The *Ganoderma*: Biodiversity and Significance

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Abstract

The genus *Ganoderma* includes intrinsic wood rotting fungi of economic importance, which are spotted widely across the globe. The various species of *Ganoderma* possess pathogenicity as well as therapeutic and aesthetic qualities. It is commonly referred as 'medicinal mushroom' across the Asia due to the presence of many chemical compounds with significant dietary and curative values. Besides the forementioned utilities, *Ganoderma* is an important phytopathogen that causes basal stem rot in oil palm, coconut, and areca nut trees, as well as many other trees in the forest environment, such as oak and maple. The fungus is a soil-borne facultative parasite that produces chlamydospores and basidiospores while living saprophytically on decaying roots and stumps. This chapter focuses on the *Ganoderma* covering biodiversity, molecular characterisation, detection, pathology including aetiology, epidemiology, mode of dissemination, and management, and economic and ecological implications. Despite the fact that in the diseases caused by *Ganoderma* spp., the primary cause of disease has been well researched, but early detection and management approaches are still in their immature stage. Future research priorities should include gaining a comprehensive understanding of the aetiology and

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epidemiology of diseases on diverse hosts, as well as addressing existing ambiguity in species nomenclature.

Keywords

Biodiversity · Basal stem rot · Characterisation · *Ganoderma* · Integrated disease management · Mushroom

12.1 Introduction

Ganoderma is a genus of the *Ganodermataceae* family, which is the part of the order Polyporales in Basidiomycota. It is well reported to trigger hardwood tree root or butt rot, and is also reported to be a therapeutically significant fungus across Asian continent. The genus *Ganoderma* was initially described in 1881 by Peter Adolf Karsten (Karsten 1881), with *Ganoderma lucidum* as the type species. *Ganoderma* species are important timber-decaying fungi with rough fruiting bodies that are prevalent both in temperate and tropical environments across the world with over 300 species. *Ganoderma* has a broad host range and may invade a variety of perennials, conifers, and palms. *Ganoderma* species are highly varied in the tropical area, impacting plantation crops like coconut, arecanut, and oil palm by inducing basal stem rot, as well as numerous trees in the forest environment like Oak, Maple, and foot rot of betelnut leading to pathogenicity and wood rots (Adaskaveg et al. 1991; Singh 1991; Flood et al. 2000; Pilotti 2005). The oil palm sector loses up to $500 million each year due to this disease (Arif et al. 2011; Ommelna et al. 2012). On the other hand, *Ganoderma* taxonomy generates a variety of biologically active chemicals of commercial value, which are farmed and possibly exploited for their curative and aesthetic qualities. *Ganoderma lucidum* is now regarded as one of the most commonly utilised medicinal mushrooms in the world (Rios et al. 2012). Antitumour, antiviral, antibacterial, anti-inflammatory, antioxidant, anti-platelet aggregation, hepatoprotective, hypotensive, immunomodulating, and immunosuppressive properties have all been documented for *G. lucidum* (Wasser and Weis 1999). The market value of '*G. lucidum'* products reached US$2.5 billion in 2003, making it a globally important commercial and pharmacological medicinal fungus (Chang and Buswell 2008).

The presence of the pathogen is typically confirmed once the fruiting bodies have developed. About 50% of the plant bole tissue gets decayed by this time, leaving the farmer with no means to cure the damaged palms and leading to a major reduction in palm agricultural productivity (Kandan et al. 2010). The *Ganoderma* species is a soil-borne facultative parasite that feeds (saprophytic) on dead, rotting roots and stumps forming chlamydospores and basidiospores. Basidiospores from conks are released for a short period of time (up to 5 months) and are accumulated on soil surfaces or their pruned or wounded fronds on standing palms, where they are passively spread by rain water runoff and air (Pilotti et al. 2018). If favourable substrates are accessible, these spores become pathogenic and may survive for

extended period under adverse circumstances (Rees et al. 2009a, b). Disease incidence was lower in areas with a lot of rain and high relative humidity. The quantity of rain and the number of wet days have a negative association with disease transmission in coconut (Palanna et al. 2012). The disease's severity increases as the soil temperature increases and decreases with the rise in its moisture content. Management control methods now in use, which include cultural and mechanical practices, do not seem to be very beneficial. Chemical therapy (Mohammed et al. 2014), root feeding and soaking (Bhaskaran and Ramanathan 1983), and proper dose of vital plant nutrients (Singh 1990) all help to minimise disease incidence. Biological control agents are used in alternative control approaches to solve the problem, and a number of potential bioagents have been created but have yet to be tested in the field. *Trichoderma* is one among them, and it is considered to be capable of controlling *Ganoderma* (Soepena et al. 2000). The conventional technique of identifying *Ganoderma* spp. based on physical and cultural traits has proven unsuccessful, and the lack of relevant morphological features has resulted in an overabundance of synonyms for the same disease. Therefore, at all levels of *Ganoderma* taxonomy and characterisation, protein- and DNA-based characteristics have become prevalent (Bruns et al. 1991). Numerous monitoring systems, including non-molecular techniques, have been formed based on serology, nucleic acid, secondary metabolites, volatile organic chemicals, remote sensing, and other approaches. Conventional PCR-based techniques have been found to be more hard to manoeuvre, compared to the faster, more accurate, and less cost-effective approach of DNA-based nanosensors and microarrays. While the primary cause of disease has been well researched, early detection and management approaches are still in their development. Research directions target on gaining a comprehensive understanding of the aetiology and epidemiology of diseases on diverse hosts, as well as addressing existing ambiguity in species nomenclature.

