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Short review of the potential and beneficial use of *Ganoderma* derived in medicinal, cultivation, and biomaterial applications

Salichanh T[1,2,3], Khyaju S[1,2] and Luangharn T[1*]

1 Center of Excellence in Fungal Research, Mae Fah Luang University, Chiang Rai 57100, Thailand
2 School of Science, Mae Fah Luang University, Chiang Rai 57100, Thailand
3 Biotechnology and Ecology Institute, Ministry of Agriculture and Forestry, Vientiane P.O Box 811, Lao PDR

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Abstract

The genus *Ganoderma*, a prominent member of the family *Ganodermataceae*, has garnered significant attention due to its complex taxonomy, medicinal properties, and industrial applications. It has been utilized in traditional medicine and modern pharmaceuticals. The cultivation techniques of *Ganoderma* mushrooms were examined for their efficiency and sustainability, emphasizing advancements in production methodologies. Additionally, *Ganoderma* mycelium has emerged as a valuable resource for producing eco-friendly biomaterials, leveraging its binding properties and growth on lignocellulosic substrates. The utilization of *Ganoderma*-derived biomaterials in various industrial sectors, such as packaging and construction, underscores their eco-friendly attributes and functional versatility. This concise overview aims to provide insights into the expanding role of *Ganoderma* in enhancing human health and advancing sustainable technologies.

Keywords – cultivation techniques – *Ganoderma* use – medicinal mushroom – mushroom mycelium-bases applications

Introduction

Ganoderma, a genus established by Karsten in 1881 with *G. lucidum* as its type species (Karsten 1881), encompasses polypore fungi classified within the *Ganodermataceae* family in Polyporales (Moncalvo & Ryvarden 1997). These fungi display a wide range of shapes and often have a glossy appearance due to a resin-like deposit (Pilotti 2005, Richter et al. 2015). Precise species classification remains challenging due to morphological and molecular data limitations (Richter et al. 2015). Once considered a single species, molecular phylogenetic studies have revealed it as a complex of multiple species with varying geographical distributions (Papp 2019, Wang et al. 2009, Cao et al. 2012, Wu et al. 2013). Despite extensive research, the *Ganodermataceae* family remains challenging in determining the exact species diversity, geographical distribution, classification, and taxonomy (Fryssouli et al. 2020, Sun et al. 2022). Sun et al. (2022) conducted a thorough examination that identified 180 different species of *Ganoderma* and 14 genera within the *Ganodermataceae* family using morphological observations and genetic analysis.

The distribution within the genus holds significant importance due to its extensive use in traditional medicine, particularly *G. lucidum*, which has been prized for its immunomodulatory and

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Corresponding Author: Thatsanee Luangharn – e-mail – thatsanee.lua@mfu.ac.th

therapeutic properties for centuries (Paterson 2006, Cao et al. 2012, Wang et al. 2012, Hapuarachchi et al. 2018, Wang et al. 2020), and *G. boninense* can also act as parasites, causing significant economic losses in palm oil plantations (Pilotti 2005, Bharudin et al. 2022). *Ganoderma* is influenced by various factors, including host specificity, climate, and geographical barriers (Moncalvo et al. 1995). *Ganoderma* can be found globally and is renowned for its woody, bracket-like fruiting bodies and medicinal properties in traditional Asian medicine (Wasser 2002, Kumar 2021, Raman et al. 2022), North America and Europe (Hennicke et al. 2016, Loyd et al. 2018, El Sheikha 2022), are primarily saprotrophic fungi that play a crucial role in forest ecosystems by decomposing woody material (Li et al. 2022). They can break down both cellulose and lignin, contributing significantly to the nutrient cycling in forest soils.

Ganoderma species are utilized in functional foods and cosmetics due to their beneficial properties (Du et al. 2019). Among functional foods, *Ganoderma* is valued for its potential health benefits, including immune support, antioxidant properties, and anti-inflammatory effects. These properties make it a popular ingredient in dietary supplements and health drinks aimed at promoting overall well-being. In cosmetics, *Ganoderma* is appreciated for its purported anti-aging, moisturizing, and skin-soothing effects and is often incorporated into skincare products such as creams, serums, and masks. Overall, the versatility of *Ganoderma* in enhancing health and beauty products underscores its growing importance in the functional food foods and cosmetic industries (Li et al. 2019). *Ganoderma* species have found utility in functional foods, cosmetics, and even as ornamental plants

Ganoderma has developed into a substantial industry that provides a renewable source of medicinal products and supports rural economies (Hapuarachchi et al. 2018). Various methods, such as log cultivation, bag cultivation, soil cultivation, and liquid cultivation, have been employed to optimize growth conditions and maximize the yield and quality of *Ganoderma* species (Luangharn et al. 2017, Rashad et al. 2019, Wannasawang et al. 2023). Additionally, the use of *Ganoderma*-derived materials as sustainable alternatives to conventional materials aligns with global efforts to reduce the environmental impact and promote eco-friendly innovations (Gryzenhout et al. 2021). Advancements in molecular phylogeny and biotechnological innovations have expanded the potential applications of *Ganoderma* species, not only in traditional medicine but also in functional foods, cosmetics, and mycelium-based biomaterials (Jones et al. 2017, Luangharn et al. 2017, Pelletier et al. 2019, Charpentier-Alfaro et al. 2023).

