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Ganoderma (Ganodermataceae, Polyporales): Historical perspectives, recent advances, and future research in Sri Lanka

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Abstract

Ganoderma P. Karst. is a cosmopolitan and species-rich genus of mushrooms that can cause root and butt rot diseases on many woody tree species. Many members of this genus are found in tropical and subtropical regions worldwide. *Ganoderma* species have been used in traditional Chinese medicine for thousands of years for maintaining vivacity and longevity. Some *Ganoderma* species are well-known for being abundant sources of highly active bioactive substances like polysaccharides, proteins, steroids, and triterpenoids. The numerous metabolic processes of *Ganoderma* have been studied both *in vitro* and *in vivo*. However, it is debatable if *Ganoderma* is a nutritional supplement that promotes health, or a medication used for therapeutic purposes. Products made from *Ganoderma* have been marketed as potent food and medication supplements with positive health effects. Over the past three decades, the *Ganoderma* market has experienced significant growth, and hundreds of products are currently being offered on the market. However, in Sri Lanka, there hasn't been much research on *Ganoderma*. Hence, a comprehensive account of the historical perspective, recent advances, and future trends of *Ganoderma* research in Sri Lanka is provided in this review. Furthermore, this review aims to increase the research interest, evaluate the recent developments, and address the missing gaps in research on *Ganoderma*.

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Introduction

Ganodermataceae is one of the largest family of polypores with fourteen accepted genera: *Amauroderma* Murrill, *Amaurodermellus* Costa-Rezende, Drechsler-Santos & Góes-Neto, *Cristataspora* Robledo & Costa-Rezende, *Foraminispora* Robledo, Costa-Rez. & Drechsler-Santos, *Furtadoa* Costa-Rez., Robledo & Drechsler-Santos, *Furtadoella* B.K. Cui & Y.F. Sun, *Ganoderma* P. Karst., *Haddowia* Steyaert, *Humphreya* Steyaert, *Neoganoderma* B.K. Cui & Y.F. Sun, *Sanguinoderma* Y.F. Sun, D.H. Costa & B.K. Cui, *Sinoganoderma* B.K. Cui, J.H. Xing & Y.F. Sun, *Tomophagus* Murrill and *Trachydermella* B.K. Cui & Y.F. Sun[1–4], of which most species are classified in the genus *Ganoderma* including 489 taxa[5], however, nearly half of these records have been identified as synonyms. Based on strong molecular and phylogenetic support, Sun et al.[4] confirmed only 181 taxa for this genus.

Ganoderma was established by Karsten[6] with *Ganoderma lucidum* (Curtis) P. Karst. as the type species[7]. This genus contains economically beneficial, basidiomycetous fungi that have a worldwide distribution from warm temperate to tropical regions. They are found as facultative parasites on living, or more commonly, from dead trunks or branches of trees[1,8,9]. Furthermore, this group of mushrooms is remarkably diverse in tropical regions[2,10].

Due to their pathogenicity and therapeutic properties, *Ganoderma* species have important economic value[9,11–14]. Several *Ganoderma* species are pathogenic, causing white rot diseases on rotting stumps, roots, and living trunks by decomposing lignin, cellulose, and related polysaccharides for nutrient mobilization[15–17]. *Ganoderma* has long been used as a popular medicinal mushroom, especially in China, Japan, and Korea, to improve longevity and health[11,18]. This fungus has been used as a traditional medicine for treating neurasthenia, debility of prolonged illness, insomnia, anorexia, dizziness, chronic hepatitis, hypercholesterolemia, mushroom poisoning, coronary heart disease, hypertension, prevention of acute mountain sickness, 'deficiency fatigue', carcinoma, and bronchial cough in the elderly[12,19–22]. Various commercial products of *Ganoderma* such as powders, dietary supplements, and capsules can be obtained worldwide for a range of biomedical applications[11,13] highlighting the immense commercial importance of this group of mushrooms. These products are derived from various parts of *Ganoderma* species including mycelia, spores, and fruit bodies[23].

Morphologically, *Ganoderma* can be recognized using their brownish hard fruit body, white margin, and red-brown colored double walled basidiospores with interwall pillars and a thin hyaline exosporium and ornamented endospore[4,6,13,24–27]. Furthermore, these species hold different characteristics, such as shape and the color of the fruit body, host specificity, and geographical origin, which are used to identify individual members of the species[2,28–30]. Hence, *Ganoderma* is a problematic and confusing genus to examine due to the highly variable morphological features of the species[2,9,11,16,31]. Therefore, to create a more stable taxonomy for *Ganoderma* and resolve taxonomic problems, some researchers recommended

combining morphological, chemotaxonomic, and molecular methods[32,33].

