloeophyllum* sp.	SK222
Incertae sedis	Gloeophyllales	Gloeophyllaceae	*Gloeophyllum*	*Gloeophyllum* sp.	SK228
Incertae sedis	*Incertae sedis*	Stereaceae	*Stereum*	*Stereum ostrea*	SK363

Table A1 (continued)

Subclass	Order	Family	Genus	Scientific name	Sample Code
Incertae sedis	Polyporales	Fomitopsidaceae	*Fomitopsis*	*Fomitopsis dochmia*	SK218
Incertae sedis	Polyporales	Fomitopsidaceae	*Fomitopsis*	*Fomitopsis feei*	SK173
Incertae sedis	Polyporales	Fomitopsidaceae	*Fomitopsis*	*Fomitopsis feei*	SK245
Incertae sedis	Polyporales	Fomitopsidaceae	*Fomitopsis*	*Fomitopsis feei*	SK299
Incertae sedis	Polyporales	Fomitopsidaceae	*Fomitopsis*	*Fomitopsis feei*	SK331
Incertae sedis	Polyporales	Fomitopsidaceae	*Fomitopsis*	*Fomitopsis ostreiformis*	SK215
Incertae sedis	Polyporales	Fomitopsidaceae	*Fomitopsis*	*Fomitopsis* sp.	SK350
Incertae sedis	Polyporales	Fomitopsidaceae	*Pilatoporus*	*Pilatoporus ostreiformis*	SK54
Incertae sedis	Polyporales	Fomitopsidaceae	*Pilatoporus*	*Pilatoprus ostreiformis*	SK242
Incertae sedis	Polyporales	Fomitopsidaceae	*Ranadivia*	*Ranadivia modesta*	SK181
Incertae sedis	Polyporales	Ganodermataceae	*Sanguinoderma*	*Sanguinoderma rugosum*	SK111
Incertae sedis	Polyporales	Ganodermataceae	*Sanguinoderma*	*Sanguinoderma rugosum*	SK32
Incertae sedis	Polyporales	Ganodermataceae	*Sanguinoderma*	*Sanguinoderma rugosum*	SK82
Incertae sedis	Polyporales	Incrustoporiaceae	*Tyromyces*	*Tyromyces* sp.	SK269
Incertae sedis	Polyporales	Irpicaceae	*Flavodon*	*Flavodon* sp.	SK300
Incertae sedis	Polyporales	Irpicaceae	*Gloeoporus*	*Gloeoporus* sp.	SK254
Incertae sedis	Polyporales	Irpicaceae	*Irpex*	*Irpex flavus*	SK137

Table A1 (continued)

Subclass	Order	Family	Genus	Scientific name	Sample Code
Incertae sedis	Polyporales	Meripilaceae	*Rigidoporus*	*Rigidoporus microporus*	SK239
Incertae sedis	Polyporales	Panaceae	*Cymatoderma*	*Cymatoderma dendriticum*	SK344
Incertae sedis	Polyporales	Panaceae	*Cymatoderma*	*Cymatoderma* sp.	SK261
Incertae sedis	Polyporales	Panaceae	*Cymatoderma*	*Cymatoderma* sp.	SK286
Incertae sedis	Polyporales	Panaceae	*Panus*	*Panus ciliatus*	SK288
Incertae sedis	Polyporales	Panaceae	*Panus*	*Panus ciliatus*	SK304
Incertae sedis	Polyporales	Panaceae	*Panus*	*Panus* sp.	SK121
Incertae sedis	Polyporales	Panaceae	*Panus*	*Panus* sp.	SK19
Incertae sedis	Polyporales	Panaceae	*Panus*	*Panus* sp.	SK328
Incertae sedis	Polyporales	Panaceae	*Panus*	*Panus* sp.	SK329
Incertae sedis	Polyporales	Panaceae	*Panus*	*Panus* sp.	SK63
Incertae sedis	Polyporales	Panaceae	*Panus*	*Panus subfasciatus*	SK43
Incertae sedis	Polyporales	Panaceae	*Panus*	*Panus subfasciatus*	SK49
Incertae sedis	Polyporales	Phanerochaetaceae	*Phanerochaete*	*Phanerochaete* sp.	SK359
Incertae sedis	Polyporales	Phanerochaetaceae	*Phanerochaete*	*Phanerochaete stereoids*	SK308
Incertae sedis	Polyporales	Podoscyphaceae	*Podoscypha*	*Podoscypha gillesii*	SK256
Incertae sedis	Polyporales	Podoscyphaceae	*Podoscypha*	*Podoscypha gillesii*	SK318

Table A1 (continued)

Subclass	Order	Family	Genus	Scientific name	Sample Code
Incertae sedis	Polyporales	Podoscyphaceae	*Podoscypha*	*Podoscypha* sp.	SK158
Incertae sedis	Polyporales	Podoscyphaceae	*Podoscypha*	*Podoscypha* sp.	SK312
Incertae sedis	Polyporales	Podoscyphaceae	*Podoscypha*	*Podoscypha tropica*	SK250
Incertae sedis	Polyporales	Polyporaceae	*Amauroderma*	*Amauroderma rugosum*	SK4
Incertae sedis	Polyporales	Polyporaceae	*Amauroderma*	*Amauroderma rugosum*	SK51
Incertae sedis	Polyporales	Polyporaceae	*Amauroderma*	*Amauroderma* sp.	SK166
Incertae sedis	Polyporales	Polyporaceae	*Amauroderma*	*Amauroderma* sp.	SK210
Incertae sedis	Polyporales	Polyporaceae	*Amauroderma*	*Amauroderma subresinosum*	SK176
Incertae sedis	Polyporales	Polyporaceae	*Amouroderma*	*Amauroderma* sp.	SK175
Incertae sedis	Polyporales	Polyporaceae	*Amouroderma*	*Amouroderma* sp.	SK194
Incertae sedis	Polyporales	Polyporaceae	*Bresadolia*	*Bresadolia uda*	SK244
Incertae sedis	Polyporales	Polyporaceae	*Bresadolia*	*Bresadolia uda*	SK247
Incertae sedis	Polyporales	Polyporaceae	*Cellulariella*	*Cellulariella warnieri*	SK360
Incertae sedis	Polyporales	Polyporaceae	*Coriolopsis*	*Coriolopsis brunneoleuca*	SK3
Incertae sedis	Polyporales	Polyporaceae	*Coriolopsis*	*Coriolopsis brunneoleuca*	SK95
Incertae sedis	Polyporales	Polyporaceae	*Cubamyces*	*Cubamyces lactineus*	SK313

Table A1 (continued)

Subclass	Order	Family	Genus	Scientific name	Sample Code
Incertae sedis	Polyporales	Polyporaceae	*Daedaleopsis*	*Daedaleopsis* sp.	SK290
Incertae sedis	Polyporales	Polyporaceae	*Daedaleopsis*	*Daedaleopsis* sp.	SK323
Incertae sedis	Polyporales	Polyporaceae	*Earliella*	*Earliella scabrosa*	SK127
Incertae sedis	Polyporales	Polyporaceae	*Earliella*	*Earliella scabrosa*	SK234
Incertae sedis	Polyporales	Polyporaceae	*Earliella*	*Earliella scabrosa*	SK240
Incertae sedis	Polyporales	Polyporaceae	*Earliella*	*Earliella scabrosa*	SK243
Incertae sedis	Polyporales	Polyporaceae	*Earliella*	*Earliella scabrosa*	SK270
Incertae sedis	Polyporales	Polyporaceae	*Earliella*	*Earliella scabrosa*	SK339
Incertae sedis	Polyporales	Polyporaceae	*Earliella*	*Earliella scabrosa*	SK55
Incertae sedis	Polyporales	Polyporaceae	*Echinochaete*	*Echinochaete thailandica*	SK134
Incertae sedis	Polyporales	Polyporaceae	*Favolus*	*Favolus glaber*	SK310
Incertae sedis	Polyporales	Polyporaceae	*Favolus*	*Favolus* sp.	SK16
Incertae sedis	Polyporales	Polyporaceae	*Favolus*	*Favolus* sp.	SK167
Incertae sedis	Polyporales	Polyporaceae	*Favolus*	*Favolus* sp.	SK212
Incertae sedis	Polyporales	Polyporaceae	*Favolus*	*Favolus* sp.	SK311
Incertae sedis	Polyporales	Polyporaceae	*Favolus*	*Favolus* sp.	SK320
Incertae sedis	Polyporales	Polyporaceae	*Favolus*	*Favolus tenuiculus*	SK246

Table A1 (continued)

Subclass	Order	Family	Genus	Scientific name	Sample Code
Incertae sedis	Polyporales	Polyporaceae	*Funalia*	*Funalia aspera*	SK135
Incertae sedis	Polyporales	Polyporaceae	*Funalia*	*Funalia aspera*	SK334
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma*	SK355
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma adspersum*	SK65
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma adspersum*	SK77
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma applanatum*	SK142
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma applanatum*	SK59
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma applanatum*	SK60
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma australe*	SK124
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma australe*	SK157
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma australe*	SK191
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma australe*	SK24
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma australe*	SK25
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma australe*	SK9
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma gibbosum*	SK109
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma gibbosum*	SK249
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma gibbosum*	SK74

Table A1 (continued)

Subclass	Order	Family	Genus	Scientific name	Sample Code
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma lucidum*	SK172
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma lucidum*	SK179
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma lucidum*	SK187
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma lucidum*	SK203
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma orbiforme*	SK184
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma orbiforme*	SK62
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma philippii*	SK105
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma sessile*	SK251
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK1
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK10
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK113
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK115
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK125
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK129
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK133
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK140
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK15

Table A1 (continued)

Subclass	Order	Family	Genus	Scientific name	Sample Code
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK178
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK186
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK192
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK199
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK2
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK213
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK231
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK232
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK233
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK255
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK278
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK279
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK297
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK341
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK61
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK76
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK8

Table A1 (continued)

Subclass	Order	Family	Genus	Scientific name	Sample Code
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK84
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK87
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma* sp.	SK88
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma tropicum*	SK37
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma williamsianum*	SK342
Incertae sedis	Polyporales	Polyporaceae	*Ganoderma*	*Ganoderma tropicum*	SK321
Incertae sedis	Polyporales	Polyporaceae	*Hexagonia*	*Hexagonia cucullata*	SK305
Incertae sedis	Polyporales	Polyporaceae	*Hexagonia*	*Hexagonia cucullata*	SK319
Incertae sedis	Polyporales	Polyporaceae	*Hexagonia*	*Hexagonia* sp.	SK41
Incertae sedis	Polyporales	Polyporaceae	*Hexagonia*	*Hexagonia tenuis*	SK114
Incertae sedis	Polyporales	Polyporaceae	*Hexagonia*	*Hexagonia tenuis*	SK141
Incertae sedis	Polyporales	Polyporaceae	*Lentinus*	*Lentinus* sp.	SK31
Incertae sedis	Polyporales	Polyporaceae	*Lentinus*	*Lentinus squarrolosus*	SK156
Incertae sedis	Polyporales	Polyporaceae	*Lignosus*	*Lignosus hainanensis*	SK202
Incertae sedis	Polyporales	Polyporaceae	*Microporus*	*Microporus flabelliformis*	SK195
Incertae sedis	Polyporales	Polyporaceae	*Microporus*	*Microporus* sp.	SK149
Incertae sedis	Polyporales	Polyporaceae	*Microporus*	*Microporus* sp.	SK190

Table A1 (continued)

Subclass	Order	Family	Genus	Scientific name	Sample Code
Incertae sedis	Polyporales	Polyporaceae	*Microporus*	*Microporus* sp.	SK196
Incertae sedis	Polyporales	Polyporaceae	*Microporus*	*Microporus* sp.	SK206
Incertae sedis	Polyporales	Polyporaceae	*Microporus*	*Microporus* sp.	SK225
Incertae sedis	Polyporales	Polyporaceae	*Microporus*	*Microporus* sp.	SK257
Incertae sedis	Polyporales	Polyporaceae	*Microporus*	*Microporus* sp.	SK307
Incertae sedis	Polyporales	Polyporaceae	*Microporus*	*Microporus* sp.	SK5
Incertae sedis	Polyporales	Polyporaceae	*Microporus*	*Microporus* sp.	SK91
Incertae sedis	Polyporales	Polyporaceae	*Microporus*	*Microporus xanthopus*	SK146
Incertae sedis	Polyporales	Polyporaceae	*Microporus*	*Microporus xanthopus*	SK33
Incertae sedis	Polyporales	Polyporaceae	*Neofomitella*	*Neofomitella fumosipora*	SK136
Incertae sedis	Polyporales	Polyporaceae	*Phaeotrametes*	*Phaeotrametes* sp.	SK40
Incertae sedis	Polyporales	Polyporaceae	*Phlebiopsis*	*Phlebiopsis friesii*	SK205
Incertae sedis	Polyporales	Polyporaceae	*Phlebiopsis*	*Phlebiopsis* sp.	SK283
Incertae sedis	Polyporales	Polyporaceae	*Polyporus*	*Polyporus* sp.	SK103
Incertae sedis	Polyporales	Polyporaceae	*Polyporus*	*Polyporus* sp.	SK168
Incertae sedis	Polyporales	Polyporaceae	*Polyporus*	*Polyporus* sp.	SK193
Incertae sedis	Polyporales	Polyporaceae	*Polyporus*	*Polyporus* sp.	SK229

Table A1 (continued)

Subclass	Order	Family	Genus	Scientific name	Sample Code
Incertae sedis	Polyporales	Polyporaceae	*Polyporus*	*Polyporus* sp.	SK236
Incertae sedis	Polyporales	Polyporaceae	*Polyporus*	*Polyporus* sp.	SK258
Incertae sedis	Polyporales	Polyporaceae	*Pseudofavolus*	*Pseudofavolus tenuis*	SK144
Incertae sedis	Polyporales	Polyporaceae	*Pycnoporus*	*Pycnoporus sanguinea*	SK53
Incertae sedis	Polyporales	Polyporaceae	*Pycnoporus*	*Pycnoporus* sp.	SK238
Incertae sedis	Polyporales	Polyporaceae	*Tomophagus*	*Tomophagus colossus*	SK347
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes caespitosa*	SK357
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes elegans*	SK128
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes elegans*	SK309
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes elegans*	SK340
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes gibbosa*	SK138
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes gibbosa*	SK48
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes glabrorigens*	SK47
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes hirsuta*	SK277
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes hirsuta*	SK333
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes lactineus*	SK332
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes polyzona*	SK132

Table A1 (continued)

Subclass	Order	Family	Genus	Scientific name	Sample Code
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes sanguinea*	SK69
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK104
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK107
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK108
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK11
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK110
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK116
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK117
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK118
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK119
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK12
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK122
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK123
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK126
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK130
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK14
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK143

Table A1 (continued)

Subclass	Order	Family	Genus	Scientific name	Sample Code
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK145
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK147
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK151
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK162
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK174
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK198
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK200
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK201
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK21
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK214
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK219
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK220
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK221
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK223
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK224
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK226
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK227

Table A1 (continued)

Subclass	Order	Family	Genus	Scientific name	Sample Code
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK23
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK230
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK259
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK260
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK262
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK272
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK274
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK275
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK28
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK285
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK287
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK316
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK324
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK325
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK326
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK35
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK356

Table A1 (continued)

Subclass	Order	Family	Genus	Scientific name	Sample Code
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK36
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK364
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK365
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK39
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK44
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK46
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK73
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK75
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK80
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK81
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK83
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK89
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK92
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK94
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK96
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes* sp.	SK97
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes versicolor*	SK267

Table A1 (continued)

Subclass	Order	Family	Genus	Scientific name	Sample Code
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes versicolor*	SK268
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes versicolor*	SK271
Incertae sedis	Polyporales	Polyporaceae	*Trametes*	*Trametes versicolor*	SK361
Incertae sedis	Polyporales	Polyporaceae	Unidentified	Unidentified	SK139
Incertae sedis	Polyporales	Polyporaceae	Unidentified	Unidentified	SK237
Incertae sedis	Polyporales	Polyporaceae	Unidentified	Unidentified	SK314
Incertae sedis	Polyporales	Polyporaceae	Unidentified	Unidentified	SK90
Incertae sedis	Polyporales	Steccherinaceae	*Trullella*	*Trullella yunnanensis*	SK280
Incertae sedis	Polyporales	Steccherinaceae	*Trullella*	*Trullella yunnanensis*	SK281
Incertae sedis	Polyporales	Unidentified	Unidentified	Unidentified	SK252
Incertae sedis	Russulales	Russulaceae	*Russula*	*Russula* sp.	SK99
Incertae sedis	Russulales	Stereaceae	*Stereum*	*Stereum ostrea*	SK161
Incertae sedis	Russulales	Stereaceae	*Stereum*	*Stereum* sp.	SK351
Incertae sedis	Russulales	Stereaceae	*Xylobolus*	*Xylobolus princeps*	SK343
Incertae sedis	Thelephorales	Bankeraceae	*Hydnellum*	*Hydnellum* sp.	SK211
Incertae sedis	Thelephorales	Thelephoraceae	*Thelephora*	*Thelephora sikkimensis*	SK207
Incertae sedis	Thelephorales	Thelephoraceae	*Thelephora*	*Thelephora* sp.	SK185

Table A1 (continued)

Subclass	Order	Family	Genus	Scientific name	Sample Code
Incertae sedis	Thelephorales	Thelephoraceae	*Thelephora*	*Thelephora* sp.	SK216
Incertae sedis	Thelephorales	Thelephoraceae	*Thelephora*	*Thelephora* sp.	SK248
Incertae sedis	Thelephorales	Thelephoraceae	*Thelephora*	*Thelephora* sp.	SK296
Phallomycetidae	Geastrales	Geastraceae	*Geastrum*	*Geastrum* sp.	SK253
Phallomycetidae	Geastrales	Geastraceae	*Geastrum*	*Geastrum* sp.	SK263
Phallomycetidae	Geastrales	Geastraceae	*Geastrum*	*Geastrum* sp.	SK264
Phallomycetidae	Geastrales	Geastraceae	*Geastrum*	*Geastrum* sp.	SK265
Phallomycetidae	Geastrales	Geastraceae	*Geastrum*	*Geastrum* sp.	SK276
Phallomycetidae	Gomphales	Gomphaceae	*Ramaria*	*Ramaria* sp.	SK197
Phallomycetidae	Gomphales	Gomphaceae	*Ramaria*	*Ramaria* sp.	SK315
Unidentified	Unidentified	Unidentified	Unidentified	Unidentified	SK100
Unidentified	Unidentified	Unidentified	Unidentified	Unidentified	SK13
Unidentified	Unidentified	Unidentified	Unidentified	Unidentified	SK171
Unidentified	Unidentified	Unidentified	Unidentified	Unidentified	SK241