Ganoderma has gained attention as a sustainable biomaterial. The growing demand for environmentally friendly alternatives to petroleum-based materials has spurred research on mycelium-based products (Balaeș et al. 2023). Mycelium, the vegetative part of fungi, exhibits promising properties for various applications, including textiles (Gandia et al. 2021), packaging (Joshi et al. 2020), and construction (Soh et al. 2023). However, the mechanical properties of mycelium materials often limit their practical use (Jones et al. 2020). Recent studies have demonstrated that incorporating glycerol into mycelium films can enhance their flexibility and durability (Ben et al. 2022), opening new possibilities for this biomaterial.

This review aims to provide a comprehensive overview of these diverse applications of *Ganoderma* mushrooms based on medical, cultivation, and biomaterials used (Fig. 1), highlighting the multifaceted potential of *Ganoderma*-derived products and ongoing research that continues to expand our understanding of this remarkable fungus.

Ganoderma for medical applications

Ganoderma species are rich in bioactive compounds, containing 18 amino acids, peptides, triterpenoids, and *Ganoderma* polysaccharides as bioactive ingredients (Taofiq et al. 2017). *Ganoderma* species, particularly *G. lucidum*, have been used in traditional medicine for thousands of years, especially in East Asia, and contain a wide array of bioactive compounds (Lu et al. 2020, Bhat et al. 2021, Pascale et al. 2022), including triterpenoids such as *Ganoderma*, contains over 150 triterpenoids, with ganoderic acids being the most studied (Baby et al. 2015, Xu et al. 2018). *Ganoderma*, which includes triterpenoids, polysaccharides, and other compounds, contributes to its wide range of medicinal properties. Triterpenoids, such as ganoderic acid, exhibit potent anti-inflammatory, antitumor, and hepatoprotective activities (Paterson 2006). Polysaccharides, particularly β-glucans, are known for their immunomodulatory effects that enhance innate and adaptive immune responses (Ren et al. 2021). *Ganoderma* also contains hypoglycemic proteins, peptides, and steroids that contribute to its antimicrobial, antioxidant, and anti-hypertensive effects, further expanding its therapeutic potential (Boh et al. 2007).

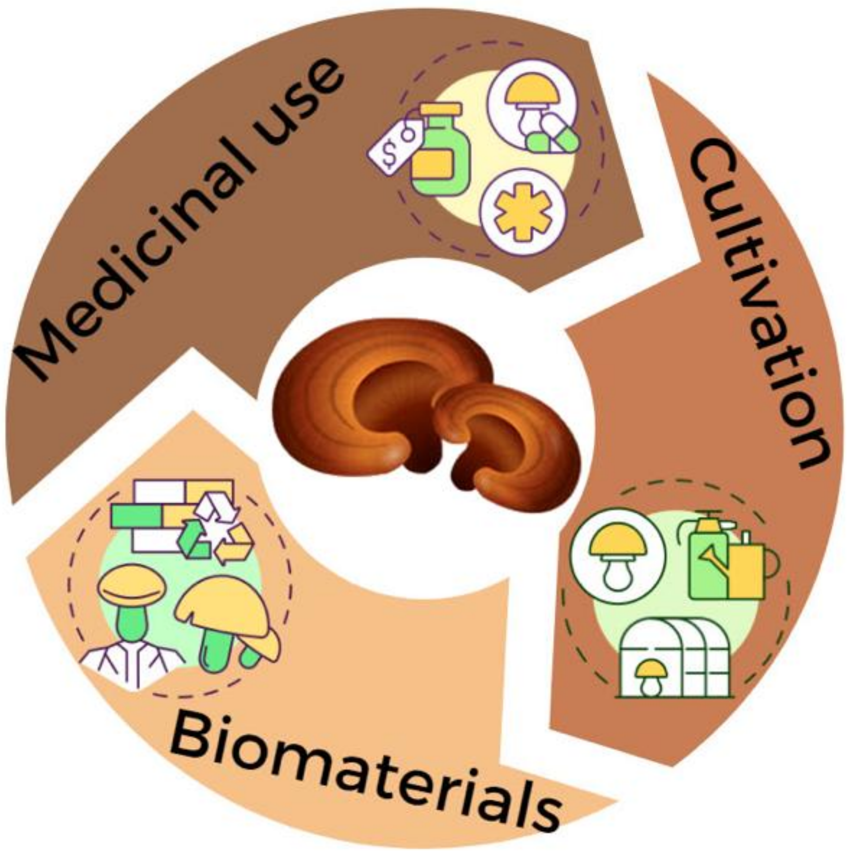

Fig. 1 – The applications used for *Ganoderma* mushroom.

The current state of knowledge on the biological activity and possible medicinal applications of selected species of the genus *Ganoderma*; *G. adspersum* (Schulzer) Donk, *G. applanatum* (Pers.) Pat., *G. carnosum* Pat., *G. lucidum* (Curtis) P. Karst., *G. pfeifferi* Bres., and *G. resinaceum* Boud (Sułkowska-Ziaja et al. 2023). These inedible wood-decaying fungi are pathogens that cause the enzymatic decomposition of wood. They have been a valued natural medicinal resource in traditional Eastern medicine for centuries (Sułkowska-Ziaja et al. 2023). These compounds have pharmacological effects, including hepatoprotective, anti-hypertensive, and hypocholesterolemic activities (Bhardwaj et al. 2016, Xu et al. 2016, Xu et al. 2017, Shi et al. 2019). Ganoderic acid T has potent anti-tumor effects (Liu et al. 2015), while ganoderic acid A and H have exhibited significant anti-HIV-1 properties (El-Mekkawy et al. 2018). Polysaccharides: β-glucans are the primary polysaccharides in *Ganoderma* and are known for their immunomodulatory and anti-tumor properties (Galappaththi et al. 2022).