Sri Lanka is a small island in the Indian Ocean that is situated at the southernmost tip of the Indian subcontinent[34]. Even though it is small, Sri Lanka is endowed with a diverse ecosystem and is one of the 34 biodiversity hotspots identified worldwide[35]. Out of an estimated 25,000 species of native fungal flora in Sri Lanka, only about 3,000 species of fungi are now being recognized[34]. The most well-known fungal group is the larger Basidiomycetes[36].

Ganoderma was first recorded in Sri Lanka as a coconut palm pathogen by Peries[37]. In Sri Lanka, the most researched species of *Ganoderma* is *Ganoderma lucidum,* which contains a wide variety of bioactive constituents such as terpenoids, steroids, phenols, glycoproteins, polysaccharides, fatty acids, and nucleosides[38,39]. Numerous authors have shown that triterpenes and polysaccharides are the major physiologically active components of *Ganoderma* for its medicinal use[40–42].

There is a novel trend in polyporus fungal research in Sri Lanka including *Ganoderma*[26,43,44] and it seems like Sri Lanka is rich in *Ganoderma* species associated with a range of hosts (Fig. 1). Hence, the *Ganoderma* species play a significant role in fungal research work. The present review aims to provide a comprehensive account of research interest in *Ganoderma*, evaluate the recent development, industry, and future works, and address some of the loopholes in *Ganoderma* study in Sri Lanka.

Historical perspectives of *Ganoderma* in Sri Lanka

The fauna and flora of Sri Lanka have a significant number of endemic species: the island's 16% of mammals and 25% of flowering plants, respectively, are endemic. In fact, endemism among the 1,920 fungal species of Sri Lanka is unknown[45]. The earliest record of Sri Lankan fungi was in 1783; two species were recorded under the names *Peziza ceylonsche* and *Peziza lembosa* in 1783 by Houttuyn[46]. In a later publication, Coomaraswamy[47], enumerated 2,180 fungal species from 106 genera in a comprehensive account of his study on fungi in Sri Lanka. However, as previously mentioned, larger Basidiomycetes are the most well-known fungus family in Sri Lanka.

Ganoderma boninense Pat. (= *G. orbiforme* (Fr.) Ryvarden) was recorded as the first *Ganoderma* species in Sri Lanka as a plant pathogen for coconut palms, causing lethal root and bole rot[37,48,49]. Subsequently, *G. philippi* (Bres. & Henn. ex Sacc.) Bres.[50], *G. lucidum*[49,51] and *G. applanatum* (Pers.) Pat.[52] were introduced from various hosts. *Ganoderma applanatum* and *G. lucidum* have been identified as the most common Sri Lankan polypores occurring all over the island[45].

Ganoderma diseases in Sri Lanka

Ganoderma species are important wood decaying fungi[53]. A variety of monocotyledons, dicotyledons and gymnosperms including many economically important trees and perennial crops are caused by the root and stem rot induced by the *Ganoderma* species, which results in the death of affected trees[2]. In Sri Lanka, awareness of the plant pathogens in agricultural, horticultural, ornamental, and forest plants, is still insufficient, with the exception of a few important plantation crops like tea and rubber[34]. In the CRI (Coconut Research Institute) studies, Peries[37]reported that one of the causes of the tapering disease of coconut (*Cocos nucifera*) in Sri Lanka is infection by *Ganoderma boninense* (= *G. orbiforme*) a new record of the fungus to the country. This causes a lethal root and bole rot of coconut palms which can become epidemic in some areas and under certain conditions[37].

Ganoderma philippi causes root rot in *Hevea brasiliensis* Müll. Arg. (Rubber)[50] and a study by Wijesekara et al.[49] also revealed that *G. boninense* was the causative agent of the root and bole rot disease of coconut. Furthermore, the hyphae of *Trichoderma viride* Pers. were always presented in the tissue of *G. boninense* and *G. lucidum* basidiocarps and *T. viride* has antagonistic effects against them[49]. In addition, *T. viride* was known to produce several cell wall degrading enzymes such as glucanases and chitinases and therefore could be used as a bio-control agent against *G. boninense*[49]. A stem bleeding condition in coconut palms was reported in 1995 in Hambantota

Fig. 1 Different *Ganoderma* species found in Sri Lanka.

district, Sri Lanka, and 10% of the palms in the district were affected by *Ganoderma* sp. However, the researchers were unable to confirm the cause of stem bleeding, although *Ganoderma* sp., was consistently isolated from the palms with fruit bodies[51]. *Ganoderma lucidum* causes root rot and butt rot in *Cassia* sp. including *C. nodosa* Buch.-Ham. ex Roxb., *C. fistula* L. and *Delonix regia* (Boj. ex Hook.) Raf.[54]. Furthermore, *G. applanatum* and *G. lucidum* cause general wood rot in *Camellia sinensis* (L.) Kuntze (Tea)[55].