APPENDIX B

DETAILS OF FUNGAL SAMPLES AND CULTURE

Table B1 Details of Collected Fungal Samples, Their Basidiomata and Culture

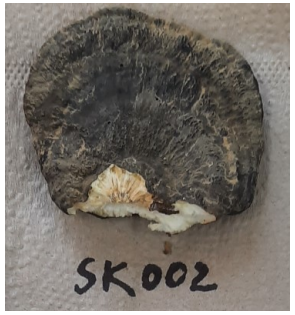
Code/ Fungus	Basidiomata	Culture	Culture days
SK1 (*Ganoderma* sp.)			9 days
SK2 (*Ganoderma* sp.)			9 days

Table B1 (continued)

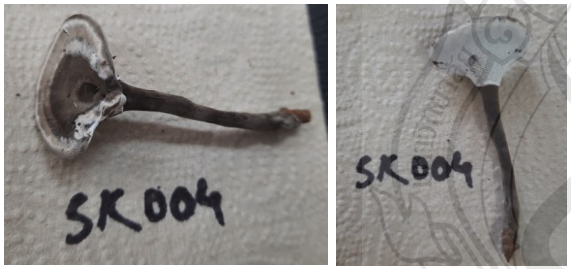
Code/ Fungus	Basidiomata	Culture	Culture days
SK3 (*Coriolopsis brunneleuca*)		N/A	
SK4 (*Amauroderma rugosum*)		N/A	
SK5 (*Microporus* sp.)		N/A	

Table B1 (continued)

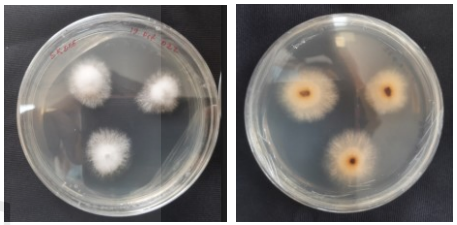
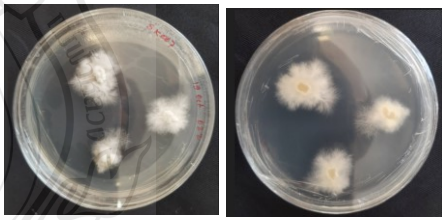
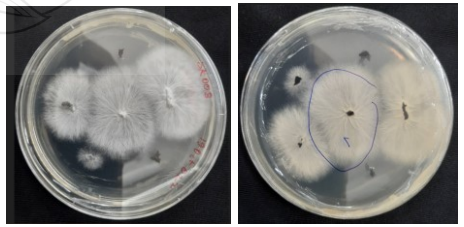
Code/ Fungus	Basidiomata	Culture	Culture days
SK6 (*Lentinula edodes*)			9 days
SK7 (*Pleurotus ostreatus*)			7 days
SK8 (*Ganoderma* sp.)			7 days

Table B1 (continued)

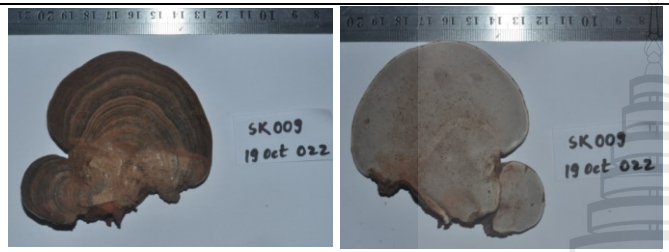
Code/ Fungus	Basidiomata	Culture	Culture days
SK9 (*Ganoderma australe*)			7 days
SK10 (*Ganoderma* sp.)		N/A	
SK11 (*Trametes* sp.)		N/A	

Table B1 (continued)

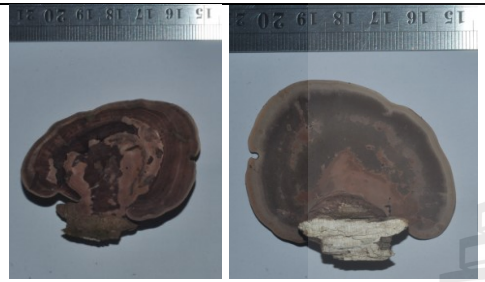
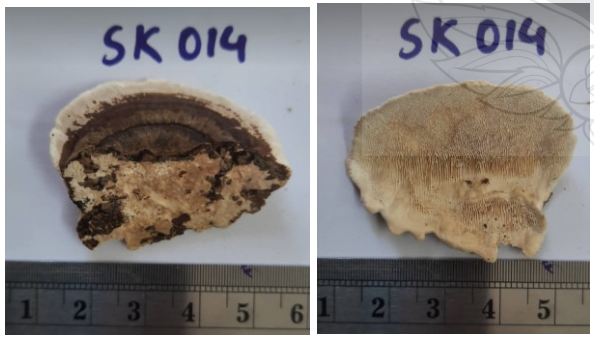
Code/ Fungus	Basidiomata	Culture	Culture days
SK12 (*Trametes* sp.)		N/A	
SK13 (Unidentified)		N/A	
SK14 (*Trametes* sp.)		N/A	

Table B1 (continued)

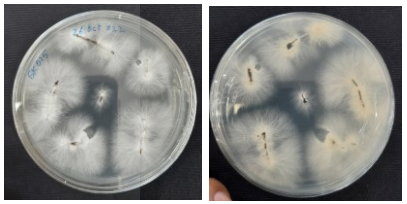
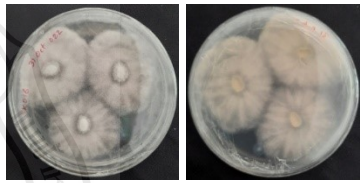
Code/ Fungus	Basidiomata	Culture	Culture days
SK15 (*Ganoderma* sp.)			5 days
SK16 (*Favolus* sp.)			4 days
SK17 (*Crepiodotus* sp.)		N/A	
SK18 (*Auricularia* sp.)		N/A	

Table B1 (continued)

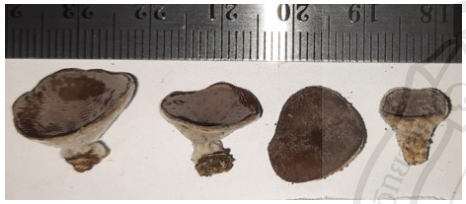
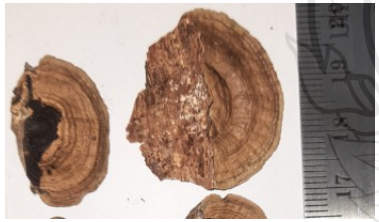
Code/ Fungus	Basidiomata	Culture	Culture days
SK19 (*Panus* sp.)		N/A	
SK20 (*Auricularia* sp.)		N/A	
SK21 (*Trametes* sp.)		N/A	
SK22 (*Gymnopus* sp.)		N/A	

Table B1 (continued)

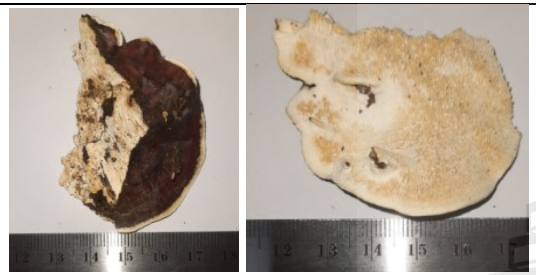
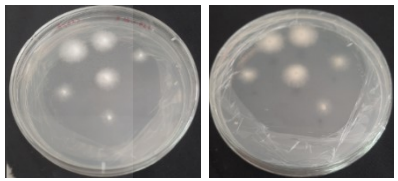
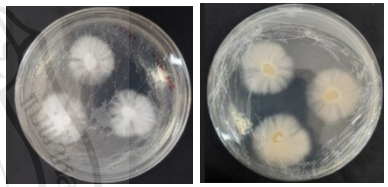
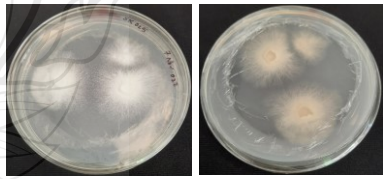
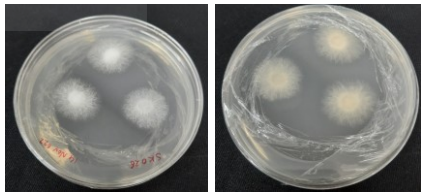
Code/ Fungus	Basidiomata	Culture	Culture days
SK23 (*Earliella scabrosa*)			4 days
SK24 (*Ganoderma australe*)			4 days
SK25 (*Ganoderma australe*)			4 days
SK26 (*Auricularia* sp.)			4 days

Table B1 (continued)

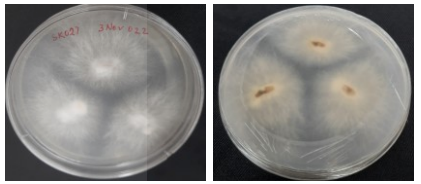
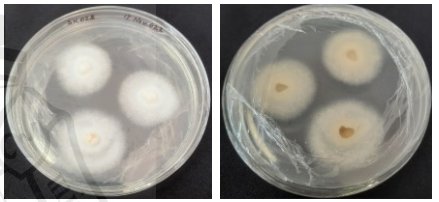
Code/ Fungus	Basidiomata	Culture	Culture days
SK27 (*Lentinula edodes*)			15 days
SK28 (*Trametes* sp.)			6 days
SK29 (*Parasola* sp.)		N/A	
SK30 (*Agaricus leptocaulis*)		N/A	

Table B1 (continued)

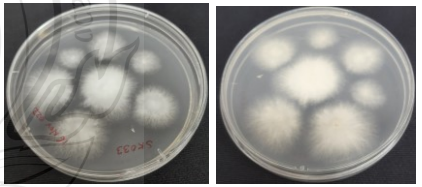
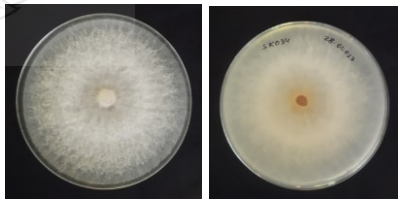
Code/ Fungus	Basidiomata	Culture	Culture days
SK31 (*Lentinus* sp.)		N/A	
SK32 (*Sanguinoderma rugosum*)		N/A	
SK33 (*Microporus xanthopus*)			6 days
SK34 (*Auricularia* sp.)			15 days

Table B1 (continued)

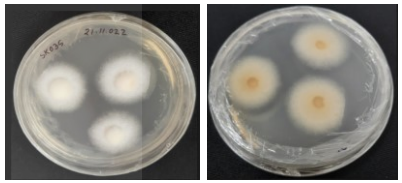
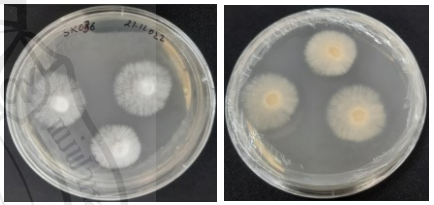
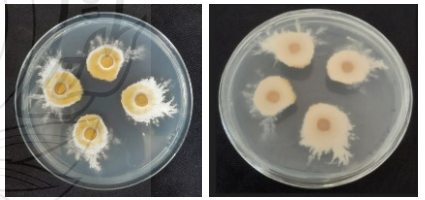
Code/ Fungus	Basidiomata	Culture	Culture days
SK35 (*Trametes* sp.)			8 days
SK36 (*Trametes* sp.)			3 days
SK37 (*Ganoderma tropicum*)			20 days
SK38 (*Coprinellus* sp.)		N/A	

Table B1 (continued)

Code/ Fungus	Basidiomata	Culture	Culture days
SK39 (*Trametes* sp.)		N/A	
SK40 (*Phaeotrametes* sp.)		N/A	
SK41 (*Hexagonia* sp.)		N/A	
SK42 (*Schizophyllum* sp.)		N/A	

Table B1 (continued)

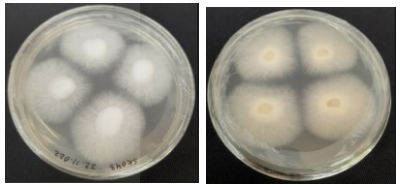
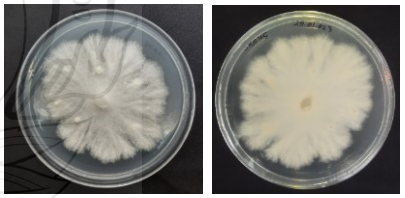
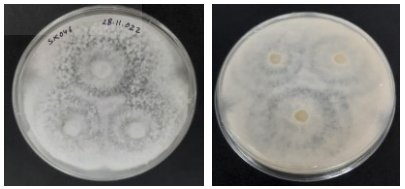
Code/ Fungus	Basidiomata	Culture	Culture days
SK43 (*Panus subfasciatus*)			4 days
SK44 (*Trametes* sp.)		N/A	
SK45 (*Auricularia* sp.)			14 days
SK46 (*Earliella scabrosa*)			7 days

Table B1 (continued)

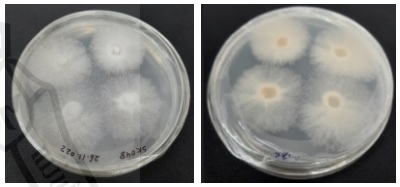
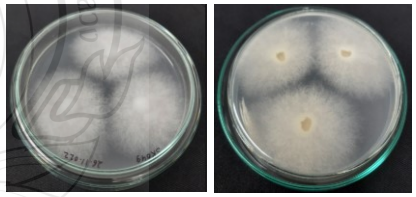
Code/ Fungus	Basidiomata	Culture	Culture days
SK47 (*Trametes glabrorigens*)		N/A	
SK48 (*Trametes gibbosa*)			6 days
SK49 (*Panus subfasciatus*)			7 days
SK50 (*Schizophyllum* sp.)		N/A	

Table B1 (continued)

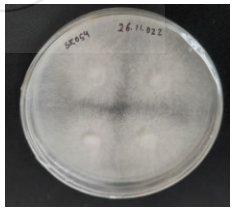
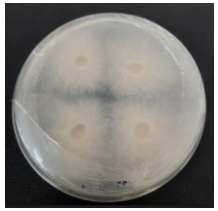
Code/ Fungus	Basidiomata	Culture	Culture days
SK51 (*Amauroderma rugosum*)		N/A	
SK52 (*Ramariopsis* sp.)		N/A	
SK53 (*Pycnoporus sanguinea*)		N/A	
SK54 (*Pilatoporus ostreiformis*)		 	6 days

Table B1 (continued)

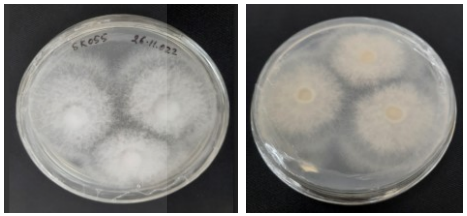
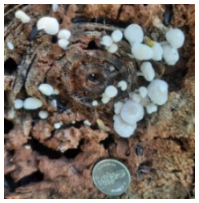
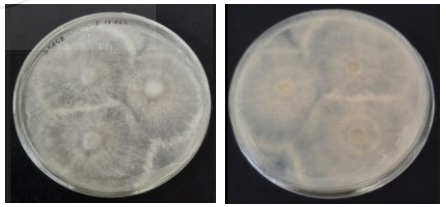
Code/ Fungus	Basidiomata	Culture	Culture days
SK55 (*Earliella scabrosa*)			7 days
SK56 (*Candolleomyces candolleanus*)		N/A	
SK57 (*Coprinellus* sp.)		N/A	
SK58 (*Schizophyllum* sp.)			9 days

Table B1 (continued)

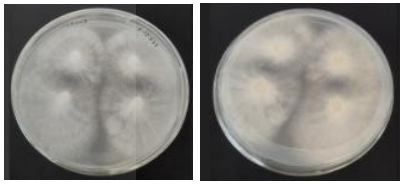
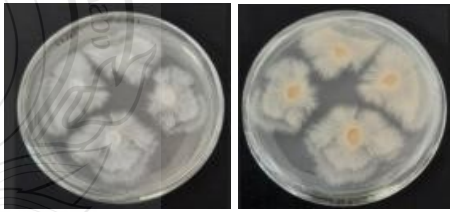
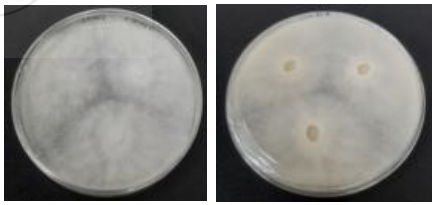
Code/ Fungus	Basidiomata	Culture	Culture days
SK59 (*Ganoderma applanatum*)			8 days
SK60 (*Ganoderma applanatum*)		N/A	
SK61 (*Ganoderma* sp.)			8 days
SK62 (*Ganoderma orbiforme*)			5 days

Table B1 (continued)

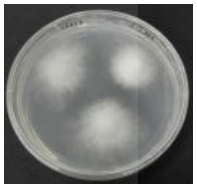
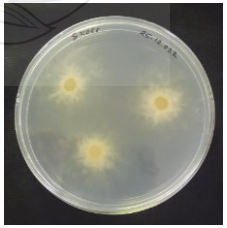
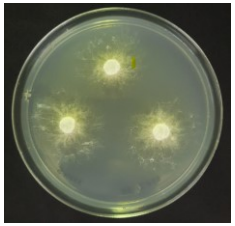
Code/ Fungus	Basidiomata	Culture	Culture days
SK63 (*Panus* sp.)			5 days
SK64 (*Gymnopilus* sp.)			Spore print but contaminated
SK65 (*Ganoderma adspersum*)		N/A	
SK66 (*Coprinellus* sp.)		 	7 days

Table B1 (continued)