12.2 Economic Importance of *Ganoderma* Species

The genus *Ganoderma* integrates far more than 300 species, and is a very common causal agent of root or butt rot on hardwood. They are also familiarly known as medicinal mushroom across different parts of Asia. Having multi-economic value *Ganoderma* species are a rich source of several bioactive compounds, a decomposer of forest wood aiding in its recycling, and also a phytopathogen that targets perennial trees. It is a highly active source of medicine due to several constituent chemicals of high dietetic and therapeutic value (Rios et al. 2012). They have been exploited as an ancient Chinese remedial source dating more than 2000 years as recorded in the Chinese script of 'Classic of Materia Medica' from the Eastern Han dynasty (25–220 AD), and Ben Cao Gang Mu by Li Shin-Zhen during the sixteenth century of Ming Dynasty.

G. lucidum is mostly constituted of polysaccharides, steroids, and triterpenes as well as alkaloids, fatty acids, glycoproteins, inorganic elements, lignins, nucleosides,

nucleotides, peptides, phenols, proteins, sterols, and vitamins (Boh et al. 2007). These bioactive compounds unveil multi-therapeutic properties ranging from antitumour, cancerostatic, antiviral, antibacterial, anti-inflammatory, antioxidant, anti-platelet aggregation, antidiabetic, hepatoprotective, hypotensive, immunomodulating and immunosuppressive effects (Wasser and Weis 1999; Sliva et al. 2003; Gao et al. 2004; Yuen and Gohel 2005; Zhang et al. 2011; Bakshi et al. 2015; Ma et al. 2015; Chiu et al. 2017).

Applications based on the bioactive compounds isolated from the varying *Ganoderma* spp. are enlisted in the Table 12.1. Constituents isolated from different *Ganoderma* spp. exhibit anti-cancerous properties against different cancer cell lines such as of lungs (Loganathan et al. 2014), breasts (Suarez-Arroyo et al. 2013), liver (Lin et al. 1993) etc., they act as antioxidants to prevent oxidative damage of the cells (Bakshi et al. 2015). The immunomodulation is induced through cytokines and by increasing the immunological effectors (Wang et al. 1997). The extracted polysaccharides are beneficial against diabetes (Jung et al. 2005) and cardiovascular diseases (Gao et al. 2004), also. Ganoderol B obtained from *G. lucidum* deter prostate cancer in male due to its anti-androgenic properties (Liu et al. 2007). Many other isolated chemicals exhibit anti-inflammatory and anti-neurodegenerative properties (Sliva et al. 2003; Xu and Beelman 2015). The mushroom is also a part of habitual Chinese and Japanese nutritional supplement (Dong and Han 2015; Zhao 2015). Their derivatives indicate antimicrobial (Sheena et al. 2003; Wang and Ng 2006) and antiviral bioactivities (El-Mekkawy et al. 1998; Eo et al. 1999), also as antimutagenic (Lakshmi et al. 2006) and are used in cosmetics (Hyde et al. 2010; Jiang 2015). Different *Ganoderma* spp. are farmed on a commercial scale for multiple properties such as anticancerous, anti-inflammatory, antioxidants, cosmeceuticals, nutricosmetics, nutraceuticals, etc. (Jeong et al. 2008; Wu et al. 2016; Chaturvedi et al. 2018).

Although the species is of high medicinal and pharmacological value globally, with '*G. lucidum'* based products ensued a market of US$2.5 billion in 2003 (Chang and Buswell 2008). However, *Ganoderma* may be regarded as a commercially significant phytopathogen due to its severity in causing white rot in woody plants by decomposing their polysaccharide content such as the lignin, cellulose, etc. (Hepting 1971; Adaskaveg et al. 1991; Sankaran et al. 2005). It acutely causes root or butt rot of hardwood trees, mostly in coconut, oil palm, and arecanut, and also affects their plantation in the tropical belt by inducing basal stem rot (Singh 1991; Ariffin et al. 2000; Flood et al. 2000; Pilotti 2005). They also infect the ornamental and forest trees of the tropical and temperate region, triggering wood rots and related diseases. They can populate both as saprophytes and parasites on a variety of hosts resulting in an expanded group of white rot fungi.