Modern research suggests that these mushrooms possess a variety of bioactive compounds with potential therapeutic applications that may offer health benefits due to the presence of bioactive compounds such as polysaccharides, triterpenoids, and other metabolites (Lu et al. 2020, Bhat et al. 2021, Raut et al. 2022, Sułkowska-Ziaja et al. 2023). Among the *Ganoderma* species, *G. lucidum* is the most researched and consumed and is often seen as an alternative to conventional medicine (El Sheikha 2022). Some potential *Ganoderma* species and their medical applications are shown in Table 1.

Table 1 *Ganoderma* species as a source of bioactive compounds for medical applications.

Species Name	**Compound name**	**Type of compound**	**Biological activity**	**References**
Ganoderma neo-japonicum	*Ganoderma neo-japonicum* Imazeki (GNJI) extract (S2)	Complex mixture	Antiviral (against enteroviruses: EV-A71, CV-A16, CV-A10), virucidal (against EV-A71)	Ang et al. 2021
G. neo-japonicum	Polysaccharides (from GNJI extract S2)	Polysaccharide	Antiviral (against enteroviruses): causing hand, foot, and mouth disease	Ang et al. 2021
G. lucidum	*Ganoderma lucidum* Extract	extract	Anti-inflammatory, anti-metastatic and human triple-negative breast cancer	Barbieri et al. 2017
G. lucidum	Ganodermanontriol, Lucidumol A, Ganoderic acid C2, Ganosporeric acid A	Triterpenoids	Antiviral (inhibits dengue virus NS2B-NS3 protease)	Bharadwaj et al. 2019
G. lipsiense	Fatty acids and derivatives	Lipids	Not specified in this study	Costa et al. 2020
G. lipsiense	Ergosta-6,22-diene-3β,5α,8α-triol	Steroid	Antiparasitic (anti-Giardia)	Costa et al. 2020
G. lipsiense	*Ganoderma lipsiense* extract (CE, HEXf, DCMf, EAf)	Complex mixture	Antiparasitic (anti-Giardia), antibacterial (against Pseudomonas aeruginosa and Staphylococcus aureus)	Costa et al. 2020
G. lucidum	Triterpenoids, polysaccharides	Bioactive compounds	Antioxidant, anti-inflammatory, immune-boosting, potential anti-diabetic, anti-obesity, and antiviral (against coronavirus - limited evidence)	Ekiz et al. 2023
G. lucidum	*Ganoderma lucidum* extract	Complex mixture	Antimicrobial (against various bacteria and fungi), potential genotoxicity	Ergun 2017
G. lucidum	Terpenoids, polysaccharides, phenolics, flavonoids, lycopene	Various	Antioxidant, anti-atherosclerotic, antibacterial, antifungal	Gharib et al. 2022
G. lucidum	*Ganoderma lucidum* polysaccharide (GLP)	Polysaccharide	Anti-melanogenic, antioxidant, inhibits UVB-induced skin pigmentation, protects against UVB-induced skin damage, regulates cAMP/PKA and ROS/MAPK signaling pathways	Hu et al. 2019

Table 1 Continued

Species Name	Compound name	Type of compound	Biological activity	References
G. lucidum	Phenolic compounds, flavonoids	Secondary metabolites	Antioxidant	Kebaili et al. 2021
G. weberianum	specific extract (CF-F3) from Ganoderma weberianum	Complex mixture	Anti-melanogenic (inhibits tyrosinase activity, reduces melanin production)	Lai et al. 2019
Ganoderma sp.	Ganoderma proteins, especially fungal immunomodulatory proteins (FIPs)	Protein	Antioxidant, anti-inflammatory, inhibition of melanin production, potential antibacterial activity	Li et al. 2019
G. lucidum	Ganoderic acids, polysaccharides	Triterpenoids, carbohydrates	Neuroprotective, anti-inflammatory, antioxidant, potential for regulating autophagy	Lian et al. 2024
G. lucidum	Hesperetin	Flavonoid	Antiviral (inhibits dengue virus NS2B-NS3 protease)	Lim et al. 2020
G. lucidum	Ganocin B	Triterpenoid	Antiviral (inhibits dengue virus NS2B-NS3 protease)	Lim et al. 2020
G. lucidum	Lucidenic acid, 11-aminoundecanoic acid, 5-carboxyvanillic acid, thymidine	Other compounds	Potential antiviral activity (not fully explored)	Lim et al. 2020
G. lucidum	Ketoconazole	Antifungal agent	Inhibits hormone synthesis, inhibits melanoma cell proliferation and migration, reduces MCP-1 secretion, inhibits AMPK activation	Lu et al. 2019
G. lucidum	*Ganoderma microsporum* immunomodulatory proteins (GMI)	Protein	Inhibits melanoma cell proliferation and migration, induces AMPK activation	Lu et al. 2019
G. lucidum	Monocyte chemoattractant protein-1 (MCP-1)	Protein	Involved in inflammation and tumor progression	Lu et al. 2019
G. lucidum	Ganodumones A-F (1-6)	Benzolactone-type Ganoderma meroterpenoids	Antibacterial (against Microsporum gypseum)	Lu et al. 2020
G. lucidum	GL-PWQ3	Glycopeptide (primarily polysaccharide)	Antioxidant	Luo et al. 2024
G. lucidum	Triterpenoids (e.g., ganosporelactone B, ganoderol A, ganoderic acids)	Terpenoids	Antioxidant	Luo et al. 2024
G. lucidum	Phenolic compounds, flavonoids	Secondary metabolites	Antioxidant, antibacterial, protective against hypoxia	Mishra et al. 2018