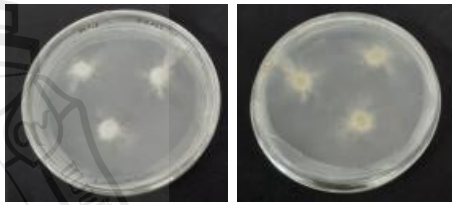
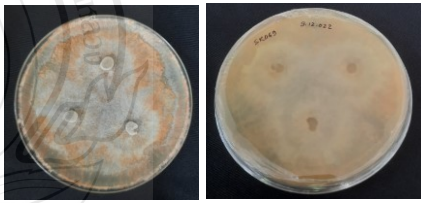
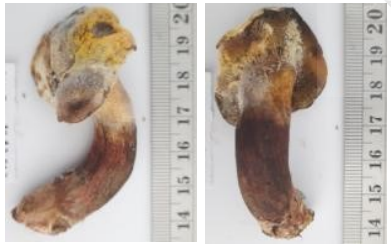
Code/ Fungus	Basidiomata	Culture	Culture days
SK67 (*Marasmiellus* sp.)		N/A	
SK68 (*Schizophyllum* sp.)			6 days
SK69 (*Pycnoporus sanguinea*)			17 days
SK70 (*Boletus* sp.)		N/A	

Table B1 (continued)

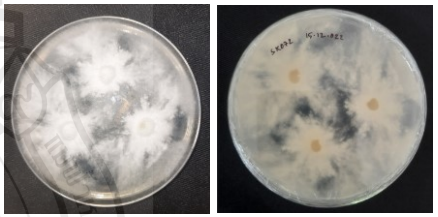
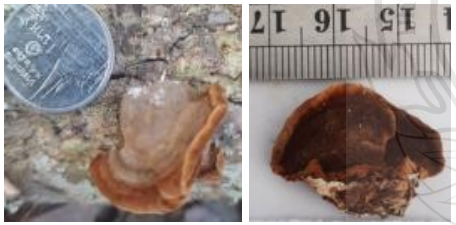
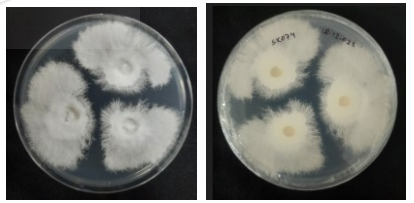
Code/ Fungus	Basidiomata	Culture	Culture days
SK71 (Unidentified)		N/A	
SK72 (*Schizophyllum* sp.)			11 days
SK73 (*Trametes* sp.)		N/A	
SK74 (*Ganoderma gibbosum*)			8 days

Table B1 (continued)

Code/ Fungus	Basidiomata	Culture	Culture days
SK75 (*Trametes* sp.)		N/A	
SK76 (*Ganoderma* sp.)		N/A	
SK77 (*Ganoderma adspersum*)			8 days
SK78 (Unidentified)		N/A	

Table B1 (continued)

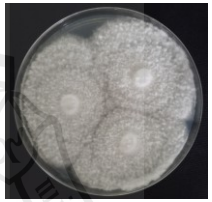
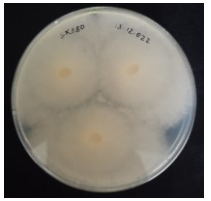
Code/ Fungus	Basidiomata	Culture	Culture days
SK79 (*Coprinus* sp.)		N/A	
SK80 (*Trametes* sp.)		 	10 days
SK81 (*Trametes* sp.)		N/A	
SK82 (*Sanguinoderma rugosum*)		N/A	

Table B1 (continued)

Code/ Fungus	Basidiomata	Culture	Culture days
SK83 (*Trametes* sp.)		N/A	
SK84 (*Ganoderma* sp.)		N/A	
SK85 (*Lactocollybia epia*)		N/A	
SK86 (*Fuscoporia gilva*)		N/A	

Table B1 (continued)

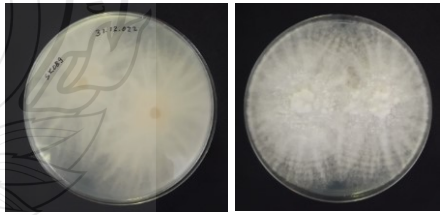
Code/ Fungus	Basidiomata	Culture	Culture days
SK87 (*Ganoderma* sp.)		N/A	
SK88 (*Ganoderma* sp.)		N/A	
SK89 (*Trametes* sp.)			16 days
SK90 (Unidentified)		N/A	

Table B1 (continued)

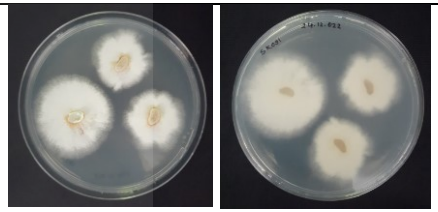
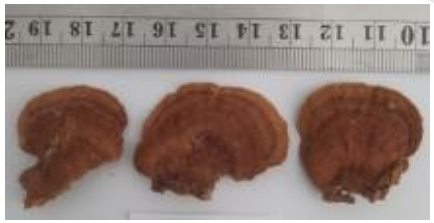
Code/ Fungus	Basidiomata	Culture	Culture days
SK91 (*Microporus* sp.)			8 days
SK92 (*Trametes* sp.)		N/A	
SK93 (*Auricularia* sp.)		N/A	
SK94 (*Trametes* sp.)		N/A	

Table B1 (continued)

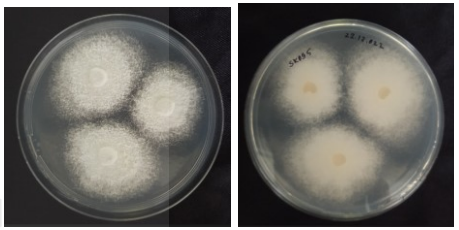
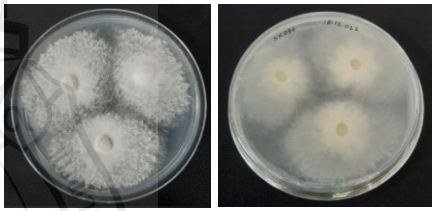
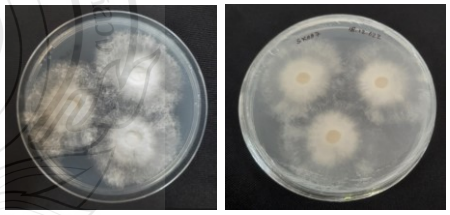
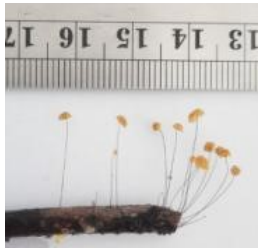
Code/ Fungus	Basidiomata	Culture	Culture days
SK95 (*Coriolopsis brunneoleuca*)			7 days
SK96 (*Trametes* sp.)			7 days
SK97 (*Trametes* sp.)			7 days
SK98 (*Marasmius* sp.)		N/A	

Table B1 (continued)

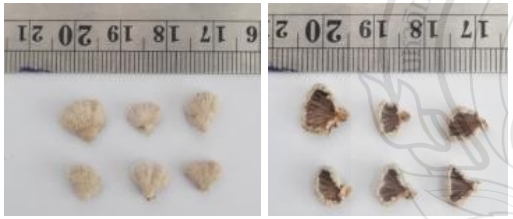
Code/ Fungus	Basidiomata	Culture	Culture days
SK99 (*Russula* sp.)		N/A	
SK100 (Unidentified)		N/A	
SK101 (*Schizophyllum* sp.)			6 days culture
SK102 (*Collybiopsis* sp.)		N/A	

Table B1 (continued)

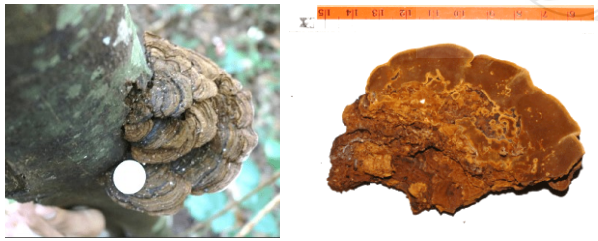
Code/ Fungus	Basidiomata	Culture	Culture days
SK103 (*Polyporus* sp.)		N/A	
SK104 (*Trametes* sp.)		N/A	
SK105 (*Ganoderma philippii*)		N/A	
SK106 (*Phylloporia clausenae*)		N/A	

Table B1 (continued)

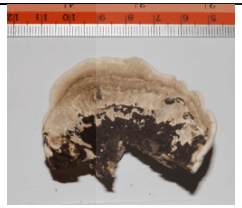
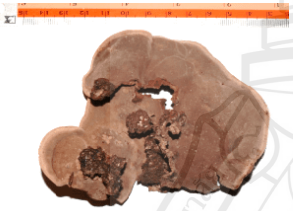
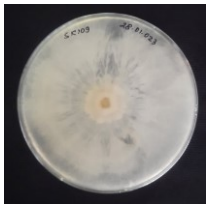
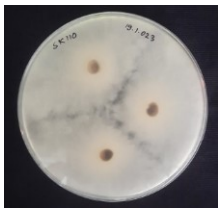
Code/ Fungus	Basidiomata	Culture	Culture days
SK107 (*Trametes* sp.)		N/A	
SK108 (*Trametes* sp.)		N/A	
SK109 (*Ganoderma gibbosum*)			15 days
SK110 (*Trametes* sp.)			24 days

Table B1 (continued)

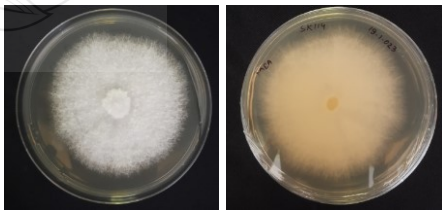
Code/ Fungus	Basidiomata	Culture	Culture days
SK111 (*Sanguinoderma rugosum*)		N/A	
SK112 (*Agrocybe flexuosipes*)		N/A	
SK113 (*Ganoderma* sp.)		N/A	
SK114 (*Hexagonia tenuis*)			8 days

Table B1 (continued)

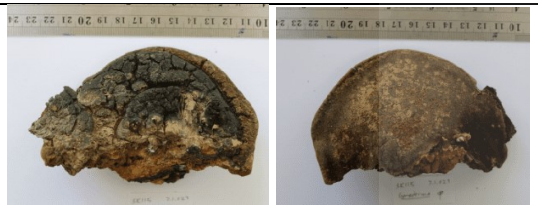
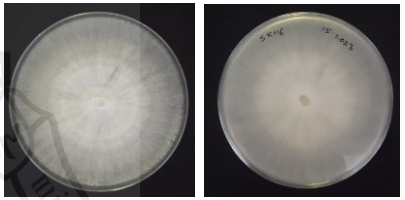
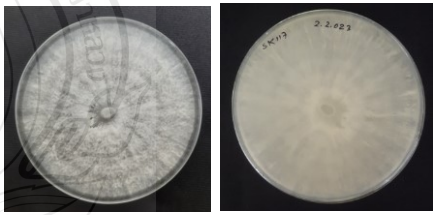
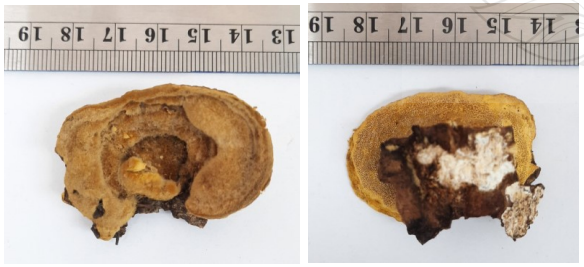
Code/ Fungus	Basidiomata	Culture	Culture days
SK115 (*Ganoderma* sp.)		N/A	
SK116 (*Trametes* sp.)			12 days
SK117 (*Trametes* sp.)			13 days
SK118 (*Trametes* sp.)		N/A	

Table B1 (continued)

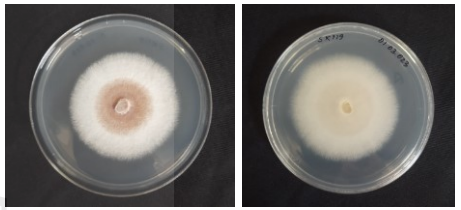
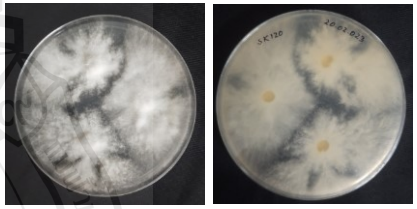
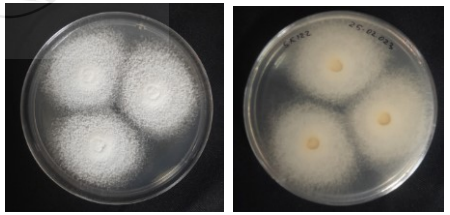
Code/ Fungus	Basidiomata	Culture	Culture days
SK119 (*Trametes* sp.)			7 days
SK120 (*Schizophyllym* sp.)			12 days
SK121 (*Panus* sp.)		N/A	
SK122 (*Trametes* sp.)			7 days

Table B1 (continued)

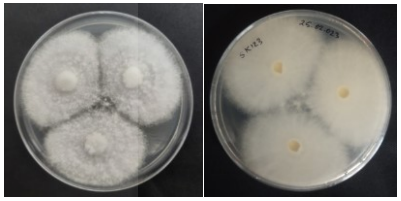
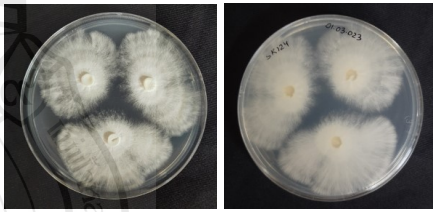
Code/ Fungus	Basidiomata	Culture	Culture days
SK123 (*Trametes* sp.)			7 days
SK124 (*Ganoderma australe*)			7 days
SK125 (*Ganoderma* sp.)			6 days
SK126 (*Echinochaete* sp.)		N/A	

Table B1 (continued)

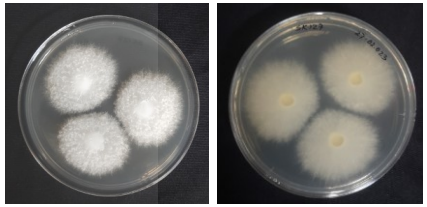
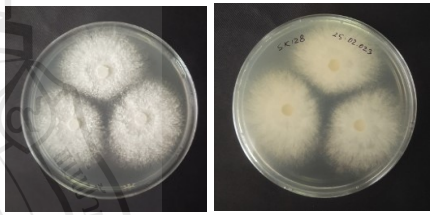
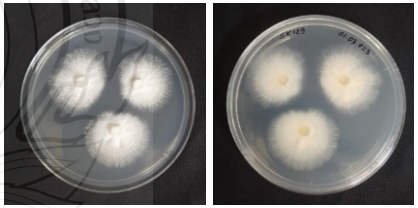
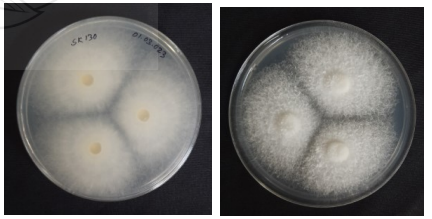
Code/ Fungus	Basidiomata	Culture	Culture days
SK127 (*Earliella scabrosa*)			6 days
SK128 (*Trametes elegans*)			7 days
SK129 (*Ganoderma* sp.)			7 days
SK130 (*Trametes* sp.)			7 days

Table B1 (continued)

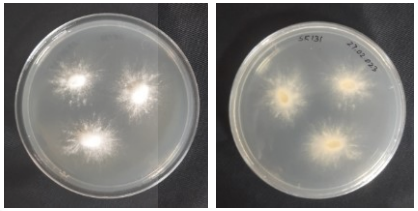
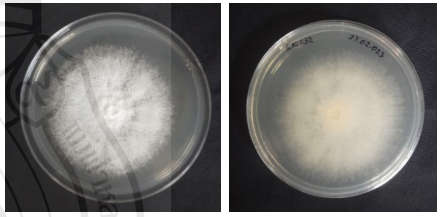
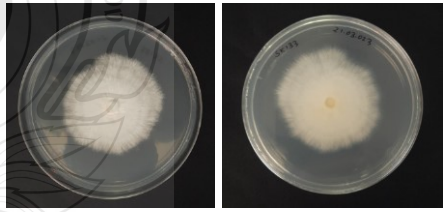
Code/ Fungus	Basidiomata	Culture	Culture days
SK131 (*Schizophyllym* sp.)			6 days
SK132 (*Trametes polyzona*)			6 days
SK133 (*Ganoderma* sp.)			7 days
SK134 (*Echinochaete thailandica*)		N/A	

Table B1 (continued)

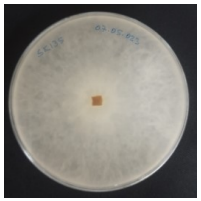
Code/ Fungus	Basidiomata	Culture	Culture days
SK135 (*Funalia aspera*)			8 days
SK136 (*Neofomitella fumosipora*)		N/A	
SK137 (*Irpex flavus*)		N/A	
SK138 (*Trametes gibbosa*)		N/A	

Table B1 (continued)

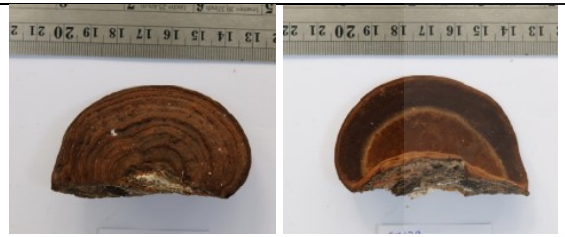
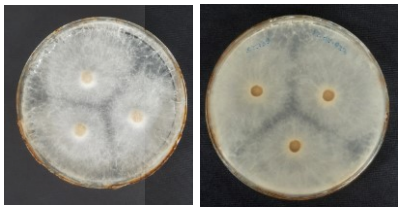
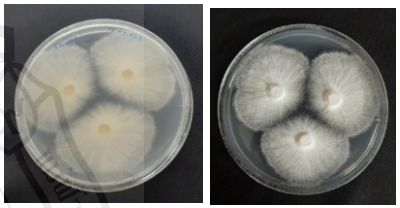
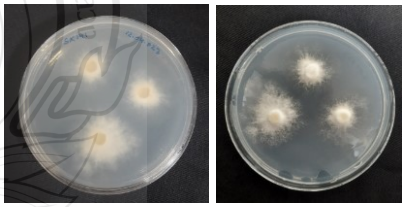
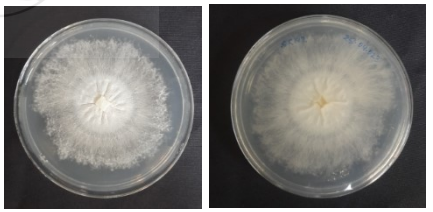
Code/ Fungus	Basidiomata	Culture	Culture days
SK139 (Unidentified)			67 days
SK140 (*Ganoderma* sp.)			7 days
SK141 (*Hexagonia tenuis*)			7 days
SK142 (*Ganoderma applanatum*)			12 days