Table 12.1 Different properties of *Ganoderma* spp. and their bioactive compounds

Properties	Active compounds	*Ganoderma* spp.	References
Medicinal properties			
Antitumour effect	Ganoderic acid X, Lanostanoid triterpenes	*G. amboinense*	Hsu et al. (2008); Li et al. (2017)
	Terpene (Presiccanochromenic acid, Myrocin C, Sphaeropsidin D, Deoxyherqueinone , Xylariacin B, Trichiol C, Comazaphilone D, Zeylasteral, Erinacine H, Applanoxidic acid C, D, E, F, G, H)	*G. applanatum*	Elkhateeb et al. (2018)
	Triterpenoids (Ganoderic acids, *Lucidum*ol, Lucialdehyde, Lucidenic acids), Polysaccharides	*G. lucidum*	Yuen and Gohel (2005), Zhang et al. (2011)
	Crude extract of *G. tsugae*	*G. tsugae*	Hsu et al. (2018)
Antioxidants	Polysaccharides, triterpenoids, polysaccharide-peptide complex and phenolic component	*G. lucidum*	Bakshi et al. (2015), Kan et al. (2015), Rajoriya et al. (2015)
	Polysaccharides	*G. atrum, G. tsugae*	Tseng et al. (2008), Zhu et al. (2016)
	Lingzhilactone B	*G. sichuanense*	Yan et al. (2015a, b)
Liver and gastric injury	Polysaccharides	*G. Lucidum*	Chiu et al. (2017)
Cardiovascular potential	Polysaccharides	*G. lucidum*	Gao et al. (2004)
Diabetes mellitus	Polysaccharides, proteoglycans, Proteins (LZ-8) and Triterpenoids	*G. amboinense, G. atrum* and *G. lucidum*	Jung et al. (2005), Zhu et al. (2013, 2016), Ma et al. (2015)
Anti-inflammatory properties	Ganodermycin, polysaccharide components	*G. applanatum*	Jung et al. (2011), Vazirian et al. (2014)
	Polysaccharide	*G. atrum, G. tsugae*	Ko et al. (2008), Li et al. (2017)
	G. capense glycopeptide (GCGP)	*G. capense*	Zhou et al. (2014)
	Colosolactones	*G. colossus*	El Dine et al. (2009)

(continued)

Table 12.1 (continued)

	Ganoderic acids T-Q and lucideinic acids A, D2, E2, and P	*G. lucidum*	Sliva et al. (2003)
	Lingzhilactone B	*G. sichuanense*	Yan et al. (2015a, b)
	Triterpenoid-enriched lipids	*G. sinense*	Yue et al. (2008)
Anti-androgenic activity	Ganoderol B	*G. lucidum*	Liu et al. (2007)
Immunomodulation	β-D-glucans, the Zhi-8 proteins and triterpenoids	*G. lucidum, G. microsporum*	Wang et al. (1997), Huang et al. (2018)
Neuroprotective effect	*Ganoderma* side A, B, C and D; Ganolucidic acid A; Ganoderic acid S1; Ganodermic acid TQ; *Ganoderma* triol; 7-oxo-ganoderic acid Z; Methyl ganoderic acid A and B	*G. lucidum*	Weng et al. (2011), Zhang et al. (2011), Zhao et al. (2012), Xu and Beelman (2015)
Traditional Chinese Medicine			
Help re-energise, calm the mind, and alleviate cough and asthma	Triterpenoids and Polysaccharides	*G. lucidum*	Wachtel-Galor et al. (2011)
Cures Palpitation, loss of breath, and sleeplessness relief	Triterpenoids and Polysaccharides	Mixture of *G. lucidum* and *Gynostemma pentaphyllum*	Yan et al. (2015a, b)
Help re-energise, calm the mind, and alleviate cough and asthma	Triterpenoids and Polysaccharides	*G. lucidum*	Wachtel-Galor et al. (2011)
Antimutagenic effect			
Inhibits mutagens	Methanolic extract from the fruiting bodies of *Ganoderma lucidum* (Mutagens inhibited: Sodium azide (NaN3), *N*-methyl-*N*-nitro-*N*-nitrosoguanidine (MNNG) and 4-nitro-O-phenylenediamine (NPD))	*G. lucidum*	Lakshmi et al. (2006)

Antimicrobial properties (compounds isolated from *G. lucidum*)			
Properties	**Active compounds**	**Tested microbe**	**References**
Antibacterial activity	Ganomycin, triterpenoid	*Escherichia coli, Bacillus subtilis, Staphylococcus aureus, Salmonella sp., Corynebacterium diphtheria, Enterobacter aerogenes* and *Pseudomonas aeruginosa*	Yoon et al. (1994), Sheena et al. (2003), Keypour et al. (2008), Kamble et al. (2011), Heleno et al. (2013), Shah et al. (2014), Singh et al. (2014)
Anti-fungal activity	Ganodermin	*Botrytis cinerea, Physalospora piricola* and *Fusarium oxysporum*	Wang and Ng (2006)
		Trichoderma viride	Heleno et al. (2013)
Antiviral activity	GLhw, GLMe-1, 2, 4 and 7; Acidic protein bound polysaccharides (APBP) and Neutral protein bound polysaccharide (NPBP); Proteoglycan (*G. lucidum* proteoglycan (GLPG))	VSV (vesicular stomatitis virus), HSV-1 and HSV-2 (herpes simplex virus 1 and 2)	Eo et al. (1999), Oh et al. (2000), Liu et al. (2004)
		HSV-1 and HSV-2	Oh et al. (2000)
		Hepatitis B virus	Li and Wang (2006)
		Varicella zoster virus	Hijikata and Yamada (1998)
Anti-HIV activity	Triterpenoids, Lucidenic acid O, Lucidenic lactone, Ganoderiol F, *Ganoderma*nontriol, Ganoderic acid B, ganoderiol B, Ganoderic acid C1, 3β-5α-dihydroxy-6β-methoxyergosta-7, 22-diene, Ganoderic acid-β, Ganoderic acid H , Ganoderiol A, Ganolucidic acid A, *Lucidum*ol B, Ganoderic acid-β, *Ganoderma*nondiol and *Ganoderma*nontriol laccases	Anti-HIV-1 protease activity and inhibits HIV-1 reverse transcriptase	El-Mekkawy (1998), Min et al. (1998), Smith et al. (1998), Gao et al. (2003)