Table 1 Continued

Species Name	Compound name	Type of compound	Biological activity	References
Ganoderma sp.		polysaccharides, triterpenoids, peptides, steroids, fatty acids, and phenolic compounds	antioxidant, anti-inflammatory, antitumor, immunomodulatory, and neuroprotective effects	Obodai et al. 2017
G. gibbosum	Gibbosicolids A-G (2-8) and Gibbosic acids I-O (9-15)	Lanostane-type triterpenoids	Antifungal (especially against fluconazole-resistant Candida albicans), potentiates fluconazole activity	Pu et al. 2019
G. applanatum	Terpenoids, phenolics, glycosides, alkaloids, flavonoids, saponins	Secondary metabolites	Antimicrobial	Rijia et al. 2024
G. australe	Lanostane triterpenoids	Triterpenoid	Cytotoxicity against cancer cells, and inhibition of α-glucosidase, PTP1B, DPP4, and ACE2 enzymes	Zhou et al. 2022
G. lucidum	Chitosan (chemical and enzymatic extracts)	Polysaccharide	Antioxidant, antimicrobial, biocompatible	Savin et al. 2020
G. curtisii	*Ganoderma curtisii* extract	Complex mixture	Antiproliferative (against cancer cell lines), antibacterial (against Staphylococcus aureus), antioxidant, low toxicity	Serrano-Márquez et al. 2021
G. lucidum	*Ganoderma lucidum* spore and fruiting body (GLSF)	Complex mixture	Anti-cancer, specifically skin cancer preventive, inhibits epidermal growth factor-induced cell transformation, attenuates UV-induced skin damage, modulates immune response (increases CD8+ T cells, decreases CD4+ and FoxP3+ T cells)	Shahid et al. 2022
G. applanatum	Phenolic acids, sterols, indoles	Various	Anti-tyrosinase, anti-hyaluronidase, sun protection (SPF)	Sułkowska-Ziaja et al. 2021
G. applanatum	Kojic acid	Organic acid	Anti-tyrosinase	Sułkowska-Ziaja et al. 2021
G. lucidum	Lanostane triterpene (1)	Triterpene	Antioxidant, neuroprotective	Wang et al. 2019
G. lucidum	Aromatic meroterpenoids (6, 7)	Meroterpenoid	Antioxidant, neuroprotective, free radical scavenging	Wang et al. 2019
G. lucidum	Triterpenes (2-5)	Triterpene	Antioxidant, some neuroprotective activity	Wang et al. 2019

Table 1 Continued

Species Name	Compound name	Type of compound	Biological activity	References
G. lucidum	*Ganoderma lucidum* polysaccharide peptide (GL-pp)	Polysaccharide and peptide	Antitumor, antimetastatic, potential immune regulatory, possible sedative and hypnotic effects.	Xian et al. 2021
G. lucidum	*Ganoderma lucidum* polysaccharides (GLP)	Polysaccharide	Hypolipidemic, antioxidant	Xu et al. 2019
G. lucidum	Degraded *Ganoderma lucidum* polysaccharides (GLPUD)	Polysaccharide	Stronger hypolipidemic and antioxidant activities than GLP, effective in reducing cholesterol levels, improving liver function	Xu et al. 2019
G. lucidum	*Ganoderma lucidum* polysaccharide (GLP)	Polysaccharide	Anti-cancer, immunomodulatory, enhances radiation-induced cell death in hepatocellular carcinoma (HCC), inhibits DNA repair proteins ATM and DNA-PK, regulates Akt signaling pathway	Yu et al. 2017
G. lucidum	*Ganoderma lucidum* polysaccharide (GL-PS)	Polysaccharide	Antioxidant, anti-photoaging, protects fibroblasts from UVB-induced damage, reduces oxidative stress, regulates collagen metabolism	Zeng et al. 2017
G. lucidum	9,11-Dehydroergosterol peroxide (9(11)-DHEP)	Steroid	Antitumor, specifically against melanoma cells, induces apoptosis via mitochondrial pathway and downregulation of Mcl-1 protein.	Zheng et al. 2018

Ganoderma cultivation: challenges and opportunities in substrate optimization and environmental control

Ganoderma cultivation offers significant potential for economic and health benefits. Technological advancements, market expansion, and sustainable practices can drive the industry forward despite persistent challenges. The cost and availability of the substrate materials affect the profitability of cultivation. Research into alternative substrates, such as agricultural waste products, and optimization of substrate formulations are essential (Ozcariz-Fermoselle et al. 2018, Rashad et al. 2019, Luangharn et al. 2020, Atila 2022, Baktemur et al. 2022, Kurd-Anjaraki et al. 2022). Various methods can be employed for *Ganoderma* cultivation, including log, bag, soil, and liquid cultivation (Luangharn et al. 2017, Rashad et al. 2019, Wannasawang et al. 2023) and a key for cultivation are summarized in Table 2, and summarized of the general cultivation methods for *Ganoderma* was summarized (Fig. 2). The life cycle of these mushrooms typically includes two phases: colonization and fructification (Rashad et al. 2019). Essential nutrients include carbon sources like cellulose and lignin, nitrogen for protein synthesis, phosphorus for energy transfer, potassium for enzyme function, and trace minerals such as iron, zinc, and manganese (Zied 2017). Selecting a suitable substrate, such as sawdust, wood chips, or agricultural residues, is crucial to providing these essential nutrients and supporting fungal growth. Environments conducive to mycelial growth during the incubation phase are vital. Mycelium grows best at temperatures between 25 and 30°C, while the optimal temperature range for fruiting body growth is between 24 and 28°C. At temperatures below 20°C, the fruiting body becomes yellow; above 35°C, it quickly deteriorates. During spawning, humidity should be maintained between 60 and 65% and increased to 85–95% within the mushroom house (Zied 2017).