Table B1 (continued)

Code/ Fungus	Basidiomata	Culture	Culture days
SK143 (*Trametes* sp.)		N/A	
SK144 (*Pseudofavolus tenuis*)			4 days
SK145 (*Trametes* sp.)			7 days
SK146 (*Microporus xanthopus*)			8 days

Table B1 (continued)

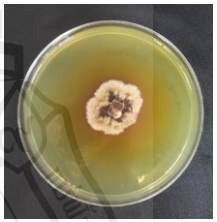
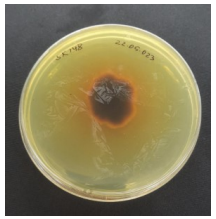
Code/ Fungus	Basidiomata	Culture	Culture days
SK147 (*Trametes* sp.)		N/A	
SK148 (*Phlebopus* sp.)		 	16 days
SK149 (*Microporus* sp.)		N/A	
SK150 (*Favolaschia* sp.)			20 days

Table B1 (continued)

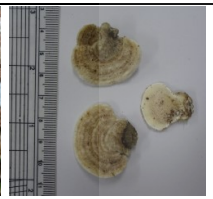
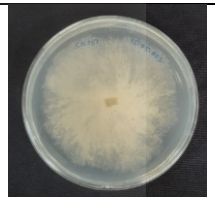
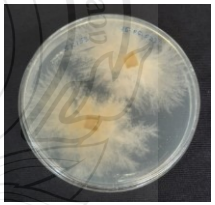
Code/ Fungus	Basidiomata	Culture	Culture days
SK151 (*Trametes* sp.)			7 days
SK152 (*Marasmiellus* sp.)			55 days
SK153 (*Mycena* sp.)			7 days
SK154 (*Campanella buittneri*)		N/A	

Table B1 (continued)

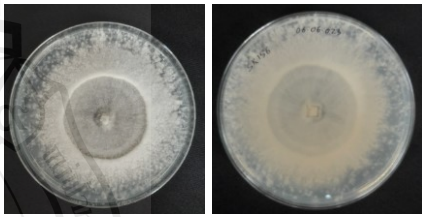
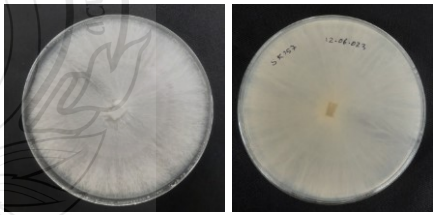
Code/ Fungus	Basidiomata	Culture	Culture days
SK155 (*Crinipellis rhizomaticola*)		N/A	
SK156 (*Lentinus squarrolosus*)			12 days
SK157 (*Ganoderma australe*)			9 days
SK158 (*Podoscypha* sp.)		N/A	

Table B1 (continued)

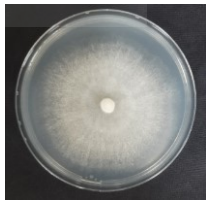
Code/ Fungus	Basidiomata	Culture	Culture days
SK159 (*Panellus luxfilamentus*)		N/A	
SK160 (*Marasmius trichotus*)		N/A	
SK161 (*Stereum ostrea*)			15 days
SK162 (*Trametes* sp.)			8 days

Table B1 (continued)

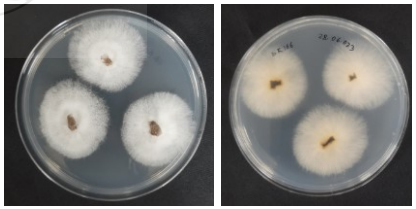
Code/ Fungus	Basidiomata	Culture	Culture days
SK163 (*Marasmius xestocephalus*)		N/A	
SK164 (*Favolaschia* sp.)		N/A	
SK165 (*Gymnopus* sp.)		N/A	
SK166 (*Amauroderma* sp.)			5 days

Table B1 (continued)

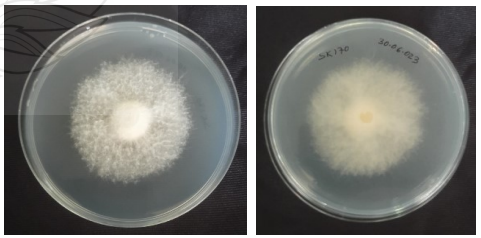
Code/ Fungus	Basidiomata	Culture	Culture days
SK167 (*Favolus* sp.)		N/A	
SK168 (*Polyporus* sp.)		N/A	
SK169 (*Marasmius* sp.)		N/A	
SK170 (*Termitomyces* sp.)			9 days

Table B1 (continued)

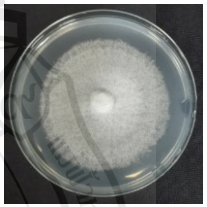
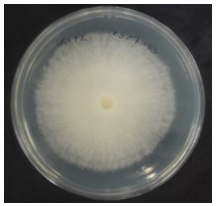
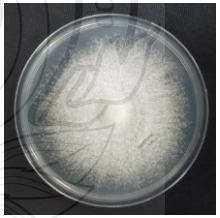
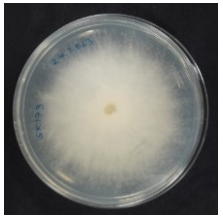
Code/ Fungus	Basidiomata	Culture	Culture days
SK171 (Unidentified)		N/A	
SK172 (*Ganoderma lucidum*)		 	6 days
SK173 (*Fomitopsis feei*)		 	13 days
SK174 (*Trametes* sp.)			8 days

Table B1 (continued)

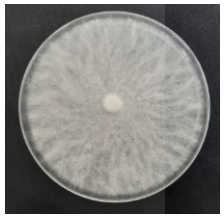
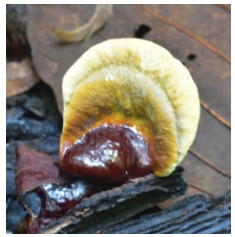
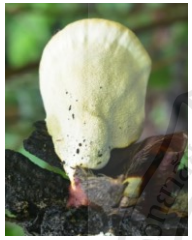
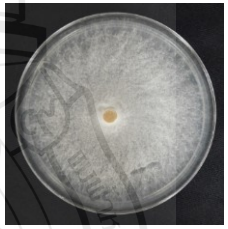
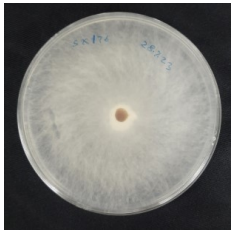
Code/ Fungus	Basidiomata	Culture	Culture days
SK175 (*Amauroderma* sp.)			8 days
SK176 (*Amauroderma subresinosum*)	 	 	9 days
SK177 (*Phellinus* sp.)		N/A	
SK178 (*Ganoderma* sp.)			7 days

Table B1 (continued)

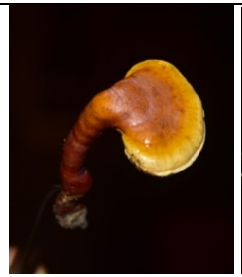
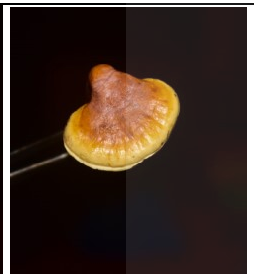
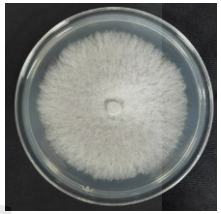
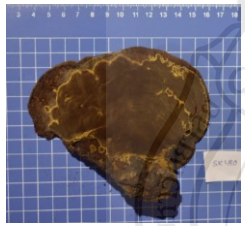
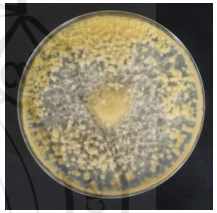
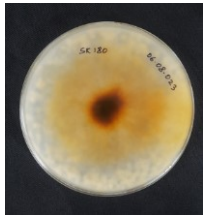
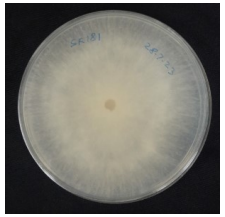
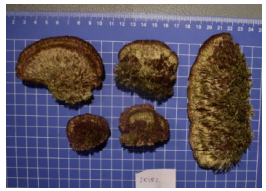
Code/ Fungus	Basidiomata	Culture	Culture days
SK179 (*Ganoderma lucidum*)	 		6 days
SK180 (*Hymenochaete* sp.)		 	44 days
SK181 (*Ranadivia modesta*)			15 days
SK182 (*Trichaptum byssogenum*)		N/A	

Table B1 (continued)

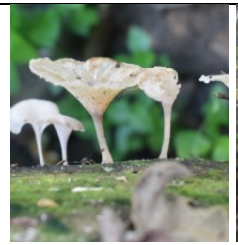
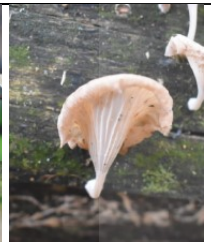
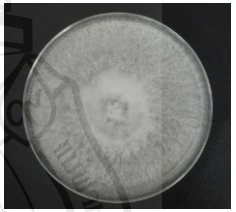
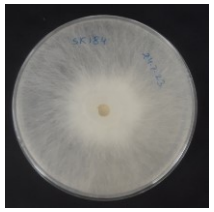
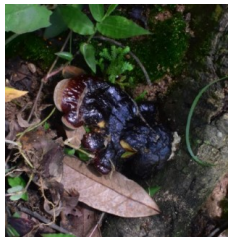
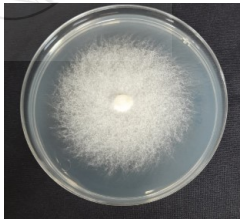
Code/ Fungus	Basidiomata	Culture	Culture days
SK183 (*Trogia* sp.)	 	N/A	
SK184 (*Ganoderma orbiforme*)		 	7 days
SK185 (*Thelephora* sp.)		N/A	
SK186 (*Ganoderma* sp.)			6 days

Table B1 (continued)

Code/ Fungus	Basidiomata	Culture	Culture days
SK187 (*Ganoderma lucidum*)		N/A	
SK188 (*Favolaschia* sp.)		N/A	
SK189 (*Fuscoporia gilvoides*)		N/A	
SK190 (*Microporus* sp.)		N/A	

Table B1 (continued)

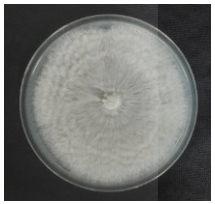
Code/ Fungus	Basidiomata	Culture	Culture days
SK191 (*Ganoderma australe*)			7 days
SK192 (*Ganoderma* sp.)		N/A	
SK193 (*Polyporus* sp.)		N/A	
SK194 (*Amouroderma* sp.)		N/A	

Table B1 (continued)

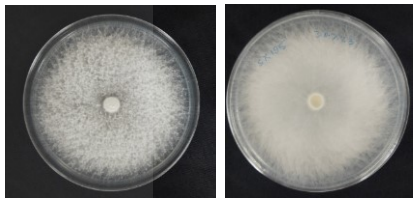
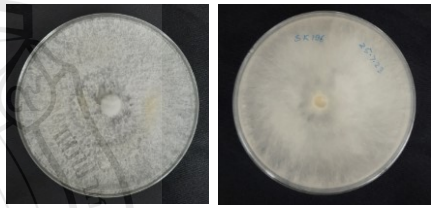
Code/ Fungus	Basidiomata	Culture	Culture days
SK195 (*Microporus flabelliformis*)			7 days
SK196 (*Microporus* sp.)			10 days
SK197 (*Ramaria* sp.)		N/A	
SK198 (*Trametes* sp.)		N/A	

Table B1 (continued)

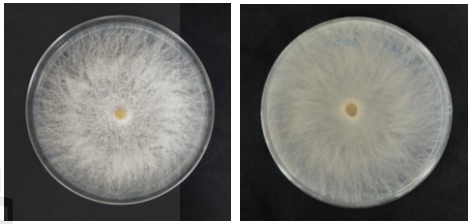
Code/ Fungus	Basidiomata	Culture	Culture days
SK199 (*Ganoderma* sp.)			7 days
SK200 (*Trametes* sp.)		N/A	
SK201 (*Trametes* sp.)		N/A	
SK202 (*Lignosus hainanensis*)		N/A	

Table B1 (continued)

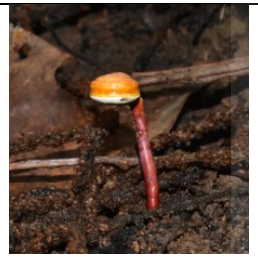
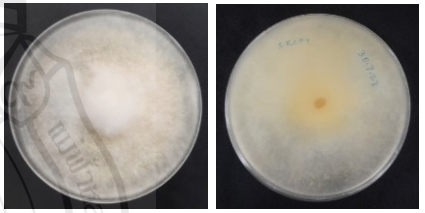
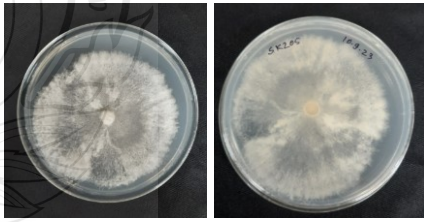
Code/ Fungus	Basidiomata	Culture	Culture days
SK203 (*Ganoderma lucidum*)		N/A	
SK204 (*Favolaschia calocera*)			64 days
SK205 (*Phlebiopsis friesii*)			13 days
SK206 (*Microporus* sp.)		N/A	

Table B1 (continued)

Code/ Fungus	Basidiomata	Culture	Culture days
SK207 (*Thelephora sikkimensis*)		N/A	
SK208 (*Favolaschia* sp.)		N/A	
SK209 (*Phellinus* sp.)		N/A	
SK210 (*Amauroderma* sp.)		N/A	

Table B1 (continued)

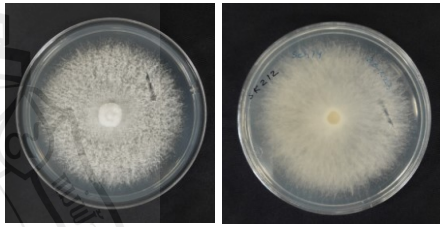
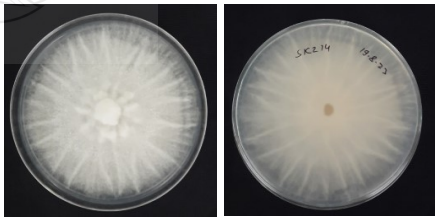
Code/ Fungus	Basidiomata	Culture	Culture days
SK211 (*Hydnellum* sp.)		N/A	
SK212 (*Favolus* sp.)			6 days
SK213 (*Ganoderma* sp.)		N/A	
SK214 (*Trametes* sp.)			12 days

Table B1 (continued)

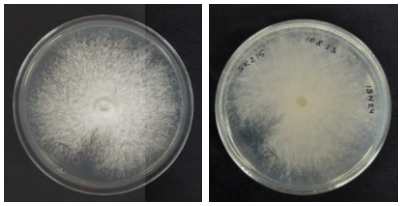
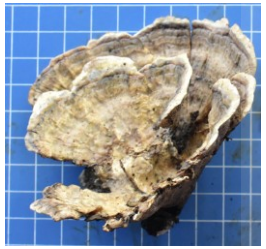
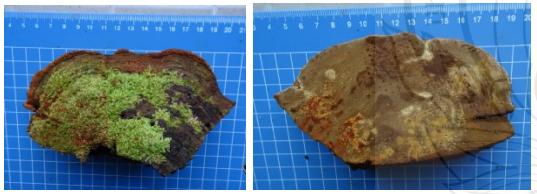
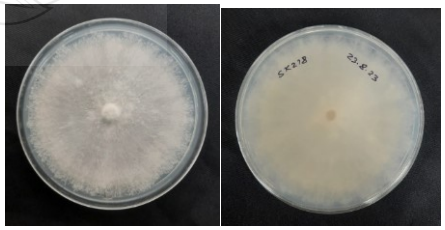
Code/ Fungus	Basidiomata	Culture	Culture days
SK215 (*Fomitopsis ostreiformis*)			11 days
SK216 (*Thelephora* sp.)		N/A	
SK217 (*Porodaedalea* sp.)		N/A	
SK218 (*Fomitopsis dochmia*)			26 days

Table B1 (continued)

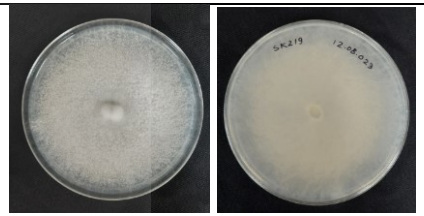
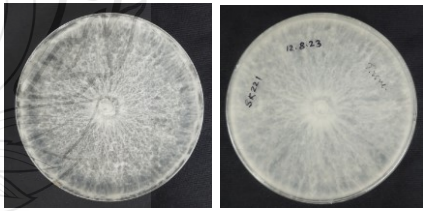
Code/ Fungus	Basidiomata	Culture	Culture days
SK219 (*Trametes* sp.)			9 days (contaminated)
SK220 (*Trametes* sp.)		N/A	
SK221 (*Trametes* sp.)			51 days
SK222 (*Gloeophyllum* sp.)		N/A	

Table B1 (continued)