(continued)

Table 12.1 (continued)

Cosmetic products		
Properties	***Ganoderma* spp.**	**References**
Skin lightening	*Ganoderma lucidum*	Hyde et al. (2010), Jiang (2015)
Tyrosinase inhibition activity		Chien et al. (2008)
Stimulate hair growth by lowering Dihydrotestosterone		Meehan (2015)
Skin anti-ageing		Taofiq et al. (2016)
Foods and dietary supplements		
Soup	*G. lucidum* with *Panax ginseng*	Dong and Han (2015), Zhao (2015)
Tea	*G. lucidum* with *Lonicera japonica, Crataegus pinnatifida, Lycium barbarum*	
Wine	*G. lucidum* mixed with *Panax notoginseng*	
Yoghurt	*G. lucidum*	
Role in forest ecosystem		
Cellulose, related polysaccharides and Lignin decomposers and recycling of nutrients	Many *Ganoderma* spp.	Hepting (1971), Adaskaveg et al. (1991), Sankaran et al. (2005)

12.3 Species Diversity and Distribution

First announced in 1881 by Peter Adolf Karsten, the genus *Ganoderma*, with *Ganoderma lucidum* as its type species, comes from the *Ganodermataceae* family and order *polyporales* of *Basidiomycota*. The family incorporates eight different genera classified on the basis of their unique double walled basidiospores. The two subgenera of *Ganoderma* (Moncalvo and Ryvarden 1997) include

- Subgenus *Ganoderma* based on *Ganoderma lucidum* for lactate species.
- Subgenus *Elvingia* based on *Ganoderma applanatum* for with non-lactating fruiting bodies.

Polypore basidiomycetous fungus with a double-walled basidiospore belongs to the *Ganodermataceae* family (Donk 1964). The genus *Ganoderma* has been ascribed to 219 species in the family, with *G. lucidum* (W. Curt.: Fr.) P. Karsten as the type species (Moncalvo 2000). The *Ganoderma* species has a wide variety of possible hosts, infecting more than 44 species from 34 plant genera. In all, 300 species of *Ganoderma* have been identified and are found in tropical and temperate regions of Asia, America, Africa and Europe. They have a large host range and a lot of genetic variation. Different species have different characteristics and pathogenicity. Table 12.2 provides a fully updated list of various species found in different areas of the world. The research reveals that *Ganoderma* has a wide range of host specificity. The two species, *G. applanatum* and *G. lucidum*, have the widest host range.

Turner (1981) identified 15 *Ganoderma* species from Africa, India, Malaysia, America, Papua New Guinea and Thailand as being associated with oil palm basal stem rot, including *G. applanatum, G. boninense, G. chalceum, G. cochlear, G. lucidum, G. miniatocinctum, G. pseudoferreum* (*G. philippi), G. tornatum (G. australe), G. tropicum and G. zonatum. Ganoderma boninense* is the most virulent pathogen that causes oil palm basal stem rot (Wong et al. 2012).

- The comparative abundance of *Ganoderma* diversity reveals that tropical nations have larger range with a total of 23 species recorded from Africa, including *G. cupreum, G. steyaertanum, G. weberianum and G. zonatum* (Kinge et al. 2015).
- China has 13 species, with *G. ellipsoideum* being the most recently discovered species in Hainan Province (Hapuarachchi et al. 2018).
- And a total of 7 species have been identified from Iran (Moradali et al. 2007), 6 from Australia including a new species, *G. steyaertanum* (Smith and Sivasithamparam 2003).
- *Ganoderma* species are extensively dispersed in India, with the exception of a few species such as *G. multicornum, G. sessiliformae and G. perzonatum*, which are confined to certain areas.
- Bakshi (1971) contributed to the study of this genus in India, reporting five species, namely *G. applanatum, G. austral, G. colossum, G. lucidum*, and *G. philippi*.