An appropriate pH control directly affects the productivity and quality of mushrooms. Most mushroom species grow best in a pH range of 5.5–7; deviations from this range can limit mycelial development (Erkel 2009, Gurung et al. 2012, Carrasco et al. 2018, Bellettini et al. 2019, Atila 2022, Nguyen et al. 2023). Research has shown that the cultivation of *G. lucidum* can be optimized by manipulating various factors such as substrate composition, environmental conditions, and supplementation (Erkel 2009, Zied 2017, Bellettini et al. 2019). Various substrates, including agricultural and forestry by-products, have been tested for their efficacy in supporting *Ganoderma* growth with significant variations in yield and quality (Gurung et al. 2012, Thakur & Sharma 2015, Atila 2022). Supplementation of substrates with protein and carbohydrate sources has been found to enhance the yield of *G. lucidum* (Erkel 2009, Carrasco et al. 2018). Additionally, recycling agro-waste provides a sustainable method for mushroom cultivation and contributes to environmental conservation by reducing waste (Rashad et al. 2019, Baktemur et al. 2022, Kurd-Anjaraki et al. 2022).

Recent studies have highlighted the importance of optimizing the cultivation conditions to maximize the medicinal properties and bioactive compounds of *Ganoderma* species (Nguyen et al. 2023, Wannasawang et al. 2023). Furthermore, the cultivation of various *Ganoderma* species, such as *G. leucocontextum*, *G. resinaceum,* and *G. gibbosum*, has expanded the potential applications of this genus in both traditional medicine and modern biotechnological innovations (Luangharn et al. 2017, 2020).

Table 2 *Ganoderma* species with key aspects related to cultivation, application, and optimization.

***Ganoderma* species**	**Cultivation factors and conditions**	**Applications**	**References**
Ganoderma lucidum	- Substrate composition: agricultural and forestry by-products, protein and carbohydrate supplementation - Environmental conditions: temperature (25–30°C mycelium, 24–28°C fruiting), humidity (60-65% spawning, 85–95% fruiting) - pH control: optimal pH 5.5–7	- Medicinal: immunomodulatory and therapeutic properties, traditional medicine - Environmental conservation: recycling of agro-wastes for cultivation	Zied 2017, Bellettini et al. 2019, Rashad et al. 2019, Baktemur et al. 2022, Kurd-Anjaraki et al. 2022
G. sinense	- Environmental Conditions: Temperature (25-30°C mycelium, 24–28°C fruiting), Humidity (60–65% spawning, 85–95% fruiting)	- Biotechnology: optimization of mycelial growth and cultivation techniques	Nguyen et al. 2023

Table 2 Continued

Ganoderma species	Cultivation factors and conditions	Applications	References
G. leucocontextum	- pH Control: Optimal pH 5.5–7	- Biotechnology: domestication and cultivation of diverse species for expanded applications	Luangharn et al. 2020
G. resinaceum	- Cultivation methods: log cultivation, bag cultivation, soil cultivation, liquid cultivation	- Biotechnology: domestication and cultivation of diverse species for expanded applications	Luangharn et al. 2017, Luangharn et al. 2020
G. gibbosum	- Environmental conditions: temperature (25–30°C mycelium, 24–28°C fruiting), humidity (60–65% spawning, 85–95% fruiting)	- Biotechnology: domestication and cultivation of diverse species for expanded applications	Luangharn et al. 2020
G. australe	- Environmental Conditions: Temperature (25–30°C mycelium, 24–28°C fruiting), Humidity (60–65% spawning, 85–95% fruiting)	- Medicinal: Antibacterial activity, optimal culture conditions	Luangharn et al. 2017
G. carnosum	- Environmental conditions: temperature (25–30°C mycelium, 24–28°C fruiting), humidity (60–65% spawning, 85–95% fruiting)	- Environmental conservation: cultivation of different agricultural wastes, recycling of agro-waste for cultivation	Rashad et al. 2019, Baktemur et al. (2022), Kurd-Anjaraki et al. 2022

Development of *Ganoderma* mycelium-based biomaterials

The presence of septa and anastomosis is an important property in species of Basidiomycota suitable for mycelium-based biomaterial preparation (Lelivelt et al. 2015, Madusanka et al. 2024). *Ganoderma*, a white rot fungus, is the most promising and widely used genus from Polyporales to produce mycelium-based biomaterials due to the strong binding properties of the mycelium (Khyaju & Luangharn 2024, Madusanka et al. 2024). *Ganoderma* mycelium functions as a biological adhesive to join substrates to prepare MBBs. *Ganoderma carnosum*, *G. lucidum*, *G. resinaceum*, and *G. sessile* have been used to test or commercially develop MBCs (Zeller & Zocher 2012, Attias et al. 2020, Gauvin et al. 2022, Van et al. 2022, Charpentier-Alfaro et al. 2023).