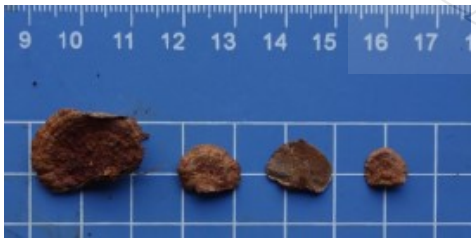
Code/ Fungus	Basidiomata	Culture	Culture days
SK223 (*Trametes* sp.)		N/A	
SK224 (*Trametes* sp.)		N/A	
SK225 (*Microporus* sp.)		N/A	
SK226 (*Trametes* sp.)		N/A	

Table B1 (continued)

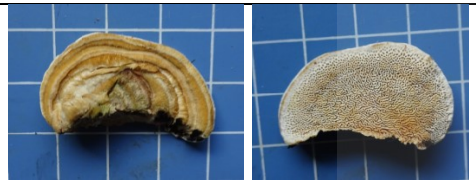
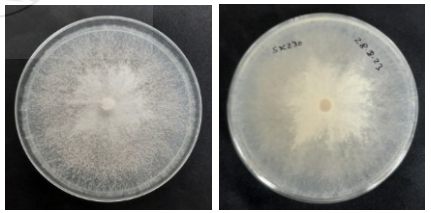
Code/ Fungus	Basidiomata	Culture	Culture days
SK227 (*Trametes* sp.)		N/A	
SK228 (*Gloeophyllum* sp.)		N/A	
SK229 (*Polyorus* sp.)		N/A	
SK230 (*Trametes* sp.)			13 days

Table B1 (continued)

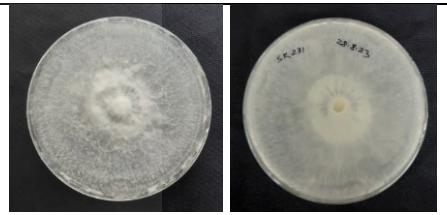
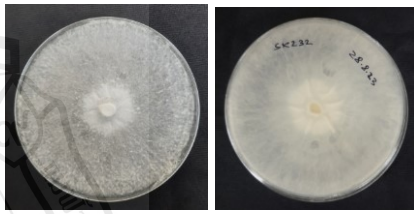
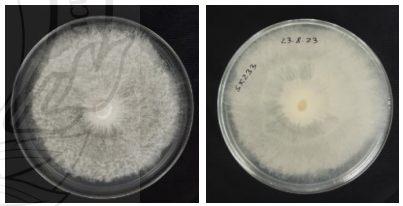
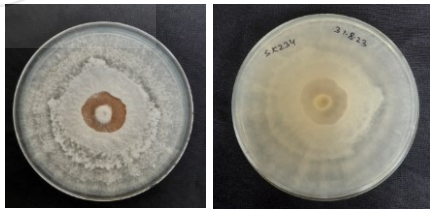
Code/ Fungus	Basidiomata	Culture	Culture days
SK231 (*Ganoderma* sp.)			13 days
SK232 (*Ganoderma* sp.)			13 days
SK233 (*Ganoderma* sp.)			8 days
SK234 (*Earliella scabrosa*)			10 days

Table B1 (continued)

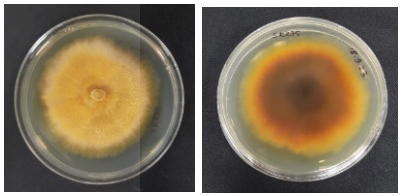
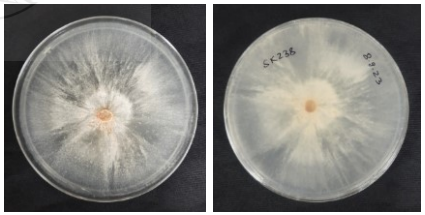
Code/ Fungus	Basidiomata	Culture	Culture days
SK235 (*Phellinus* sp.)			48 days
SK236 (*Polyporus* sp.)		N/A	
SK237 (Unidentified)		N/A	
SK238 (*Pycnoporus* sp.)			10 days

Table B1 (continued)

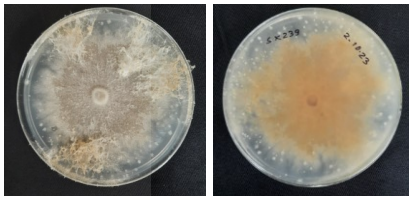
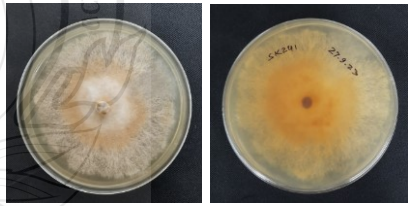
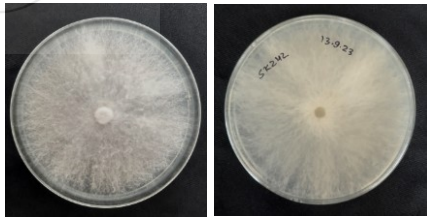
Code/ Fungus	Basidiomata	Culture	Culture days
SK239 (*Rigidoporus microporus*)			93 days
SK240 (*Earliella scabrosa*)		N/A	
SK241 (Unidentified)			43 days
SK242 (*Pilatoporus ostreiformis*)			10 days

Table B1 (continued)

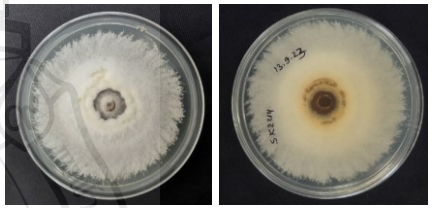
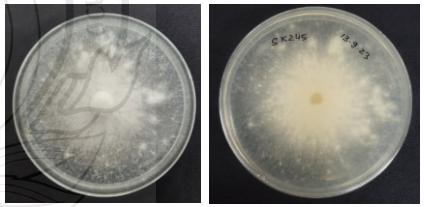
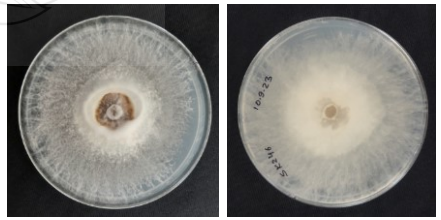
Code/ Fungus	Basidiomata	Culture	Culture days
SK243 (*Earliella scabrosa*)		N/A	
SK244 (*Bresadolia uda*)			9 days
SK245 (*Fomitopsis feei*)			9 days
SK246 (*Favolus tenuiculus*)			13 days

Table B1 (continued)

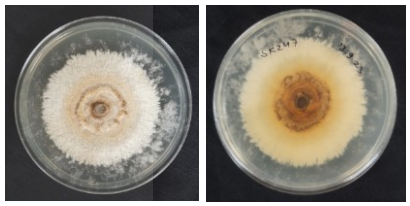
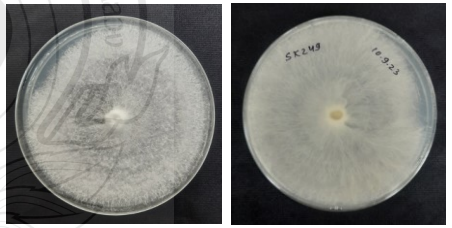
Code/ Fungus	Basidiomata	Culture	Culture days
SK247 (*Bresadolia uda*)			31 days
SK248 (*Thelephora* sp.)		N/A	
SK249 (*Ganoderma gibbosum*)			8 days
SK250 (*Podoscypha tropica*)		N/A	

Table B1 (continued)

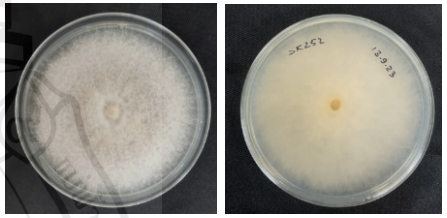
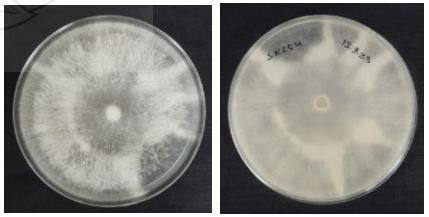
Code/ Fungus	Basidiomata	Culture	Culture days
SK251 (*Ganoderma sessile*)		N/A	
SK252 (Unidentified)			10 days
SK253 (*Geastrum* sp.)		N/A	
SK254 (*Gloeoporus* sp.)			5 days

Table B1 (continued)

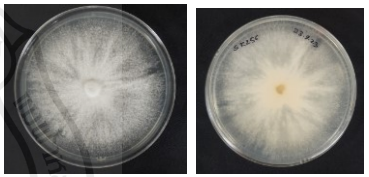
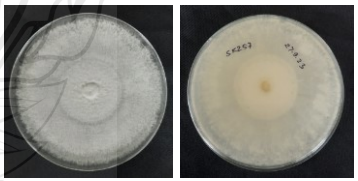
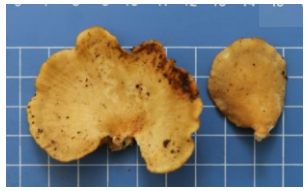
Code/ Fungus	Basidiomata	Culture	Culture days
SK255 (*Ganoderma* sp.)		N/A	-
SK256 (*Podoscypha gillesii*)			18 days
SK257 (*Microporus* sp.)			17 days
SK258 (*Polyporus* sp.)		N/A	

Table B1 (continued)

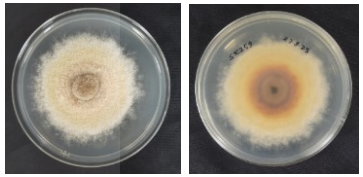
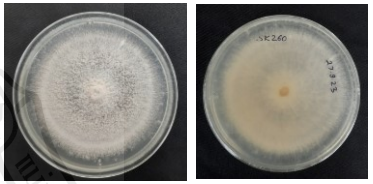
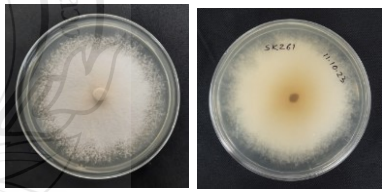
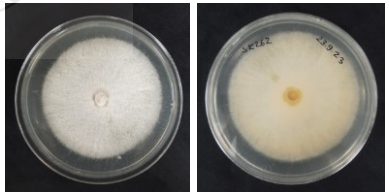
Code/ Fungus	Basidiomata	Culture	Culture days
SK259 (*Trametes* sp.)			17 days
SK260 (*Trametes* sp.)			14 days
SK261 (*Cymatoderma* sp.)			25 days
SK262 (*Trametes* sp.)			21 days

Table B1 (continued)

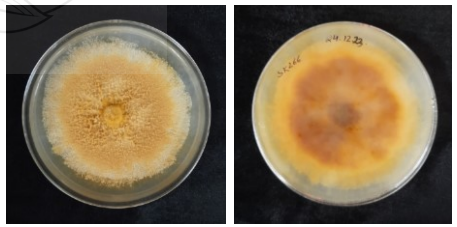
Code/ Fungus	Basidiomata	Culture	Culture days
SK263 (*Geastrum* sp.)		N/A	
SK264 (*Geastrum* sp.)		N/A	
SK265 (*Geastrum* sp.)		N/A	
SK266 (*Porodaedalea* sp.)			8 months

Table B1 (continued)

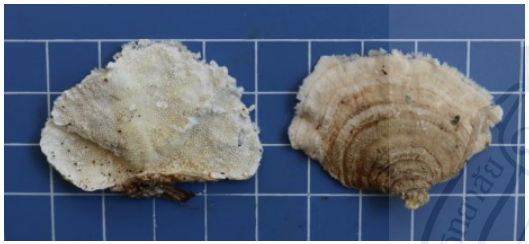
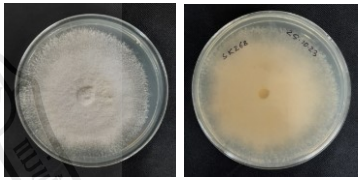
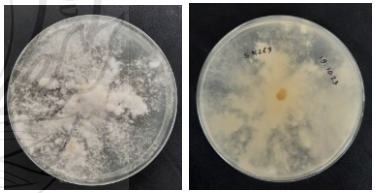
Code/ Fungus	Basidiomata	Culture	Culture days
SK267 (*Trametes versicolor*)			13 days
SK268 (*Trametes versicolor*)			13 days
SK269 (*Tyromyces* sp.)			17 days
SK270 (*Earliella scabrosa*)		N/A	

Table B1 (continued)

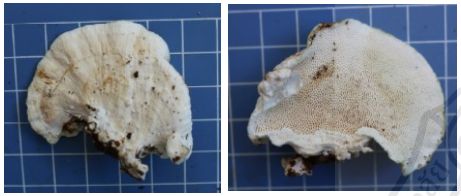
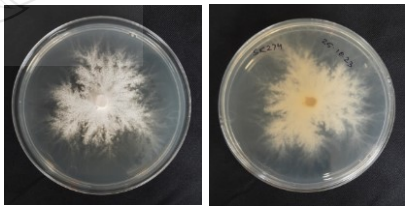
Code/ Fungus	Basidiomata	Culture	Culture days
SK271 (*Trametes versicolor*)		N/A	
SK272 (*Trametes* sp.)		N/A	
SK273 (*Leucoagaricus* sp.)		N/A	
SK274 (*Trametes* sp.)			14 days

Table B1 (continued)

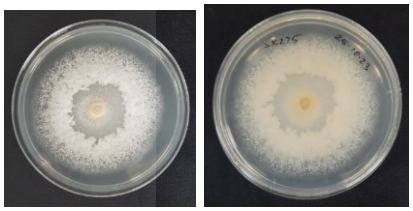
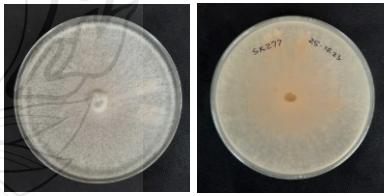
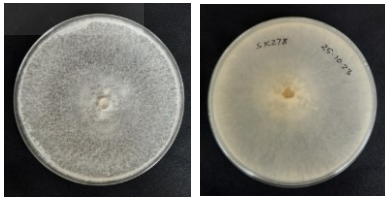
Code/ Fungus	Basidiomata	Culture	Culture days
SK275 (*Trametes* sp.)			11 days
SK276 (*Geastrum* sp.)		N/A	
SK277 (*Trametes hirsuta*)			11 days
SK278 (*Ganoderma* sp.)			11 days

Table B1 (continued)

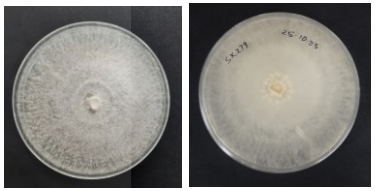
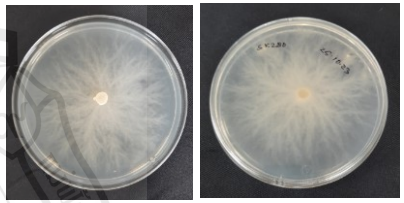
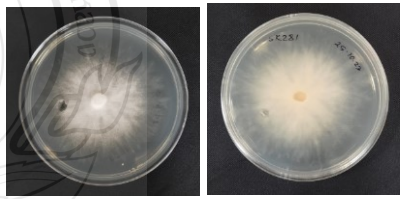
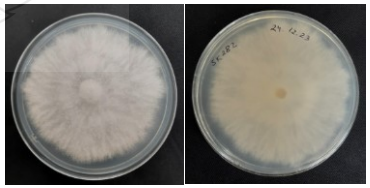
Code/ Fungus	Basidiomata	Culture	Culture days
SK279 (*Ganoderma* sp.)			11 days
SK280 (*Trullella yunnanensis*)			13 days
SK281 (*Trullella yunnanensis*)			13 days
SK282 (*Schizophyllum* sp.)			10 days

Table B1 (continued)

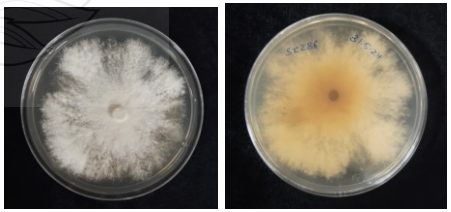
Code/ Fungus	Basidiomata	Culture	Culture days
SK283 (Unknown)		N/A	
SK284 (*Trogia* sp.)		N/A	
SK285 (*Trametes* sp.)			14 days
SK286 (*Cymatoderma* sp.)			29 days

Table B1 (continued)

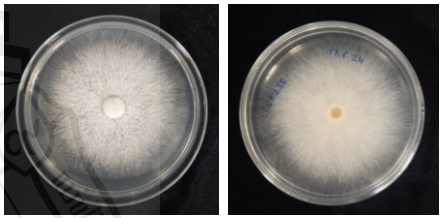
Code/ Fungus	Basidiomata	Culture	Culture days
SK287 (*Trametes* sp.)		N/A	
SK288 (*Panus ciliatus*)			12 days
SK289 (*Favolaschia* sp.)		N/A	
SK290 (*Daedaleopsis* sp.)		N/A	

Table B1 (continued)

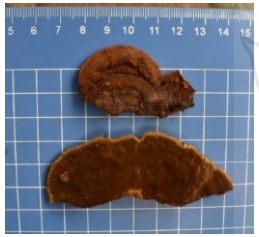
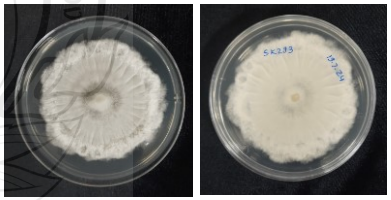
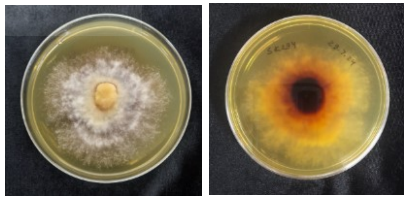
Code/ Fungus	Basidiomata	Culture	Culture days
SK291 (*Fuscoporia* sp.)		N/A	
SK292 (*Auricularia asiatica*)			33 days
SK293 (*Phellinus* sp.)			10 days
SK294 (*Serpula* sp.)			37 days

Table B1 (continued)