The recent development of *Ganoderma* research in Sri Lanka

Bioactive compounds and beneficial medicinal properties

Members of the *Ganoderma* have long been used in Asia to support health and longevity, as previously mentioned[18,56]. Due to their highly valued medicinal value and numerous chemical components with potential nutritional and therapeutic benefits, *Ganoderma* species are significant for extensive research[11,18,38,39]. Analyses of bioactive compounds of *Ganoderma* in Sri Lanka were a relatively new study. In the following part of this paper, we discuss several bioactive compounds produced by *Ganoderma* species found in Sri Lanka and their beneficial medicinal properties.

Anti-bacterial, anti-cancer and antioxidant activities

Lanostane triterpenoids are essential metabolites of *Ganoderma* and possess massive substitution diversity and remarkable biological functions, significantly anti-cancer, antioxidant, and anti-inflammatory effects[52]. They were known to be prolific producers of lanostane-type triterpenoids, with over 100 such compounds having been recognized from the genus[52]. Former researchers isolated five new lanostane triterpenoids, along with three known derivatives; 16R-hydroxy-3-oxolanosta-7,9(11),24-trien-21-oic acid, 3R-carboxyacetoxy-24-methylen-23-oxolanost-8-en-26-oic acid, and 3R-carboxyacetoxy-24-methyl-23-oxolanost-8-en-26-oic acid, and two new compounds; 3R,16R-dihydroxylanosta-7,9(11),24-trien-21-oic acid and R,16R,26-trihydroxylanosta-7,9(11),24-trien-21-oic acid, by Ethyl acetate extract of the *G. applanatum* fruit bodies. Furthermore, the initial crude extract of *G. applanatum* was moderately active against the P388 murine leukemia cell line[52]. The methanol extract of *G. lucidum* has shown strong antibacterial activity against Gram-positive; *Bacillus subtilis* and *Staphylococcus aureus*, Gram-negative *Escherichia coli* and *Klebsiella aerogenes* bacterial strains[45].

Research was carried out on locally cultivated *Ganoderma lucidum*, to use as a low-cost herbal drink, especially for people suffering from various non-communicable diseases[57]. This drink was prepared with *Ganoderma* extract, cinnamon oil, sucralose sweetener, and citric acid. The preservation was done exclusively by the synergistic the effect of natural anti-microbial and anti-oxidative activity of *G. lucidum* extract, the antimicrobial activity of cinnamon oil, and the low pH value of the final beverage. The prepared herbal drink was highly acceptable to get valuable bio-active ingredients such as Phenol, 4-(1,1,3,3-tetrametylbutyl), Hertriacontane, Pentacosane, Linoleic acid, Ethyl oleate, and Ergosterol[57].

Active secondary metabolites in *Ganoderma lucidum* were found to have good antioxidant characteristics leading to the development of drug leads for the remedy of various degenerative diseases caused by radical-mediated toxicity[26,45]. The scavenging activity of three different organic solvent extracts, including methanol, chloroform, and ethyl acetate fractions of *G. lucidum*, were measured against DPPH (diphenylpicryl hydrazine)free radicals and the chloroform fraction showed the highest DPPH radical scavenging activity[45]. Due to their potent ability to scavenge free radicals, bioactive phenols, and derivatives of flavonoids, predominate among the secondary metabolites produced by *Ganoderma*[26]. Hot water extract of *G. lucidum* was found to have an EC_{50} of 5.28 mg/ml against the DPPH scavenging assay Methanolic extracts of *G. lucidum* exhibited a free radical scavenging effect on the 1,1-diphenyl-2-picrylhydrazyl radical with an EC_{50} value of 1.162 ± 0.016 mg/ml[26]. Furthermore, former researchers revealed *G. applanatum* also shows potential antioxidant activities.

Ganoderma cultivation in Sri Lanka.