Table 12.2 Morphological features of different *Ganoderma* spp

Ganoderma species	Morphological features							
	Stipe	Colour of pore surface	Upper surface	Context	Hyphal system	Generative hyphae (width (μm) and colour)	Skeletal hyphae (width (μm) and colour)	Curtis type
G. applanatum	Absent	Whitish	Woody to corky, applanate	Thick, purplish brown, shining	Trimitic	3.3–4.1, pale yellow with clamp connection	5.8 to 6.6, dark brown	Trichodermis
G. chalceum	Absent	Coffee colour	Reddish brown, laccate, highly sulcate, with crust	Coffee	Dimitic	3.5 μm, hyaline, thin walled with clamps	7.5 μm, brown	Claviform29.1–32.8 × 5–5.5 μm
G. curtisii	Subsessile to stipitate	Brownish	Variegated from ochraceous buff to carbo brown	Milky coffee ochraceous buff to ochraeous	Trimitic	2.5 μm, yellowish	5 μm, brown	Claviform 33.3–41.6 × 6.6–8.3 μm
G. lipsiense		Milky coffee	Slightly zonate, pulverulent glabrous	Reddish brown	Trimitic	3.3 μm, yellow	5 μm, brown	Trichodermis
G. lucidum	Subsessile to laterally stipitate	Creamish to milky coffee	Laccate, dark reddish, purplish, yellowish	Brown without horny deposition	Trimitic	3.3 μm, hyaline, with clamp connection	5.8 to 7.5 μm, brown coloured	Claviform type35–42 × 6–8.5 μm
G. multicornum	Subsessile to laterally stipitate	Creamish brown	Slightly sulcate and zonate, reddish black	Cocoa coloured	Dimitic	3–5 μm, hyaline, clamps present	15 μm, yellowish brown	Diverticulatetype50–65 × 4.5–6 μm

G. multiplicatum	Stipitate	Creamy white	Concentrically sulcate, brown of chestnut	Snuff brown, shiny	Dimitic	3.8 µm, hyaline with clamp connection	5.8–7.5 µm, yellowish green colour	Diverticulate28–30.8 × 14 µm
G. orbiformum	Dimidiate to sessile	Creamy white	Flat to concave, sulcate, glabrous, laccate	Umber	Dimitic	3.3–5 µm, pale yellow with clamp	5–6.6 µm, pale brown	Diverticulate40–46 × 9–12 µm
G. perzonatum	Dimidiate	Greyish brown	Glabrous, laccate, sulcate	Ochraceous brown	Dimitic	3.3–4.1 µm hyaline, thin walled, with clamp connection	5–6.6 µm, yellowish	Diverticulate45–51 × 6–10 µm
G. philippi	Sessile, non-laccate	Greyish brown to dull brown	Dull brown, milky coffee	Soft, shiny	Trimitic	5–58 µm, clamps connection	6.6–7.5 µm, brown	Similartoplecodermis
G. praelongum	Rarely umbonate to stipitate		Glaberous, sulcate, laccate, bay to brownish	Soft, without melanoid deposition	Trimitic	3.3 µm	5 µm, thick walled, brown	Diverticulate20–38 × 8.3–9 µm
G. resinaceum	Stipitate, dimidiate	Creamish brown	Bay to wine coloured, slightly zonate, laccate, glabrous when fresh	Ochraceous brown	Dimitic	3.8–4.5 µm, hyaline with clamp connection	7.5 µm, thin brownish yellow	Claviform 37.5–40.6 × 4.1–5 µm
G. sessiliforme	Stipitate	Yellowish white	Sulcate, brittle, rugose, reddish brown	Pale yellow	Trimitic	2.5 µm, by line clamp connection	5 µm, pale yellow	Spheroid pendunculate, 28–30 × 4.1–8.3 µm

(continued)

Table 12.2 (continued)

Ganoderma species	Morphological features							
	Stipe	Colour of pore surface	Upper surface	Context	Hyphal system	Generative hyphae (width (μm) and colour)	Skeletal hyphae (width (μm) and colour)	Curtis type
G. stipitatum	Stipitate	Milky coffee	Flat, sulcate, glabrous, laccate, reddish to chestnut	Bay colour with melanoid	Dimitic	3.3 to 4.1 μm hyaline, clamp connection	5–5.8 μm thick walled, brown	Spheroid pendunculate, 26–40 × 6–8 μm
G. testaceum	Sessile to subsessile	Cream to white yellowish	Brown	Deposits of melanoid substance	Trimitic,	3–4 μm, hyaline with clamp	5–6 μm, yellowish brown	
G. subresinosum	Stipitate	White to creamy	Surface irregular/ wrinkled, blackish blue					

- Additionally, *G. tronatum* was described by Steyaert (1972), and three more species, *G. adspermum, G. annulare, and G. leucophaeum,* were identified by Bilgrami et al. in 1991. In their list, 'Fungi of India,' Bilgrami (1991)) included seven *Ganoderma* species. Considering the taxonomic status of *Ganoderma* in India established 9 genuine species, of which Bhosle et al. found 5 species namely G. *lucidum*, *G. applanatum, G. philippi, G. multiplicatum, and G. resinaceum* (2010). As per Sankaran et al. (2005), the status of majority of the *Ganoderma* species documented from India has been identified solely on the basis of morphological and cultural features. A study of the literatures reveals that there have been a total of 20 species described so far. *G. chalceum, G. curtisii, G. lipsiense, G. multicornum, G. multiplicatum, G. orbiformum, G. perzonatum, G. praelongum, G. sessiliformae, G. stipitatum, and G. testaceum* are among the 11 new species described by Bhosle et al. (2010).