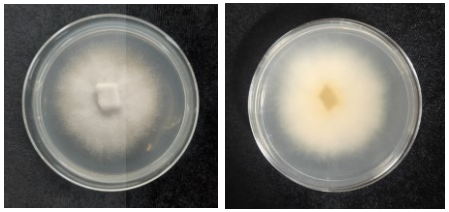
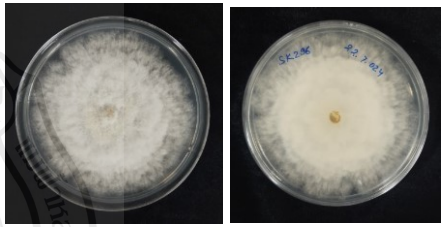
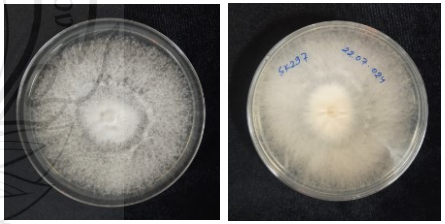
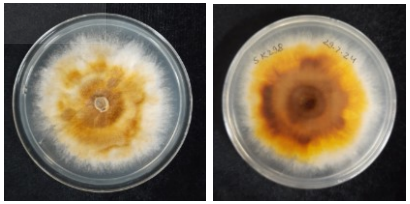
Code/ Fungus	Basidiomata	Culture	Culture days
SK295 (*Hymenochaete conchata*)			13 days
SK296 (*Thelephora* sp.)			7 days (contaminated)
SK297 (*Ganoderma* sp.)			7 days
SK298 (*Phellinus* sp.)			28 days

Table B1 (continued)

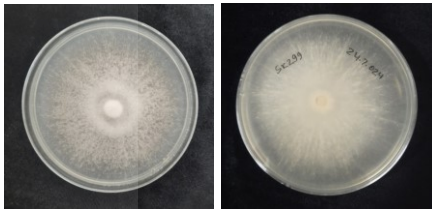
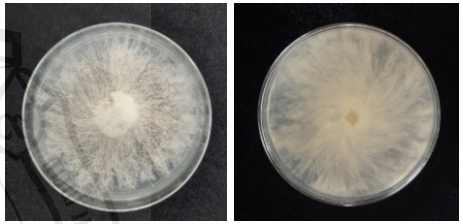
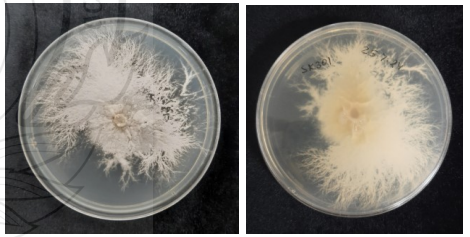
Code/ Fungus	Basidiomata	Culture	Culture days
SK299 (*Fomitopsis feei*)			13 days
SK300 (*Flavodon* sp.)			10 days
SK301 (*Auricularia asiatica*)			32 days
SK302 (*Termitomyces* sp.)		N/A	

Table B1 (continued)

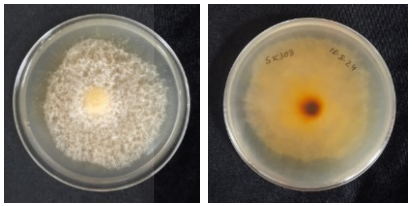
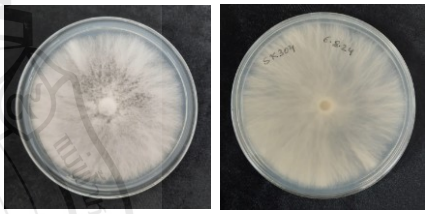
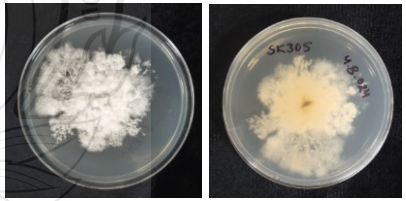
Code/ Fungus	Basidiomata	Culture	Culture days
SK303 (*Fulvifomes* sp.)			16 days
SK304 (*Panus ciliatus*)			9 days
SK305 (*Hexagonia cucullata*)			22 days
SK306 (*Hymenochaete* sp.)		N/A	

Table B1 (continued)

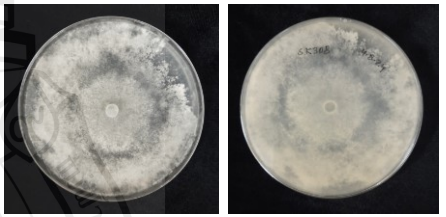
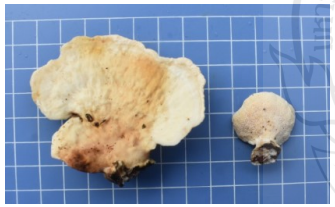
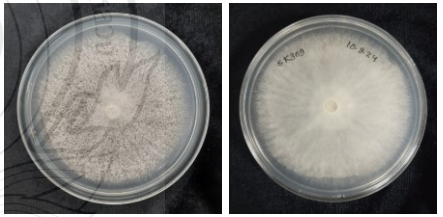
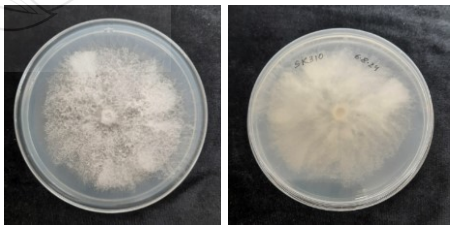
Code/ Fungus	Basidiomata	Culture	Culture days
SK307 (*Microporus* sp.)		N/A	
SK308 (*Phanerochaete stereoids*)			11 days
SK309 (*Trametes elegans*)			9 days
SK310 (*Favolus glaber*)			9 days

Table B1 (continued)

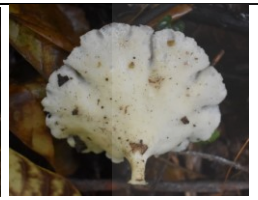
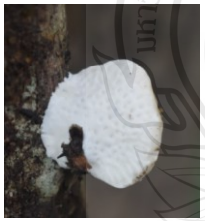
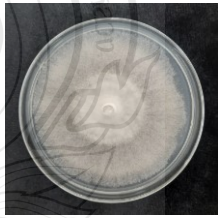
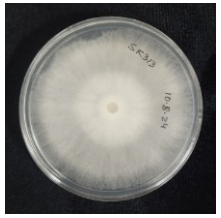
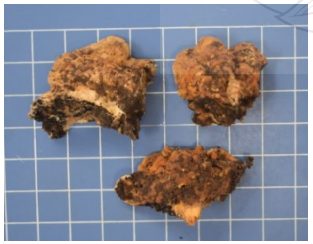
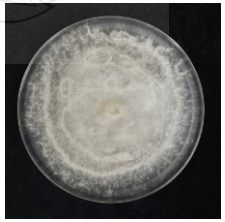
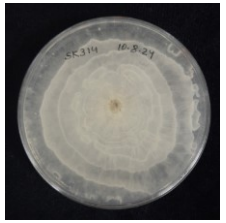
Code/ Fungus	Basidiomata	Culture	Culture days
SK311 (*Favolus* sp.)		N/A	
SK312 (*Podoscypha* sp.)		N/A	
SK313 (*Cubamyces lactineus*)		 	9 days
SK314 (Unidentified)		 	9 days

Table B1 (continued)

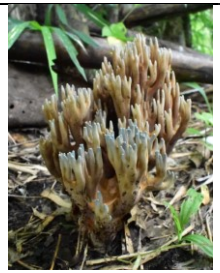
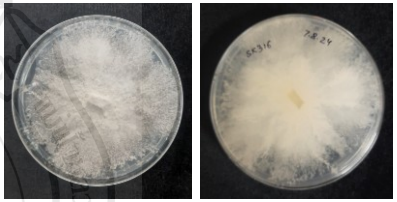
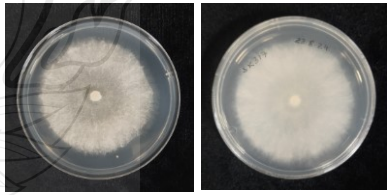
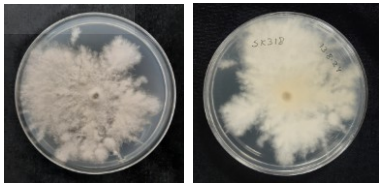
Code/ Fungus	Basidiomata	Culture	Culture days
SK315 (*Ramaria* sp.)		N/A	
SK316 (*Trametes* sp.)			16 days
SK317 (*Psathyrella cacao*)			10 days
SK318 (*Podoscypha gillessi*)			20 days

Table B1 (continued)

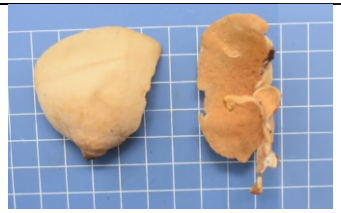
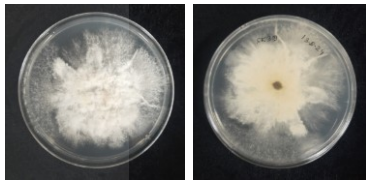
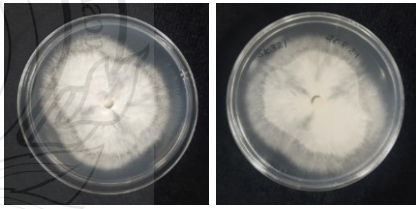
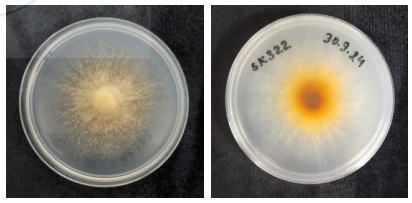
Code/ Fungus	Basidiomata	Culture	Culture days
SK319 (*Hexagonia cucullata*)			22 days
SK320 (*Favolus* sp.)		N/A	
SK321 (*Ganoderma tropicum*)			9 days
SK322 (*Phylloporia pulla*)			28 days

Table B1 (continued)

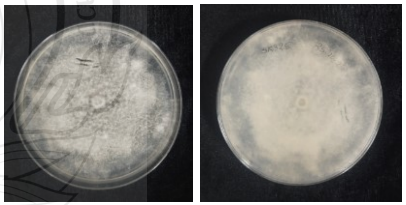
Code/ Fungus	Basidiomata	Culture	Culture days
SK323 (*Daedaleopsis* sp.)		N/A	
SK324 (*Trametes* sp.)		N/A	
SK325 (*Trametes* sp.)			12 days
SK326 (*Trametes* sp.)		N/A	

Table B1 (continued)

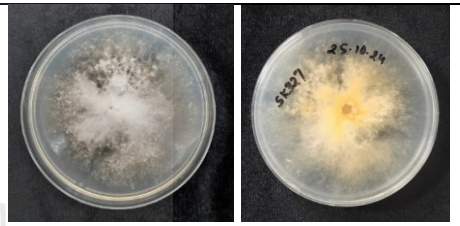
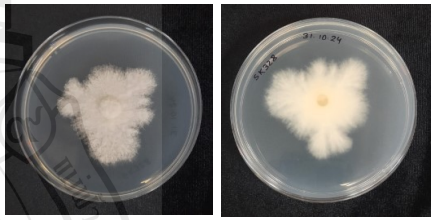
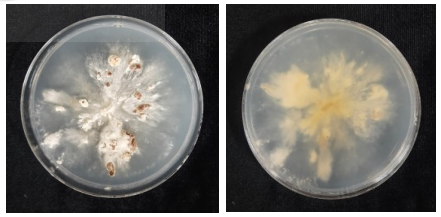
Code/ Fungus	Basidiomata	Culture	Culture days
SK327 (*Oudemansiella canarii*)			15 days
SK328 (*Panus* sp.)			14 days
SK329 (*Panus* sp.)		N/A	
SK330 (*Collybiopsis* sp.)			93 days

Table B1 (continued)

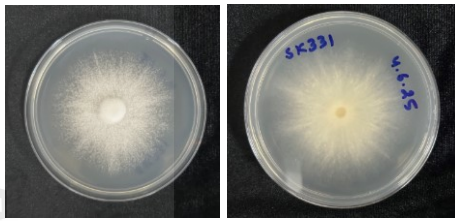
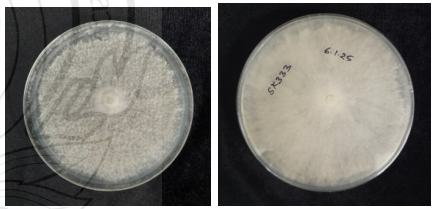
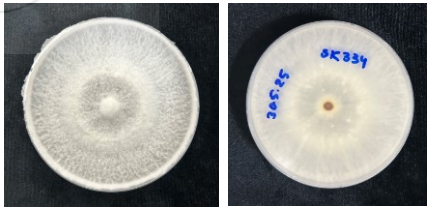
Code/ Fungus	Basidiomata	Culture	Culture days
SK331 (*Fomitopsis feei*)			9 days
SK332 (*Trametes lactineus*)		N/A	
SK333 (*Trametes hirsuta*)			7 days
SK334 (*Funalia aspera*)			14 days

Table B1 (continued)

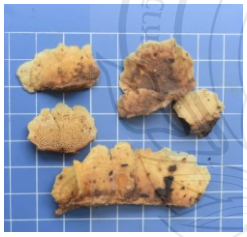
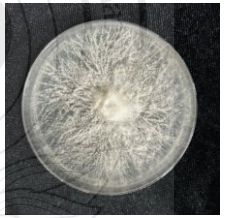
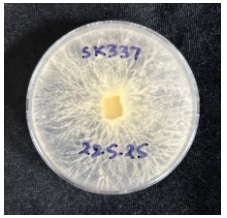
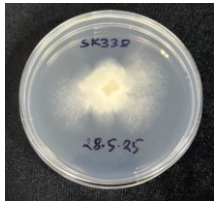
Code/ Fungus	Basidiomata	Culture	Culture days
SK335 (*Campanella* sp.)		N/A	
SK336 (*Campanella* sp.)		N/A	
SK337 (*Elmerina sclerodontia*)		 	16 days
SK338 (*Filoboletus manipularis*)			17 days

Table B1 (continued)

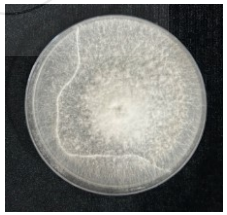
Code/ Fungus	Basidiomata	Culture	Culture days
SK339 (*Earliella scabrosa*)		N/A	
SK340 (*Trametes elegans*)			14 days
SK341 (*Ganoderma* sp.)		N/A	
SK342 (*Ganoderma williamsianum*)			9 days

Table B1 (continued)

Code/ Fungus	Basidiomata	Culture	Culture days
SK343 (*Xylobolus princeps*)		N/A	
SK344 (*Cymatoderma dendriticum*)		N/A	
SK345 (*Inocybe hopeae*)		N/A	
SK346 (Unidentified)		N/A	

Table B1 (continued)

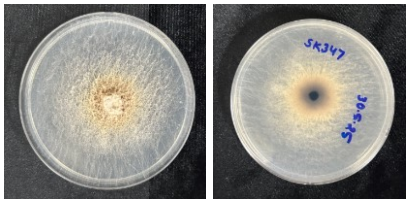
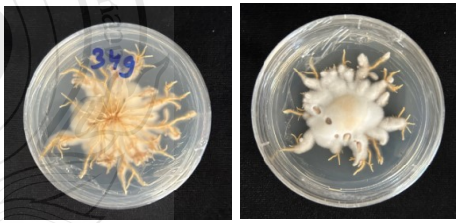
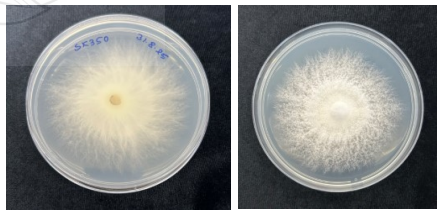
Code/ Fungus	Basidiomata	Culture	Culture days
SK347 (*Tomophagus colossus*)			14 days
SK348 (*Galerina* sp.)		N/A	
SK349 (*Armillariella tabesens*)			14 days
SK350 (*Fomitopsis* sp.)			7 days

Table B1 (continued)

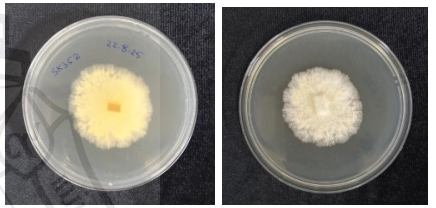
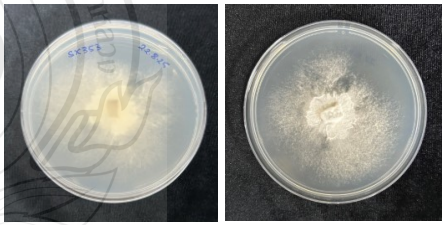
Code/ Fungus	Basidiomata	Culture	Culture days
SK351 (*Stereum* sp.)		N/A	
SK352 (*Neonothopanus nambi*)			23 days
SK353 (*Favolaschia manipularis*)			23 days
SK354 (*Inocybe virosa*)		N/A	

Table B1 (continued)

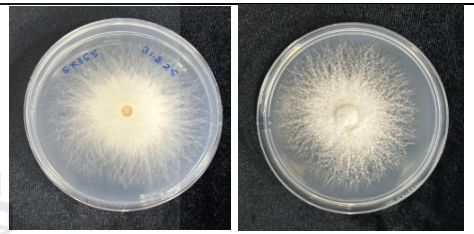
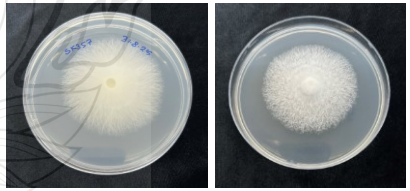
Code/ Fungus	Basidiomata	Culture	Culture days
SK355 (*Ganoderma* sp.)			7 days
SK356 (*Trametes* sp.)		N/A	
SK357 (*Trametes caespitosa*)			7 days
SK358 (*Trametes* sp.)		N/A	

Table B1 (continued)