Ganoderma mycelium can grow on a wide range of lignocellulosic substrates (Table 3, Fig. 3), with its mechanical, physical, chemical, and biological properties influenced by factors such as the behaviour of mushroom strain (e.g., white rot fungi, trimitic hyphal system) and post-processing techniques (Manan et al. 2021). For instance, pressing biomaterials at 200°C improves their physical, mechanical, and thermal properties (Liu et al. 2019, Manan et al. 2021). The material developed from the mycelium of *Ganoderma* provides greater stiffness and strength

(Lelivelt et al. 2015). In solid-state fermentation, hyphae grow outwards from the substrate and into air (Vandelook et al. 2021). Aerial mycelium can be cultivated by solid-state fermentation in tightly controlled incubation chambers with temperature (± 30°C), humidity (40–99%), and carbon dioxide (50–70 k ppm) (Vandelook et al. 2021, Madusanka et al. 2024).

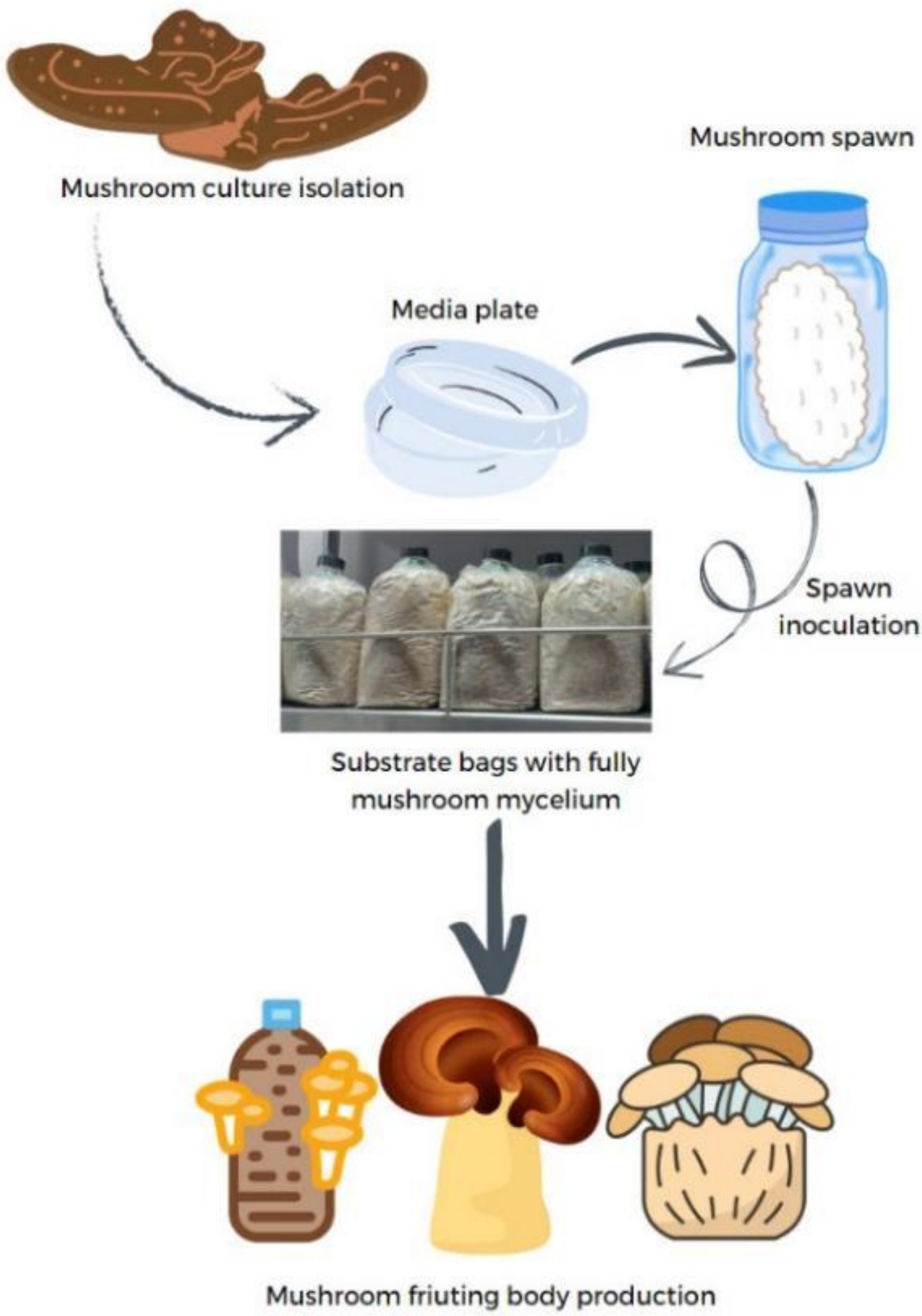

Fig. 2 – General cultivation methods for *Ganoderma.*

Applications of *Ganoderma* species in biomaterial development

Several prominent companies, including Ecovative Design LLC, Mycoworks Inc., and Mogu, have significantly expanded the use of mycelium-based biomaterials (Khyaju & Luangharn 2024). The instances of *Ganoderma* strains employed in various biomaterial applications are also highlighted. Since the utilization of *Ganoderma lucidum* and sawdust in architectural design, "Mycotectural Alpha" mycelium bricks have been used in construction (Jones et al. 2017). Mycelium foam developed using *Ganoderma* sp. showed promising sound-shielding behavior, especially for low to mid-frequency noise (Pelletier et al. 2019). The mycelium of *Ganoderma* spp. is efficient at synthesizing leather (Charpentier-Alfaro et al. 2023).