12.4 Cultural and Morphological Characteristics

Cultural features like chlamydospore generation, growth rate, and thermophily have been utilised to distinguish *Ganoderma* species in addition to basidiocarp shape. The culture colony of *Ganoderma* appears white to pale yellow, even felty to floccose, and becomes more yellowish when exposed to light. The cultures develop at various optimal temperatures depending on the species. Various hyphal structures, including generative hyphae with clamp connections, skeletal hyphae, stag-horn hyphae, vesicles, and hyphal rosettes, as well as chlamydospores, are produced by *Ganoderma* species in culture. Chlamydospore generation, growth rate, and thermophily are the main culture-specific features utilised to identify *Ganoderma* species (Seo and Kirk 2000). A significant number of scientists have tried using cultural characteristics to differentiate between *Ganoderma* species. The use of only the cultural morphology in *Ganoderma* taxonomy might lead to erroneous findings and different classification than based on the outcomes of morphological features-based identifications. Individual members of the *Ganoderma* species are distinguished by characteristics such as the shape and colour of the fruit body (red, black, blue/green, white, yellow, and purple), host specialisation, and geographical origin (Zhao and Zhang 1994; Woo et al. 1999; Upton et al. 2000). Murrill (1902, 1903), Atkinson (1908), and Coleman (1927) all applied a combination of taxonomic criteria to identify their subjects. Steyaert (1972, 1980) studied the genus from almost every continent on the planet. Ryvarden (1994) questioned the morphology of *Ganoderma* by examining morphological differences in 53 *G. lucidum* specimens from Norway. By assessing various morphological characteristics it was concluded that for correct basidiocarp shape and size at least 3–5 samples should be investigated. The colour of the pileus and stipe changes with age and should be taken into account. Pore size can be considered as an important taxonomic feature since it remains consistent. Because the colour of the pore surface and surroundings varies with age, specimens of various ages should be studied. The hyphal system was found to be less useful because the majority of G. *lucidum* species have a Trimitic

Fig. 12.1 Fruiting body of Ganoderma spp. on **A** Ficus tree **B** Arecanut **C** Indian rosewood

hyphal system; however Ryvarden (2000) found 15 species with a Dimitic hyphal system from the *lucidum* group. Ryvarden (1994) found that unless there are conspicuous microscopic characteristics combined with unique macromorphological features, low samples ranging from 1 to 2 samples are inadequate to identify a species. *Ganoderma* is the most complicated genus in the *Ganodermataceae* family, and it is split into two subgenera. The genus has been divided into two groups based on the presence of laccase: *G. applanatum* complex and *G. lucidum* complex.

Laccase-positive specimens are classified as G. *lucidum*, whereas laccase-negative specimens are classified as *G. applanatum*. For taxonomical categorisation, basidiocarpic features such as context colour, bracket size, and bracket form were taken into account. Furthermore, basidiocarp size and form, pilear colour, hyphal system and features including generative hypha and clamp connections, shape and size of apical pilear cells, and pore size have all been used to distinguish the species (Ryvarden 1994) (Fig. 12.1). Environmental changes cause morphological variations in basidiocarp development, resulting in substantial variation in size and colour of the basidiocarps across specimens while pore diameters remain unchanged. Sessile, stipitate, imbricate, and non-imbricate morphological features have been seen in naturally occurring G. *lucidum* basidiocarps (Seo and Kirk 2000). The colour of the pileus surface and hymenophore ranges from deep red (non-laccate: laccate) to light yellow to white, and the shape of the isolates varied as well (Shin and Seo 1988). While the typical fruit body is laterally attached to the stipe, eccentric, central, imbricate, and sessile fruiting bodies are seldom formed. Ryvarden (1994) observed considerable differences in the stipe attachment pattern of pileus and the host range. Despite the fact that mycologists who only described fruit bodies as stipitate or sessile had overlooked its significance, stipe characteristics such as attachment type, relative thickness and length were thought to be relevant for species identification. In the taxonomy of this family, the laccate feature of the pileus and stipe has been used in several ways. The colour of the context varies from white to dark brown, and the colour changes with age. Unfortunately, owing to variances in cultivation in different geographical areas under varying climatic circumstances and natural genetic evolution (e.g., mutation, recombination) of particular species, physical features

vary. As a result of the use of macroscopic features, this mushroom now has a huge number of names and a confusing, overlapping, and ambiguous taxonomy. Because of differences in environmental circumstances during growth, the shape of the basidiocarps may change between isolates (Seo and Kirk 2000). The morphological and biological characteristics of *Ganoderma* species are illustrated in Fig. 12.1 and Table 12.2.

12.5 Molecular Characterisation

Across the globe, great diversity is observed in *Ganoderma* species w.r.t. phenotype (shape and colour of the fruit body), host specificity, and geographical origin; that are used to differentiate the individual members of the species (Zhao and Zhang 1994; Woo et al. 1999; Upton et al. 2000). However, morphological features of particular species are prone to change owing to variability in agriculture in different geographical areas under varying climatic regions and natural genetic factors (e.g., mutation, recombination). Due to the use of macroscopic features, this mushroom has a large number of names and a conflicting, overlapping, and imprecise nomenclature. Traditional taxonomic approaches have been ineffective in creating a stable taxonomy for the group, and are unhelpful in defining individual strains. Traditional techniques of identifying wood-decay fungus from decaying trees are challenging due to morphological differences across various populations of this species. In researching these macrofungi, there are taxonomic ambiguities due to a lack of unifying criteria. As a result, protein- and DNA-based markers have become common in *Ganoderma* taxonomy and characterisation at all levels (Bruns et al. 1991). Enzyme gel electrophoresis, Ribosomal DNA (rDNA) sequencing (Moncalvo et al. 1995a; Gottlieb et al. 2000), Internal Transcribed Spacer (ITS) sequencing (Hseu et al. 1996), have been carried out to evaluate the genetic relatedness of *Ganoderma* species complex. For instance, Bonde et al. (1993), Gottlieb et al. (1995, 1998), Mwenje and Ride (1996, 1997) and Gottlieb and Wright (1999) used isozyme analysis to distinguish various *Ganoderma* species.