To address the steadily rising demand for the mushroom as a natural treatment, and since its irregular distribution in the wild, commercial cultivation of *Ganoderma* has been promoted worldwide, particularly in tropical Asian countries[11,58]. However, only 15 *Ganoderma* species; *G. amboinense* (Lam.) Pat.[59], *G. applanatum*[1], *G. australe* (Fr.) Pat.[60], *G. capense* (Lloyd) Teng[11], *G. carnosum* Pat.[61], *G. duropora* Lloyd[62], *G. enigmaticum* M.P.A. Coetzee, Marinc. & M.J. Wingf.[63], *G. gibbosum* (Blume & T. Nees) Pat.[64], *G. leucocontextum* T.H. Li et al.[65], *G. lucidum*[66–68], *G. mbrekobenum E.C. Otto et al.*[63], *G. neojaponicum* Imazeki[69,70], *G. resinaceum* Boud.[71,72], *G. sessile* Murrill[62], *G. sichuanense* J.D. Zhao & X.Q. Zhang[87], *G. tropicum* (Jungh.) Bres.[73] and *G. tsugae* Murrill[74] have been domesticated globally.

Although Sri Lanka has a long history of mushroom growing due to its favorable environmental conditions, mushroom cultivation became a trend in the country as an industry only in the late 1980s[75]. Commercial mushroom cultivation was initiated in the latter part of the nineteenth century with American oyster (*Pleurotus ostreatus* (Jacq.) P. Kumm.)[76], button (*Agaricus bisporus* (J.E. Lange) Imbach)[77], milky white (*Calocybe indica* Purkay. & A. Chandra), black ear (*Auricularia* sp.)[78] and straw (*Volvariella volvacea* (Bull.) Singer) mushrooms[23,79]. Sri Lanka exported US$ 229,765 worth of mushrooms in 2014 (Sri Lanka Export Development Board, 2016).

However, in Sri Lanka, *Ganoderma* cultivation research was carried out only for *G. lucidum*[80,81]. The former researchers tested the best medium for the cultivation of *G. lucidum* under local conditions using different media formulations (Fig. 2) and it was revealed that mango sawdust could replace the rubber sawdust entirely or in combination with rubber sawdust to achieve the optimal growth of *G. lucidum*[81]. Furthermore, they concluded that the growth parameters alone cannot predict the final yield of the medium and the growth of *G. lucidum* may be influenced by the combination of biological factors that lead to the final mushroom yield[81].

Further research was carried out by Jeewanthi et al.[43] to identify a suitable substrate from local raw materials; rubber, mango, jack (*Artocarpus heterophyllus* Lam.), and lunumidella, for artificial cultivation of *G. lucidum* in polypropylene bags. Higher predicted total yields for a duration of 3 months were as

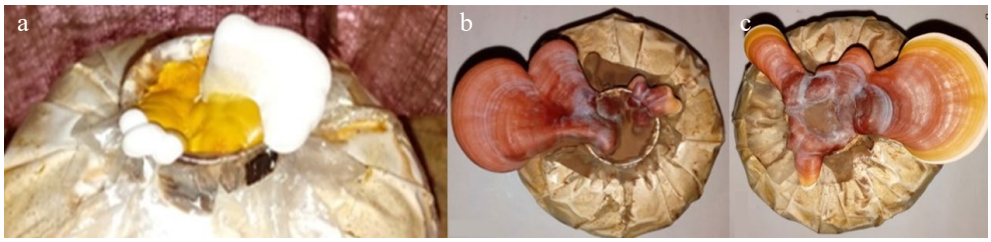

Fig. 2 *Ganoderma lucidum* cultivation in Sri Lanka. Growth stages of *G. lucidum* in grow bags with rubber saw-dust. (a) Pinhead formation. (b) Early stages of fruiting body growth, (c) Harvesting stage. Photo Credits: W.G.B.P. Dharmasena.

a result of sawdust; 100% Mango, Rubber + Mango, and Rubber + Lunumidella, followed by Rubber. However, considering the shortage of rubber and mango wood as a sole source of substrate, the mixture of rubber and mango (50%:50%) or rubber and Lunumidella (50%:50%) were recommended for *G. lucidum* cultivation[43].

Ganoderma industry and marketing

Ganoderma is an economically valuable mushroom that is significant for its medicinal properties rather than for its nutrients. Over the past 10 years, *Ganoderma*-based products have grown in popularity in Europe, Malaysia, North America, and Singapore, furthermore, China, Japan, and Korea are the major producers and suppliers of these products[11,82]. The global market of this mushroom is valued at US$ 3,096 million in 2019 and predicted to be US$ 5,059 million in 2027, and the demand is increasing in Europe and America (Press release 2022, Functional mushroom market, IndustryARC, Hyderabad, India). Hence, artificial cultivation of *Ganoderma* is required to produce pharmacological products and other dietary supplements. This underlines the enormous commercial significance of *Ganoderma*.