Table 3 Uses of *Ganoderma* species in mycelium-based biomaterials.

Fungal species	Substrate used	Target use	References
Ganoderma carnosum	pine sawdust, oak shavings, tree of wood chips, wheat straw, shredded beech wood	Insulation biomaterials	Charpentier-Alfaro et al. 2023
G. curtisii	Guayule bagasse	Composite	César et al. 2023
G. lucidum	palm sugar fiber and cassava bagasse	Composite board	Agustina et al. 2019
G. lucidum	cotton stalk	Blocks	Liu et al. 2019
G. lucidum	bamboo fiber	Test composite samples	Saez et al. 2020
G. lucidum	wheat straw	Boards	Răut et al. 2021
G. lucidum	sawdust, empty fruit bunch fibres	Blocks	Chan et al. 2021
G. lucidum	cellulose fibre, rapeseed straw	Foam-like wall insulation	Gauvin et al. 2022
G. lucidum	hemp fibres, hemp hurds, pinewood sawdust, Silver grass shavings	Boards with wood reinforcement	Özdemir et al. 2022
G. lucidum	cellulose and cellulose/potato dextrose	Fibrous film	Haneef et al. 2017
G. lucidum	beech sawdust, oak sawdust, bleached cellulose pulp, shredded cardboard, shredded newspaper, cotton fibres, soy silk fibres, wheat bran, wheat straw, burlap, clay, and sand	Test samples	Vašatko et al. 2022
G. lucidum	spent coffee grounds, coffee chaff, hay straw, hemp dust, cereal mixture	Acoustic Insulating materials	Barta et al. 2024
G. resinaceum	hemp hurds, beech wood sawdust	Blocks	Elsacker et al. 2021
G. resinaceum	wheat straw	Thermal insulation block	Xing et al. 2018
G. resinaceum	Beechwood, hemp fibre	Composite and pure mycelium test samples	Van et al. 2022
G. sessile	ground woodchips	Architecture block	Attias et al. 2020

Future advancement and challenges

Green economy and sustainability have been top priorities in the development pathway. Modern biotechnological tools, such as strain improvement, recombinant DNA technology, gene editing, and silencing, have been incorporated into MBBs (Madusanka et al. 2024). The introduction of a *Saccharomyces cerevisiae* CDA1 chitin deacetylase-encoding gene controlled by glyceraldehyde-3-phosphate dehydrogenase (GPD) promoter into a strain utilized for MBBs production resulted in a product with a higher compressive modulus (Vandelook et al. 2021, Madusanka et al. 2024). The utilization of the GPD constitutive promoter in engineering the expression of β-1, 3-glucan synthases (BGS1 and BGS2) in *Ganoderma* sp. resulted in 135-165% higher β-glucan content (Vandelook et al. 2021, Madusanka et al. 2024).

Mycelium-based biomaterials can be used as alternatives to other synthetic materials. He et al. (2019) reported 180 species of *Ganoderma*, a vast opportunity to test and find suitable strains for specific biomaterial applications.

The mushroom mycelium-based biomaterial sector, being novel, has its unsolved limitations. The illustrates the general process of *Ganoderma* mycelium-based biomaterial production (Fig. 4). Most wild *Ganoderma* spp. hinder the expression of their potential due to the presence of undesirable genes, thereby demanding gene editing. Efficient biomaterial production requires optimization of growth conditions such as carbon dioxide, temperature, relative humidity, and substrate nutrients. It cannot be denied that the research results are subject to patenting, and some important information is hidden.