Smith and Sivasithamparam (2000) used cellulose acetate gel electrophoresis (CAGE) and Polyacrylamide gel electrophoresis (PAGE) to investigate isoenzymes from five Australian species. Pectinase zymograms for 150 *Ganoderma* strains indicated groups that matched the host type from which the strains were acquired. Isolates from palm hosts (*Elaeis guineensis*, *Cocos nucifera*, *Areca catechu, Oncosperma horridum and Ptychosperma macarthurii*) eventually formed a single large cluster (cluster A), wherein palm-derived isolates accounting for 99% of the isolates. Within this functionally defined category, there were no significant differences across isolates obtained from widely different geographic areas such as Colombia, Nigeria, Malaysia, and the Solomon Islands. A second cluster (group B) similarly had a high percentage (85%) of palm-derived isolates (Miller et al. 1995a). *G. lucidum* has been differentiated from several other temperate *Ganoderma* spp. based on intracellular esterase isozymes (Park et al. 1986; Tseng and Lay 1988). *G. applanatum, G. boninense, G. formosanum, G. fornicatum, G. microsporum,*

G. neojaponicum, G. tropicum and G. tsugae isolates can be distinguished by intracellular and extracellular laccase isozymes, according to Hseu et al. (1989), and *Ganoderma* isolates from perennial regions were characterised using intracellular catalase, acid phosphatase, and propionyl esterase profiles. In contrast to pectinase-derived groups, which showed no clear connection to the source host, these isozymes displayed widespread genetic variation in isolates (Miller 1995; Miller et al. 1995b).

PCR-RFLPs, ITS, and rDNA sequences, among other DNA-based methods, have been found to be more useful in *Ganoderma* taxonomy. Among the various molecular DNA markers, Hseu et al. (1996) employed RAPD–Polymerase chain reaction (PCR) and internal transcribed spacer (ITS) sequences to distinguish the isolates of G. *lucidum* complex. Moncalvo et al. (1995a, b) applied ribosomal DNA sequencing to investigate the evolutionary connections of the *G. lucidum* complex. The ITS sequencing has been found to be effective for distinguishing lineages within the *G. lucidum* complex, and RAPDs were useful in distinguishing species with similar ITS sequences at lower taxonomic levels.

Gottlieb et al. (2000) examined ITS sequences to describe South American *Ganoderma* isolates and observed that morphological and molecular data were in accord at the subgeneric level. ITS markers were also applied by Wang and Yao (2005) to identify genetic diversity among *Ganoderma* isolates. ITS sequences were used to identify two biological species of *G. adspersum* and *G. cupreum* from the southern portion of India (Arulpandi and Kalaichelvan 2013). Based on ITS 1 and 2 sequences from Mizoram, six *Ganoderma* species, *G. lingzhi, G. mastoporum, G. mizoramense, G. multipileum, G. subresinosum and G. williamsianum*, were identified to the species level (Zohmangaiha et al. 2019). Park et al. (2012) used the ITS and partial tubulin regions of Korean *Ganoderma lucidum* isolates to differentiate them from isolates of China, Taiwan, and Canada. Haroun et al. (2020) used ITS regions to describe *G. lucidum* isolates from Abuja and Nigeria.

Ganoderma-specific primers (Gan1 and Gan2), as well as a PCR method developed by GanET and ITS3, were used to identify *Ganoderma* infection early (Utomo and Niepold 2000; Mandal et al. 2014; Rajendran et al. 2014). Tang et al. (2005) utilised RAPD and isoenzyme esterase to analyse genetic diversity in a species complex and found that species clustered into three groups based on RAPD analyses: the first group included *G. lucidum, G. resinaceum*, *and G. lucidum* var *xinzhou*; the second group included *G. subamboinense*; and the third group included *G. applanatum*. RAPD and PCR-RFLP techniques were used to examine *Ganoderma* isolates from *G. boninense, G. philipii* and *G. australe*, and it was discovered that species of the same host from different parts of Peninsular Malaysia clustered together. Despite the high degree of similarity among *G. boninense* isolates, RAPD analysis revealed differences (Zakaria et al. 2009). Miller (1999) and Karthikeyan et al. (2007) performed RAPD analyses of *Ganoderma* spp. in a similar fashion (2009). Zakaria et al. (2005) adopted random Amplified Microsatellites (RAMS) markers in addition of RAPD markers to examine genetic diversity among *G. boninense* isolates. Sun et al. (2006) used polymorphic sequence related amplified polymorphism (SRAP) markers to differentiate *G. lucidum* from