The mushroom industry in Sri Lanka is currently developing as a cottage business, and the market offers only a small number of mushroom varieties and products, restricting consumer options[79]. Furthermore, socioeconomic research on the mushroom industry is rare in Sri Lanka, although, this industry has a great deal of potential to improve[79,83–85]. Due to the lack of modern technology and lack of knowledge and awareness of the economic, nutritive, and medicinal benefits, *Ganoderma* cultivation is not popular in Sri Lanka. Hence, a number of *Ganoderma* products are being imported from China, India, Thailand, and Malaysia to fulfill the demand (Fig. 3). However, to increase public consumption of *Ganoderma* in Sri Lanka, there is a possibility to develop a variety of herbal products at the domestic or industrial levels[43].

Drawbacks and future trends

To achieve the growing economic potential of the *Ganoderma* industry in Sri Lanka, many obstacles must first be overcome. Misidentifying taxa in *Ganoderma* and duplicated entries across different studies will lead to confusion in biotechnology; hence, the systematics and taxonomy of *Ganoderma* species need to be studied and resolved. Distribution and the gene flow of *Ganoderma* species in Sri Lanka are significant, thus molecular characterization of *Ganoderma* sp.

Fig. 3 Several *Ganoderma* products used as drugs and food supplements in Sri Lanka. (a) *Ganoderma lucidum* extract (Ceylon nature mushroom (PVT) Ltd). (b) *G. lucidum* coffee 3 in 1 (Ceylon nature mushroom (PVT) Ltd). (c) *G. lucidum* coffee 2 in 1 (Ceylon nature mushroom (PVT) Ltd).

will also be a novel turning point in the world of microbial genetics. Poor knowledge and lack of modern technology are the main reasons which affect research, industry, and market of the mushrooms in Sri Lanka. The entrepreneurs in Sri Lanka hesitate to invest to export value-added mushroom products abroad due to rules and regulations of the Sri Lankan government, and the policies of other authorities such as the central environmental authority. Hence, the cost of local mushroom products increases. The hazardous waste contamination and toxicity of fungi are other drawbacks.

There are more than 400 species of *Ganoderma* on the globe (www.mycobank.org). However, in Sri Lanka, experiments were carried out on only *Ganoderma applanatum, G. boninense, G. lucidum* and *G. tsugae*[52,79,81]. Furthermore, technological advancements in mushroom growing are not at a satisfactory level in Sri Lanka[79]. Harvesting techniques and applying modern biotechnology for the cultivation of *Ganoderma* sp. are still open to investigation. Even though there are mushroom growing programs being introduced by many government and non-government organizations for poverty alleviation and empowering people in rural areas, value addition is little developed[23,86].

In many countries, *Ganoderma* has been taken as a dietary supplement, and the side effects of consumption should also be investigated. The involvement of *Ganoderma* in non-communicable diseases like diabetes, cardiovascular disease, cancers, and chronic kidney diseases is a fascinating investi-

gation of what the future needs. Furthermore, cellular and physical effects on human health, anti-bacterial/anti-microbial effects, and secondary metabolites of *Ganoderma* sp., and it as a nutraceutical are future pathways for researchers. The research interest in *Ganoderma* in Sri Lanka is becoming more significant with the development of computational biotechnology.

Discussion, conclusions, and recommendations

Due to its favorable climate and diverse floral species, Sri Lanka has a high potential for mycology. However, with a significant number of endemic species, the majority of mushrooms from Sri Lanka are still uninvestigated and many of them have unknown chemical, biological, and pharmacological properties[26]. Hence, a huge pharmacological potential has been hindered due to the scarcity of scientific studies on the therapeutic values of these mushrooms[26]. Thus, there could be more *Ganoderma* species, novel therapeutic strategies, and advancements in molecular biology which are yet to be discovered in Sri Lanka

School and university students, farmers, and other rural communities should be educated through conferences, guidebooks, seminars, and workshops to enhance the research interest in *Ganoderma* and to make a market for it. Also, commercial cultivation can provide a significant boost to rural incomes and nutrition[81]. If Sri Lanka has national fungi herbarium for *Ganoderma* and other fungi culture collections that would be an excellent investment for the enhancement of future human health and to conduct further research[81]. A strong network of local fungi research groups to identify *Ganoderma,* as well as collaboration with other fungi research groups worldwide, would be a great next step toward becoming more significant in fungal research in Sri Lanka[81]. With the development of computational biotechnology, researchers could have the ability to interpret their research results in an accurate and precise manner. Furthermore, the distribution and the ease of approaching the species are added advantages to developing research interest in *Ganoderma*. In the near future, Sri Lanka will hopefully make more steps in the therapeutic and drug industry with *Ganoderma*.

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Conflict of interest

The authors declare that they have no conflict of interest.

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