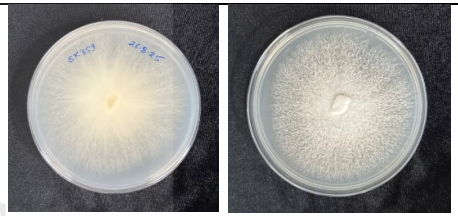
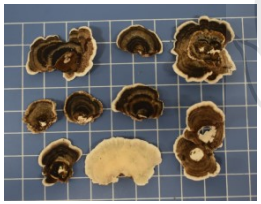
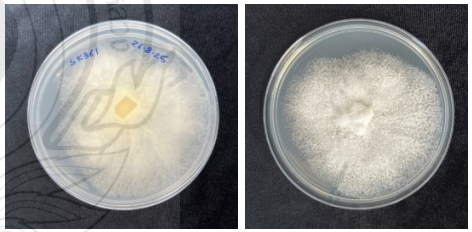
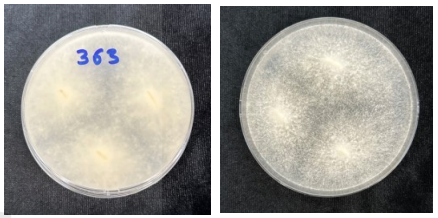
Code/ Fungus	Basidiomata	Culture	Culture days
SK359 (*Phanerochaete* sp.)			9 days
SK360 (*Cellulariella warnieri*)		N/A	
SK361 (*Trametes versicolor*)			9 days
SK362 (*Lycoperdon* sp.)		N/A	

Table B1 (continued)

Code/ Fungus	Basidiomata	Culture	Culture days
SK363 (*Stereum ostrea*)			days
SK364 (*Trametes* sp.)		N/A	
SK365 (*Trametes* sp.)		N/A	

APPENDIX C

DETAILS OF MUSHROOM MYCELIUM-BASED BIOMATERIALS DEVELOPED

Table C1 Details of Mushroom Mycelium-Based Biomaterials Developed During This Research

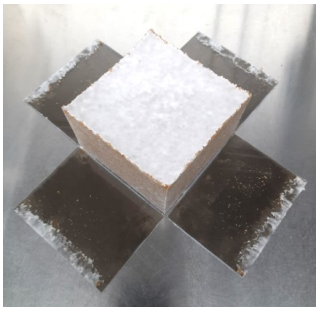
SN	Sample	Fungi/code	Substrate	Product	Sample Photo
1	BMS1	*Pleurotus ostreatus* (SK7)	Sawdust	Rectangular cup	
2	BMS2	*Ganoderma* sp. (LT130)	Sawdust	Circular bowl	
3	BMS3	*Lentinus* sp. (LT228)	Sawdust	Rectangular block	
4	BMS4	*Ganoderma* sp. (LT130)	Sawdust	Rectangular block	

Table C1 (continued)

SN	Sample	Fungi/code	Substrate	Product	Sample Photo
5	BMS5	*Pleurotus ostreatus* (SK7)	Paddy straw	Rectangular block	
6	BMS6	*Pleurotus ostreatus* (SK7)	Paddy straw and sawdust	Rectangular block	
7	BMS7	*Ganoderma* sp. (LT91)	Sawdust	Rectangular cup	
8	BMS11	*Ganoderma* sp. (LT130)	Sawdust	Rectangular panel	
9	BMS12	*Ganoderma tropicum* (SK37)	Rice husk	Rectangular block	

Table C1 (continued)

SN	Sample	Fungi/code	Substrate	Product	Sample Photo
10	BMS16	*Trametes sanguinea* (SK69)	Rice husk	Rectangular block	
11	BMS20	*Ganoderma* sp. (LT91)	Sawdust	Cube	
12	BMS21	*Ganoderma* sp. (LT145)	Sawdust	Cube	
13	BMS23	*Ganoderma* sp. (LT91)	Sawdust	Hollow tube	
14	BMS24	*Trametes sanguinea* (SK69)	Sawdust	Circular cylinder	

Table C1 (continued)

SN	Sample	Fungi/code	Substrate	Product	Sample Photo
15	BMS25	*Ganoderma* sp. (LT91)	Sawdust	Ashtray	
16	BMS27	*Ganoderma* sp. (LT91)	Sawdust	Insulation board	
17	BMS28	*Trametes polyzona* (SK132)	Sawdust	Cube	
18	BMS29	*Trametes polyzona* (SK132)	Sawdust	Rectangular block	
19	BMS30	*Trametes polyzona* (SK132)	Sawdust	Tea pad	

Table C1 (continued)

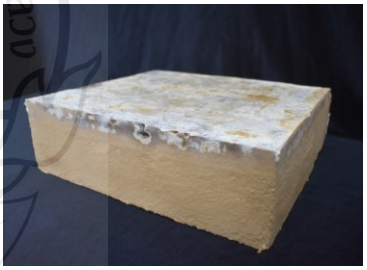
SN	Sample	Fungi/code	Substrate	Product	Sample Photo
20	BMS31	*Pleurotus ostreatus* (SK7)	Sawdust	Rectangular block	
21	BMS32	*Ganoderma tropicum* (SK37)	Sawdust	Circular bowl	
22	BMS33	*Ganoderma tropicum* (SK37)	Sawdust	Rectangular bowl	
23	BMS34	*Earliella scrabosa* (SK127)	Sawdust, spent coffee	Rectangular block	
24	BMS35	*Hexagonia tenuis* (SK141)	sawdust	Circular bowl	

Table C1 (continued)

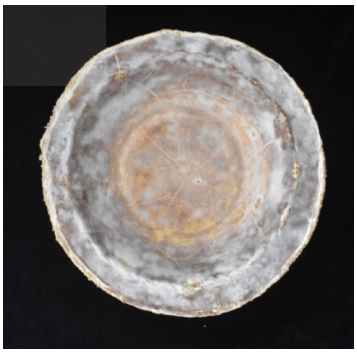
SN	Sample	Fungi/code	Substrate	Product	Sample Photo
25	BMS36	*Hexagonia tenuis* (SK141)	sawdust	Circular bowl	
26	BMS37	*Hexagonia tenuis* (SK114)	Sawdust	Rectangular block	
27	BMS38	*Trametes sanguinea* (SK69)	Sawdust	Rectangular block	
28	BMS39	*Trametes polyzona* (SK132)	Sawdust	Rectangular block	
29	BMS40	*Lentinus squarrosulus* (SK156)	Sawdust	Circular bowl	

Table C1 (continued)

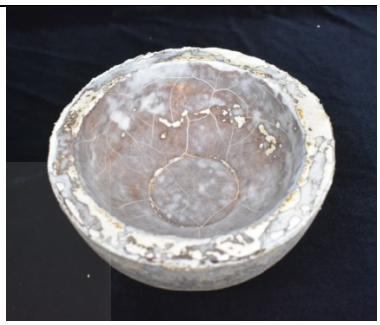
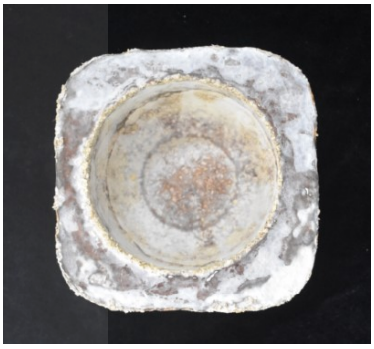
SN	Sample	Fungi/code	Substrate	Product	Sample Photo
30	BMS41	*Lentinus squarrosulus* (SK156)	Sawdust	Circular bowl	
31	BMS42	*Lentinus squarrosulus* (SK156)	Sawdust	Circular bowl	
32	BMS43	*Earliella scabrosa* (SK55)	Sawdust	Rectangular block	
33	BMS46	*Panus subfasciatus* (SK49)	Sawdust	Rectangular bowl	
34	BMS47	*Panus subfasciatus* (SK49)	Sawdust	Circular bowl	

Table C1 (continued)

SN	Sample	Fungi/code	Substrate	Product	Sample Photo
35	BMS48	*Panus subfasciatus* (SK49)	Sawdust	Circular bowl	
36	BMS49	*Panus ciliatus* (SK288)	Sawdust	Vase	
37	BMS50	*Panus ciliatus* (SK288)	Sawdust	Vase	
38	BMS51	*Panus subfasciatus* (SK49)	Sawdust	Rectangular bowl	
39	BMS52	*Panus subfasciatus* (SK49)	Sawdust	Rectangular bowl	

Table C1 (continued)

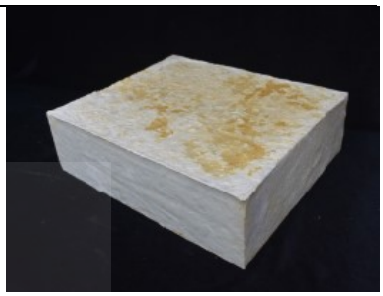
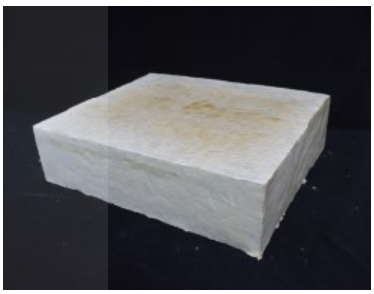
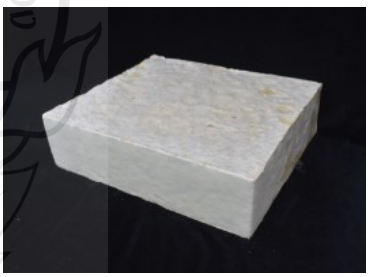
SN	Sample	Fungi/code	Substrate	Product	Sample Photo
40	BMS53	*Panus subfasciatus* (SK49)	Sawdust	Rectangular block	
41	BMS54	*Panus ciliatus* (SK288)	Sawdust	Rectangular block	
42	BMS55	*Panus subfasciatus* (SK49)	Sawdust	Rectangular block	
43	BMS56	*Panus ciliatus* (SK288)	Sawdust	Rectangular block	
44	BMS57	*Panus subfasciatus* (SK49)	Sawdust	Rectangular block	

Table C1 (continued)

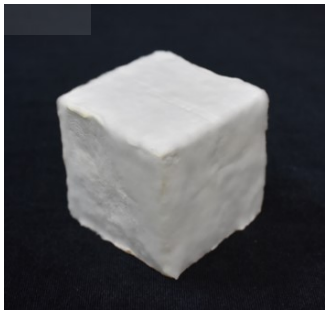
SN	Sample	Fungi/code	Substrate	Product	Sample Photo
45	BMS58	*Panus subfasciatus* (SK49)	Sawdust	Rectangular block	
46	BMS59	*Panus ciliatus* (SK288)	Sawdust	Circular bowl	
47	BMS60	*Pleurorus djamor*	Sawdust	Rectangular block	
48	BMS61	*Pleurorus djamor*	Sawdust	Rectangular block	
49	BMS62	*Phlebiopsis friesii* (SK205)	MEB	Myceliu m mats	
50	BMS63	*Panus ciliatus* (SK288)	Sawdust	Cube	

Table C1 (continued)

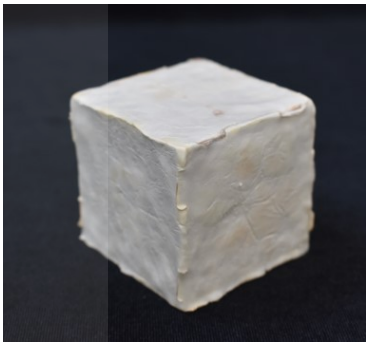
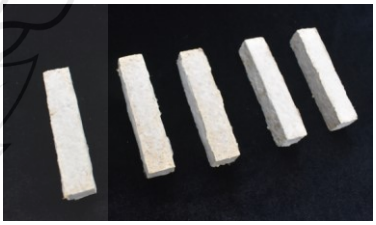
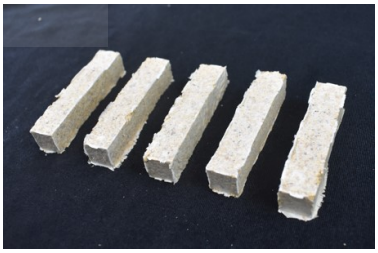
SN	Sample	Fungi/code	Substrate	Product	Sample Photo
51	BMS64	*Panus ciliatus* (SK288)	Sawdust	Rectangular block	
52	BMS65	*Panus subfasciatus* (SK49)	Sawdust	Cube	
53	BMS66	*Panus subfasciatus* (SK49)	Sawdust	Rectangular block	
54	BMS67	*Panus ciliatus* (SK288)	Sawdust	Rectangular block	
55	BMS68	*Panus subfasciatus* (SK49)	Sawdust	Rectangular block	

Table C1 (continued)

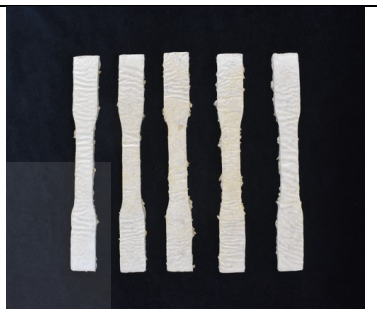
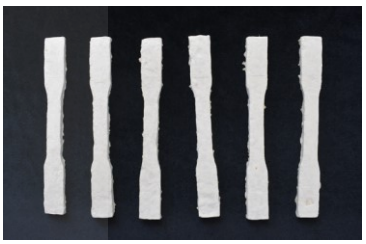
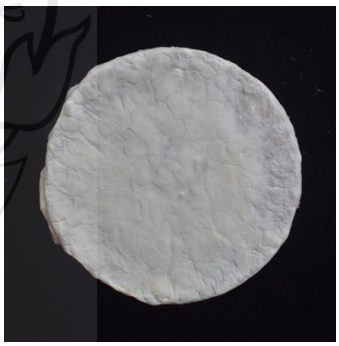
SN	Sample	Fungi/code	Substrate	Product	Sample Photo
56	BMS69	*Panus ciliatus* (SK288)	Sawdust	Dumbell -shaped product	
57	BMS70	*Panus subfasciatus* (SK49)	Sawdust	Dumbell -shaped product	
58	BMS71	*Panus ciliatus* (SK288)	Sawdust	Tea plate	
59	BMS72	*Panus subfasciatus* (SK49)	Sawdust	Tea plate	
60	BMS73	*Coriolopsis brunneoleuca* (SK95)	Sawdust	Cube	

Table C1 (continued)

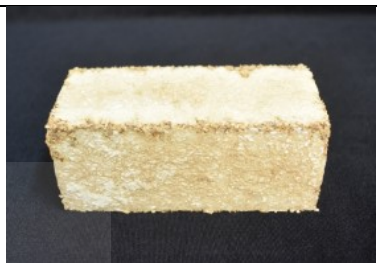
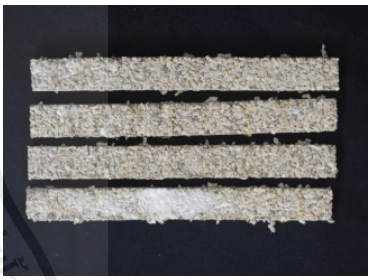
SN	Sample	Fungi/code	Substrate	Product	Sample Photo
61	BMS74	*Coriolopsis brunneoleuca* (SK95)	Sawdust	Rectangular block	
62	BMS75	*Coriolopsis brunneoleuca* (SK95)	Sawdust	Rectangular block	
63	BMS76	*Coriolopsis brunneoleuca* (SK95)	Sawdust	Rectangular strip	
64	BMS77	*Coriolopsis brunneoleuca* (SK95)	Sawdust	Circular cylinder	
65	BMS78	*Coriolopsis brunneoleuca* (SK95)	Sawdust	Square block	

Table C1 (continued)

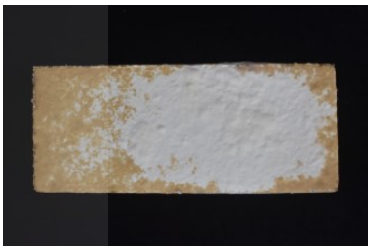
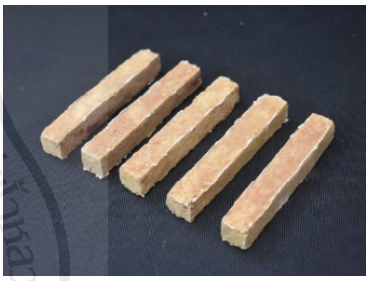
SN	Sample	Fungi/code	Substrate	Product	Sample Photo
66	BMS79	*Earliella scabrosa* (SK55)	Sawdust	Cube	
67	BMS80	*Earliella scabrosa* (SK55)	Sawdust	Rectangular block	
68	BMS81	*Earliella scabrosa* (SK55)	Sawdust	Rectangular block	
69	BMS82	*Earliella scabrosa* (SK55)	Sawdust	Rectangular strip	
70	BMS83	*Earliella scabrosa* (SK55)	Sawdust	Circular cylinder	

Table C1 (continued)

SN	Sample	Fungi/code	Substrate	Product	Sample Photo
71	BMS84	*Earliella scabrosa* (SK127)	Sawdust	Cube	
72	BMS85	*Earliella scabrosa* (SK127)	Sawdust	Rectangular block	
73	BMS86	*Earliella scabrosa* (SK127)	Sawdust	Rectangular block	
74	BMS87	*Earliella scabrosa* (SK127)	Sawdust	Rectangular strip	
75	BMS88	*Earliella scabrosa* (SK127)	Sawdust	Circular cylinder	

Table C1 (continued)

SN	Sample	Fungi/code	Substrate	Product	Sample Photo
76	BMS89	*Ganoderma tropicum* (SK37)	Sawdust	Cube	
77	BMS90	*Ganoderma tropicum* (SK37)	Sawdust	Rectangular block	
78	BMS91	*Ganoderma tropicum* (SK37)	Sawdust	Rectangular block	
79	BMS92	*Ganoderma tropicum* (SK37)	Sawdust	Rectangular strip	
80	BMS93	*Ganoderma tropicum* (SK37)	Sawdust	Circular cylinder	

Table C1 (continued)

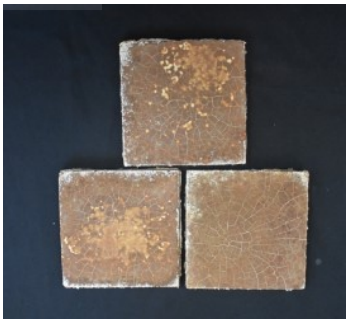
SN	Sample	Fungi/code	Substrate	Product	Sample Photo
81	BMS94	*Ganoderma tropicum* (SK37)	Sawdust		
82	BMS95	*Hexagonia tenuis* (SK114)	Sawdust	Cube	
83	BMS96	*Hexagonia tenuis* (SK114)	Sawdust	Rectangular block	
84	BMS97	*Hexagonia tenuis* (SK114)	Sawdust	Circular cylinder	
85	BMS98	*Hexagonia tenuis* (SK114)	Sawdust	Square block	