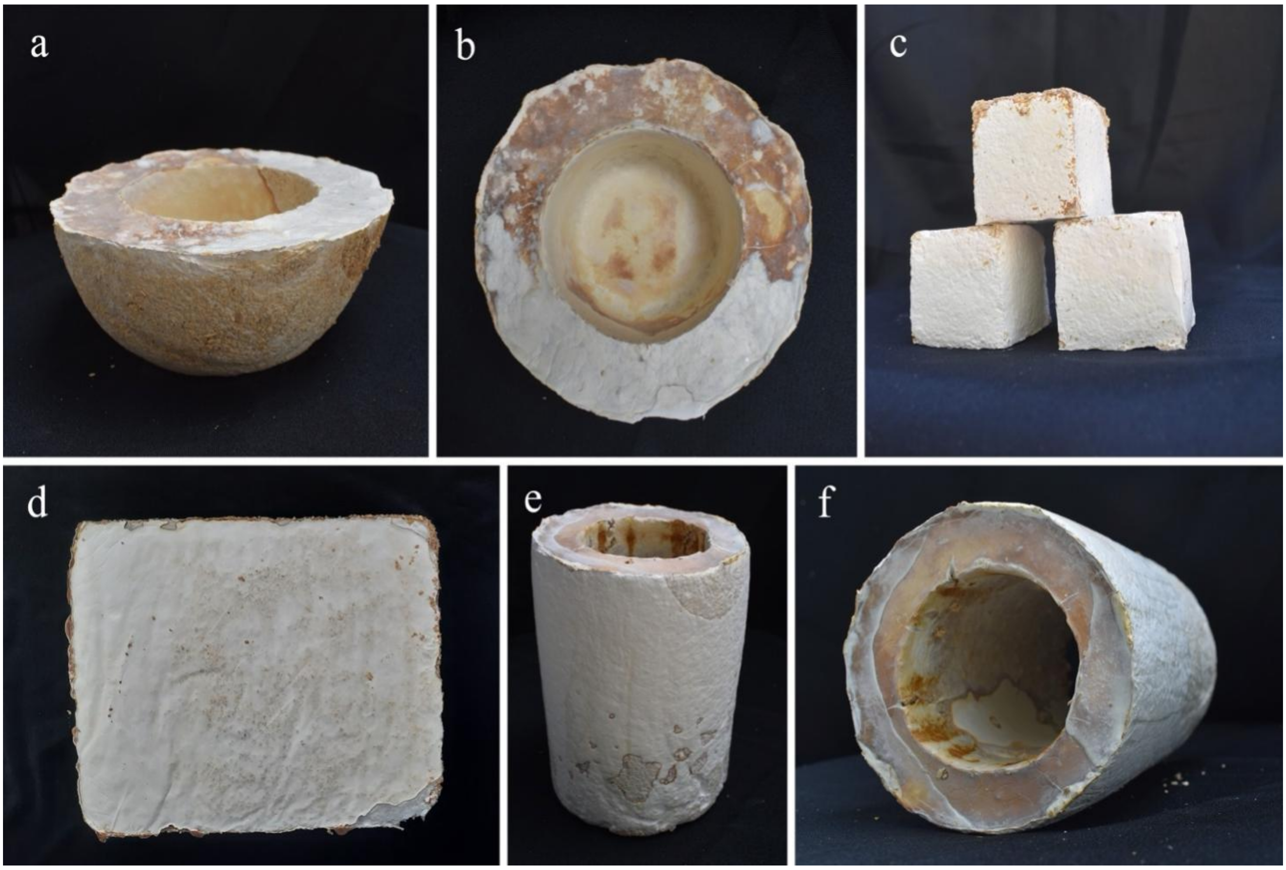

Fig. 3 – Biomaterial products utilizing *Ganoderma* species were prepared using various substrate media. a Sawdust. a–b Ashtray. c Cubes, d Insulation panel. e–f Hollow tube. Photo by Sabin Khyaju.

Fig. 4 – The primary step of the mycelium-based composite for biomaterial products.

Discussion

Ganoderma species, particularly *G. lucidum* (also known as "Lingzhi" or "Reishi"), have been used in traditional medicine for centuries and are renowned for their bioactive compounds. These include triterpenoids, polysaccharides, and peptides that exhibit various therapeutic properties. Triterpenoids, such as ganoderic acids, are known for their anti-inflammatory, anti-tumor, and hepatoprotective effects (Paterson 2006, Baby et al. 2015). Polysaccharides, particularly β-glucans, have been recognized for their immunomodulatory and antitumor properties (Ren et al. 2021). Other compounds, including proteins, peptides, and steroids, have antimicrobial, antioxidant, and hypoglycemic effects (Boh et al. 2007). Research into specific species like

G. adspersum, *G. applanatum*, and *G. carnosum* highlights their potential for hepatoprotection, anti-hypertensive effects, and even anti-HIV properties (Bhardwaj et al. 2016, Xu et al. 2016, El-Mekkawy et al. 2018, Shi et al. 2019). The therapeutic potential of *Ganoderma* is vast, with *G. lucidum* being the most studied owing to its extensive use in alternative medicine.

Ganoderma cultivation has become a significant industry because of its medicinal and economic value (Hapuarachchi et al. 2018). Various cultivation methods have been employed, including log, bag, soil, and liquid cultivation (Luangharn et al. 2017, Rashad et al. 2019). Successful cultivation requires optimal substrate selection, with sawdust, wood chips, and agricultural residues commonly used. Environmental conditions such as temperature, humidity, and pH are crucial for growth and fruiting (Zied 2017). For example, temperatures 24–28°C are ideal for fruiting body growth (Zied 2017). Nutrient requirements include carbon sources, nitrogen, phosphorus, potassium, and trace minerals (Zied 2017). Advances in cultivation techniques, such as optimizing substrate compositions and exploring alternative substrates, such as agricultural waste, are essential for enhancing yield and sustainability (Ozcariz-Fermoselle et al. 2018, Rashad et al. 2019, Luangharn et al. 2020).

Ganoderma mycelium has shown promise in biotechnological innovations, particularly in the development of mycelium-based biomaterials. The mycelium's binding properties and ability to grow on lignocellulosic substrates make it valuable for the production of eco-friendly materials (Khyaju & Luangharn 2024). These include mycelium-based biomaterials (MBBs), which are used in construction, sound insulation, and leather synthesis (Jones et al. 2017, Pelletier et al. 2019, Charpentier-Alfaro et al. 2023). The mycelium-based materials sector is part of a broader green economy and sustainability movement. Recent studies have emphasized the potential of genetic engineering to improve the properties of *Ganoderma* mycelia. For instance, the introduction of genes for chitin deacetylase and β-glucan synthases has enhanced the physical and chemical properties of the resulting biomaterials (Vandelook et al. 2021, Madusanka et al. 2024).

Ganoderma represents a multifaceted group of fungi with extensive applications in medicine, industry, and sustainability. Its complex taxonomy, rich bioactive compound profile, and potential for innovative biomaterial production make it a significant subject for ongoing research. Advances in molecular techniques, cultivation methods, and biotechnological applications have continued to expand our understanding and utilization of this fungus.

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