Table C1 (continued)

SN	Sample	Fungi/code	Substrate	Product	Sample Photo
86	BMS99	*Hexagonia tenuis* (SK141)	Sawdust	Cube	
87	BMS100	*Hexagonia tenuis* (SK141)	Sawdust	Rectangular block	
88	BMS101	*Hexagonia tenuis* (SK141)	Sawdust	Rectangular block	
89	BMS102	*Hexagonia tenuis* (SK141)	Sawdust	Rectangular strip	
90	BMS103	*Hexagonia tenuis* (SK141)	Sawdust	Circular cylinder	

Table C1 (continued)

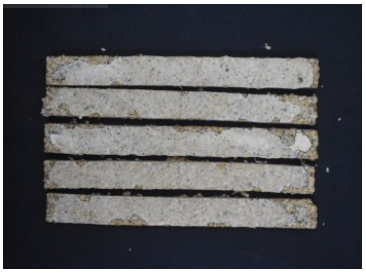
SN	Sample	Fungi/code	Substrate	Product	Sample Photo
91	BMS104	*Hexagonia tenuis* (SK141)	Sawdust	Square block	
92	BMS105	*Lentinus squarrosulus* (SK156)	Sawdust	Cube	
93	BMS106	*Lentinus squarrosulus* (SK156)	Sawdust	Rectangular block	
94	BMS107	*Lentinus squarrosulus* (SK156)	Sawdust	Rectangular block	
95	BMS108	*Lentinus squarrosulus* (SK156)	Sawdust	Rectangular strip	

Table C1 (continued)

SN	Sample	Fungi/code	Substrate	Product	Sample Photo
96	BMS109	*Lentinus squarrosulus* (SK156)	Sawdust		
97	BMS110	*Pleurotus ostreatus* (SK7)	Sawdust	Cube	
98	BMS111	*Pleurotus ostreatus* (SK7)	Sawdust	Rectangular block	
99	BMS112	*Pleurotus ostreatus* (SK7)	Sawdust	Rectangular block	
100	BMS113	*Pleurotus ostreatus* (SK7)	Sawdust	Dumbell-shaped product	

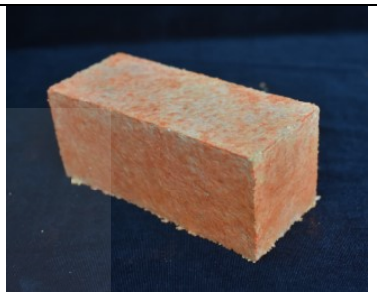
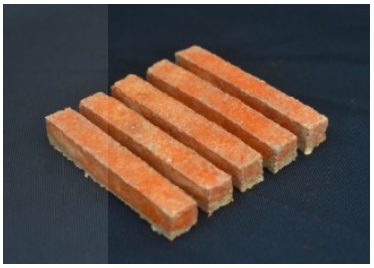
Table C1 (continued)

SN	Sample	Fungi/code	Substrate	Product	Sample Photo
101	BMS114	*Pleurotus ostreatus* (SK7)	Sawdust	Rectangular strip	
102	BMS115	*Pleurotus ostreatus* (SK7)	Sawdust	Circular cylinder	
103	BMS116	*Trametes polyzona* (SK132)	Sawdust	Cube	
104	BMS117	*Trametes polyzona* (SK132)	Sawdust	Rectangular block	
105	BMS118	*Trametes polyzona* (SK132)	Sawdust	Rectangular block	

Table C1 (continued)

SN	Sample	Fungi/code	Substrate	Product	Sample Photo
106	BMS 119	*Trametes polyzona* (SK132)	Sawdust	Dumbell -shaped product	
107	BMS 120	*Trametes polyzona* (SK132)	Sawdust	Rectangular strip	
108	BMS 121	*Trametes polyzona* (SK132)	Sawdust	Circular cylinder	
109	BMS 122	*Trametes polyzona* (SK132)	Sawdust	Square block	
110	BMS 123	*Trametes sanguinea* (SK69)	Sawdust	Cube	

Table C1 (continued)

SN	Sample	Fungi/code	Substrate	Product	Sample Photo
111	BMS 124	*Trametes sanguinea* (SK69)	Sawdust	Rectangular block	
112	BMS 125	*Trametes sanguinea* (SK69)	Sawdust	Rectangular block	
113	BMS 126	*Trametes sanguinea* (SK69)	Sawdust	Dumbell-shaped product	
114	BMS 127	*Trametes sanguinea* (SK69)	Sawdust	Rectangular strip	

APPENDIX D

ABSTRACT OF PUBLICATIONS

Fungal Biotec 4(1): 56–67 (2024) ISSN 2774-0323

www.fungalbiotec.org **Article**

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Diverse use of mushroom mycelium-based as biomaterial products: A mini review

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Khyaju S, Luangharn T. 2024 – Diverse use of mushroom mycelium-based as biomaterial products: A mini review. Fungal Biotec 4(1), 56–67, Doi 10.5943/FunBiotec/4/1/4

Abstract

Maximum use of non-renewable natural resources is proven to be unsustainable. Extensive research on mushroom mycelium has revealed its potential and applications in daily products. The mushroom mycelium-based biomaterials concept has been used to produce diverse products as an alternative to plastic products. Agriculture waste products, often considered effluents, are effectively repurposed as primary substrates for producing biomaterials. This approach contributes to the promotion of a closed-loop or circular economy. Numerous commercial companies have integrated mushroom mycelium-based biomaterials that adhere to international standards into their products. Mycelium-based materials have applications in various sectors, including packaging, architectural designs, construction, thermal and acoustic insulation, and textiles, specifically synthetic leather. Several prior studies have established that these products demonstrate biodegradability with a lack of residual impact on the environment. This article presents a diverse use of mushroom mycelium to develop different eco-friendly products.

Keywords – biotechnology – circular economy – mycelium-based biomaterials – sustainable development

Introduction

The world population is increasing rapidly, with a current population of 7.7 billion in 2019 from 6.8 billion in 2009 and an estimated 9.7 billion by 2050 (Maraveas 2020). According to United Nations projects (2018), it is anticipated that by the year 2050, approximately 68% of the global population will reside in urban areas. Annual waste generation is anticipated to escalate to 2.2 billion tons by 2025 and reach an imposing 3.40 billion tons by 2050, which implies that annual waste will increase to 2.2 billion tons by 2025 and a staggering 3.40 billion tons by 2050 (Chattopadhyay et al. 2008, Hoornweg & Bhada-Tat 2012, Alemu et al. 2022). According to the escalating waste landscape, synthetic plastics, known as non-biodegradable, have emerged as a significant source of environmental pollution (Holt et al. 2012, Lin et al. 2017). These plastic products are predominantly sourced from finite natural resources, posing sustainability challenges and obstructing the shift towards a circular economy. The manufacturing processes of extruded polystyrene and expanded polyethylene foams are sourced from petroleum-based origins, which involve significant energy consumption. So, the limited and non-renewable petroleum sources direct the world towards crises. There are substantial risks to human health, underscoring the pressing requirement for sustainable waste management solutions (Lopez Nava et al. 2016).

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RESEARCH ARTICLE

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Phlebiopsis friesii (Phanerochaetaceae, Polyporales), a New Record in Thailand and the First Preliminary Characterization of Its Potential in Mycelium Mats

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ABSTRACT

This study reports a new record of the white-rot mushroom species *Phlebiopsis friesii* (MFLUCC 24-0323) from Chiang Mai Province, Thailand. The specimen is described based on morphological characteristics and phylogenetic analysis of the combination of internal transcribed spacer (ITS) and large subunit (LSU) regions. After identification of the fungus, its culture was used to develop pure mycelial mats in broth media and for preliminary characterization. Thermogravimetric properties, Fourier-transform infrared (FTIR) spectroscopy profiles, scanning electron microscopy (SEM), and water contact angle (CA) measurements were investigated to determine the potential of mycelium-based leather (MBL). These findings provide new insights into Thai *P. friesii*, focusing on its morphology, genetics, and the potential use of mushroom mycelium mats for developing mycelium-biomaterial.

ARTICLE HISTORY
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KEYWORDS
Geographical record; mycelium-based biomaterials; pure mycelium mat; resupinate mushroom

1. Introduction

Phlebiopsis Jülich (1978) (Phanerochaetaceae, Polyporales, Agaricomycetes, Agaricomycotina, Basidiomycota) is a white-rot fungus and is typified by *P. gigantea* (Fr.) Jülich [1,2]. This genus is distinguished by its combination of resupinate to effused-reflexed basidiomata, a membranous to subceraceous texture when fresh, not cracking when dry, a smooth to odontoid or poroid hymenophore, a monomitic hyphal system composed of simple septate generative hyphae, and smooth, thin-walled, cylindrical to ellipsoid basidiospores which are acyanophilous and inamyloid [3,4]. Species of *Phlebiopsis* are widely distributed in all continents except Antarctica [4–8]. There are 42 records of *Phlebiopsis* in Index Fungorum (www.indexfungorum.org; accessed on: 26 March 2025). To date, 22 species have been recognized in the genus worldwide [2,3,6,7,9,10–16].

Phlebiopsis species have been relatively underexplored in terms of their applications. Biomaterials derived from mushroom mycelium offer numerous benefits, including energy-efficient production, low cost, reduced carbon footprint, sustainable sourcing, lightweight properties, low density, low combustibility, complete biodegradability, and nontoxic characteristics [17–19]. Mycelium-based leather (MBL), one of the applications of biomaterials, is a ground-breaking and sustainable alternative to plastic-based products, with potential applications in packaging, architectural design, construction, thermal and acoustic insulation, and textiles [20]. Conventional leather production involves animal slaughter and contributes to significant environmental challenges [21–23]. In contrast, MBL is a sustainable, eco-friendly, and nonpolluting alternative [24]. With its emerging benefits, several prominent companies, including Ecovative (www.ecovative.com), Mycoworks (www.mycoworks.com), Bolt Threads (www.boltthreads.com), Mycel (www.mycelproject.com), and Mogu (www.mogu.bio), have scaled up production of mycelium-based biomaterials [25,26]. However, research on MBL derived from diverse potential mushroom species remains limited. Additionally, a substantial portion of information on MBL development is confined by patents despite the numerous ongoing studies conducted worldwide. *Phlebiopsis* is also no exception, where mycelium mat applications are underexplored. Beside the usage of *P. gigantea* as a biological control agent in conifer root and butt diseases [27] and in biological processing for the pulp

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Article

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Echinochaete thailandica sp. nov. (Polyporaceae, Basidiomycota) from northern Thailand

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Abstract

The genus *Echinochaete* is a low-diversity genus within the family Polyporaceae, currently comprising only five taxonomically recognized species worldwide, suggesting the need for comprehensive revisionary studies. During a fungal survey in northern Thailand, a novel taxon was discovered, representing the first report of the genus. Here, we describe *Echinochaete thailandica sp. nov*., based on detailed morphological characteristics and two locus phylogenetic analyses (ITS and LSU). The new species is distinguished by lanceolate to cylindrical, longer (37–103 × 6–9 µm) setoid elements bearing lateral spines on the pileus, and cylindrical and large basidiospores (10.5–14.5 × 4.1–6.8 µm). Phylogenetic analyses position *E. thailandica* within the genus *Echinochaete*, distinct from all previously described taxa. This finding expands the known distribution of *Echinochaete*.

Key words: 1 new species, phylogeny, Polyporaceae, taxonomy, tropical region

Introduction

Echinochaete D.A. Reid is a small genus within the Polyporaceae Fr. ex Corda, established by Reid (1963) with *E. megalopora* (Bres.) D.A. Reid as the type species. This species was later renamed *E. brachypora* (Mont.) Ryvarden. Alongside the type species, Reid (1963) also included *E. cinnamomeosquamulosa* (Henn.) D.A. Reid and *E. russiceps* (Berk. & Broome) D.A. Reid (Reid 1963, Sotome *et al*. 2009). Species of *Echinochaete* are characterized by their annual, short, laterally stipitate basidiomata, which are flabelliform to spathulate with a tomentose surface, and poroid hymenophore (Reid 1963, Ryvarden & Johansen 1980, Corner 1984, Núñez & Ryvarden 1995, 2001, Sotome *et al*. 2009, Cui *et al*. 2019). The hyphal system is dimitic, comprising dextrinoid arboriform skeleton-binding hyphae, and clamped generative hyphae (Reid 1963, Ryvarden & Johansen 1980, Corner 1984, Núñez & Ryvarden 1995, 2001, Sotome *et al*. 2009, Cui *et al*. 2019). The genus exhibits spinulose setoid elements in the pileus surface and hymenium, along with cylindrical basidiospores (Reid 1963, Ryvarden & Johansen 1980, Corner 1984, Núñez & Ryvarden 1995, 2001, Sotome *et al*. 2009, Cui *et al*. 2019). Species delimitation is based primarily on macroscopic features and setoid elements morphology, with only minor differences in hyphal structure and basidiospore size (Reid 1963, Núñez & Ryvarden 2001, Cui *et al*. 2019). Notably, the pore surface varies from white to cream or dirty brown, with pores that range from angular to hexagonal and vary in pore size (Cui *et al*. 2019).

Before *Echinochaete* was established, Bondartsev & Singer (1941) proposed the genus *Asterochaete* Bondartsev & Singer to accommodate fungi with morphological features similar to those later associated with *Echinochaete*.

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Article

A Comprehensive Characterisation of Mycelium-Based Biomaterials Developed from *Panus ciliatus* and *P. subfasciatus* (Panaceae, Polyporales)

Sabin Khyaju [1,2,3], Kevin D. Hyde [1], Kitiphong Khongphinitbunjong [2], Sitthi Duangphet [2,4], Worawoot Aiduang [5,6] and Thatsanee Luangharn [1,*]

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Abstract

Mushroom mycelium-based biomaterials (MMBs) are sustainable materials derived from fungal species and lignocellulosic substrates. In this study, fresh specimens of *Panus ciliatus* and *P. subfasciatus* collected from mixed deciduous forests in Chiang Rai Province, Thailand, were identified through a combination of morphological characteristics and phylogenetic analyses based on the ITS region. *Panus ciliatus* is reported as a new geographical record from Thailand. This is the first comprehensive study on MMB samples developed using mycelia of these species and rubber sawdust for their physical, mechanical, hydrodynamic, and chemical properties. Additional analyses included FTIR spectroscopy, thermogravimetric analysis, flammability testing, and soil burial degradability. Based on the material properties and successfully developed prototypes, the MMBs are potential in packaging, indoor uses, construction, and insulation purposes, as an alternative to conventional synthetic materials. Notably, Ashby chart of mechanical properties showed the MMB could substitute foam. Thermogravimetric analysis of MMB showed thermal stability with weight loss approximately 50–60% at 293–298 °C. Soil burial of MMB for 90 days shows cumulative weight loss exceeding 60% proving biodegradable. Additionally, a new approach for mycelial viability maintenance is described and verified, addressing the problem to maintain vigorous mycelium.

Keywords: biobased material; mycelium-based application; new geographical record; sustainable materials

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1. Introduction

Panus Fr. (Panaceae, Polyporales) was described by Fries [1], with *P. conchatus* (Bull.) Fr. as the type species. Members of this genus are wood-inhabiting saprobes distributed worldwide, particularly in subtropical and tropical regions [2,3]. *Panus* species are characterised by a centrally to eccentrically stipitate basidiomata; infundibuliform to cyathiform pilei; a hymenophore with decurrent lamellae, free gills; ellipsoid, smooth, thin-walled, inamyloid basidiospores; thin to thick-walled cystidia; and a dimitic hyphal system with unbranched skeletal hyphae [1,3,4].

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A global checklist of mushrooms (Basidiomycota) in biomaterials and the challenges and opportunities of mycelium-based biomaterials

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Khyaju S, Hyde KD, Khongphinitbunjong K, Duangphet S, Luangharn T 2025 – A global checklist of mushrooms (Basidiomycota) in biomaterials and the challenges and opportunities of mycelium-based biomaterials. Asian Journal of Mycology 8(2), 112–142, Doi 10.5943/ajom/8/2/9

Abstract

Mushroom mycelium-based biomaterials (MMBs) are innovative, environment-friendly, biodegradable, and sustainable alternatives to plastic- and foam-based products. MMBs are popular due to their biodegradability, low carbon footprint, and alignment with the principles of the circular economy. MMBs are developed using the mycelium of suitable mushroom species and lignocellulosic substrates, derived from agricultural and forest byproducts. Research on several mushroom species is increasing, and the choice of species plays a pivotal role in determining the mechanical and overall characteristics of the end products. This review is the first compiled report of all mushroom species within Basidiomycota utilized in MMBs production. The mushroom genera used in its development have also been presented according to hyphal system type. This paper is based on all the relevant published and available articles till 2024. Additionally, it highlights key challenges in developing MMBs and explores potential solutions.

Keywords – fungal application – hyphal system – mushroom species – renewable – sustainable material

Introduction

Mushrooms are the fruiting bodies of fungi that grow above ground or on a substrate, primarily belonging to the phylum Basidiomycota. They include gilled fungi, puffballs, bracket fungi, coral fungi, jelly fungi, and crust fungi (Rathore et al. 2019). Since ancient times, mushrooms have been widely used in food, medicine, and the extraction of secondary compounds (Rathore et al. 2019). They are an important source of bioactive and medicinal compounds, such as terpenoids, polysaccharides, proteins, and vitamins, and are known for their antioxidant, antimicrobial, anticancer, antitumor, and immunomodulatory properties. Among several applications of mushrooms, mushroom mycelium-based biomaterials (MMBs) are a novel class of sustainable, eco-friendly, and biodegradable materials. As a result, research and development on MMBs is growing worldwide, with major efforts in Asia, Europe, and North America (Fig. 1).

Mycelium, the vegetative structure of filamentous fungi, acts as a unit-binding agent, connecting hyphae and substrates (Jiang et al. 2016, Abhijith et al. 2018). It grows on lignocellulosic

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PUBLICATION

First Author Publications

Khyaju, S., & Luangharn, T. (2024). Diverse use of mushroom mycelium-based biomaterial products: A mini review. *Fungal Biotec, 4*(1), 56–67. https://doi.org/10.5943/FunBiotec/4/1/4

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Co-author Publications

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