G. sinense and discovered *G. lucidum* isolates differed between China and Yugoslavia. Su et al. (2008) created a *G. lucidum* strain 9 unique sequence characterised amplified region (SCAR) marker to identify it from other strains, it has inter simple sequence repeats (ISSR). The ISSR method was used by Praphruet and Peangon (2010) to detect genetic polymorphism among nine *G. lucidum* isolates. The *Ganoderma* taxa were identified using PCR-RFLPs of ribosomal DNA (rDNA) and mitochondrial DNA (mtDNA) (Bruns et al. 1991; Bunyard et al. 1996; Nicholson et al. 1997). Zheng et al. (2009) used Amplified Fragment Length Polymorphism (AFLP) and ITS-PCR-RFLP to uncover *Ganoderma* spp. taxonomic diversity. Moncalvo et al. (1995a, b), Latiffah (2001), and Utomo and Niepold have all demonstrated that ITS-PCR-RFLP is an effective technique for studying genetic diversity in *Ganoderma* (2000). Multiplex PCR (MPCR) is a method for identifying several *Ganoderma* species in a single test (Wong et al. 2012). DNA microarray, which employs an electrochemical DNA biosensor, is another intriguing approach for detecting *G. boninense* (Dutse et al. 2013).

Two new *Ganoderma* species, *G. angustisporum and G. casuarinicola*, were discovered and described in South-Eastern China based on phylogenetic analyses of sequences of the Internal Transcribed Spacer (ITS) region, the translation Elongation Factor 1-gene (EF1–1), and the second subunit of RNA polymerase II (RPB2) (Xing et al. 2018).

A multilocus phylogenetic approach was established based on the analysis of four separate loci (ITS, tef1a, rpb1, and rpb2), which were further utilised to morphologically compare 13 different species, namely *G. boninense, G. curtisii, G. flexipes, G. lingzhi, G. lucidum, G. multipileum, G. oregonense*, and *G. resinaceum* (Zhou et al. 2015). Using ITS molecular phylogeny, Wang et al. (2009) segregated Asian *G. lucidum* specimens into two clades, each of which was differentiated from European *G. lucidum* (Clade D) and *Ganoderma tropicum* from Taiwan (Clade C). One clade (Clade A), which comprised of tropical specimens was represented as *G. multipileum*, whereas the other clade (Clade B) was unknown (Wang et al. 2009). Later, *G. lingzhi* was the name given to this hitherto unidentified clade (Wang et al. 2012).

The research into the ITS and other conserved gene areas is going to be helpful in providing information on *Ganoderma* species diversity in various ecosystems. It will also serve as a valid tool for phylogenetic analyses and inter- and intraspecific characterisation of the *Ganoderma* species complex. ITS sequencing might also give a starting point for the creation of new molecular markers for the accurate identification of the therapeutic *Ganoderma* spp. complex, as well as for determining host specificity and distribution of virulent *Ganoderma* species. For example, the creation of genetic markers for particular strains, as well as an accurate identification system and phylogeny based categorisation of *Ganoderma* species, would have practical consequences in epidemiological research, the wood industry, and medicine. It would, for illustration, aid in the monitoring of fungal proliferation inside and between fields, as well as bioprospecting for novel genes and metabolites, as well as providing relevant information for genetic engineering and commercial strain breeding.

12.6 Detection Methods of *Ganoderma*

Symptoms such as fading and drooping of mature leaves, stem oozing, or the appearance of pathogen basidiomata on the tree are now the only method to diagnose sickness visually (Lelong et al. 2010). However, by then, it gets too late for any management measures, therefore early diagnosis of disease is critical. For early detection, a colorimetric method, utilising ethlylene di-amine-tetraacetic acid (EDTA) was used (Natarajan et al. 1986). Another approach employed in the early days was semi selective medium for detecting infection by growing fungus (Darus et al. 1993). Antibodies were employed by Reddy and Ananthanarayanan (1984) to detect *Ganoderma* in culture media. Many novel early detection methods were created throughout the PCR and Post-PCR eras. For the identification and detection of *G. boninense*, Utomo and Niepold (2000) employed an enzyme linked immunosorbent test (ELISA) using polyclonal antibodies and PCR, as well as cultural characteristics, but the ELISA findings were found to be false negative. Monoclonal antibodies were created and tested against *G. boninense*, with promising results (Shamala et al. 2006). Madihah et al. (2018) utilised loop mediated isothermal amplification (LAMP) for early detection, and *G. boninense* and nonpathogenic *G. tornatum* were successfully distinguished. The 18 s rDNA gene is viewed as a marker gene for infection detection as well as biodiversity and phylogenetic research (Meyer et al. 2010). The function was served by DNA-based nanosensors (Dutse et al. 2013), Microfocus X-ray fluorescence (MeorYusoff et al. 2009), electronic nose (e-nose) device (Markom et al. 2009; Abdullah et al. 2011), and Terrestrial laser scanner (TLS) device (As'wad et al. 2011; Muniroh et al. 2014; Azuan et al. 2019). Ergosterol content is utilised as a biomarker for primary prevention of *Ganoderma* infection in oil palm. Early diagnosis of diseased trees was done using electrical resistance (Nurnadiah et al. 2014). Secondary metabolites were used by Nusaibah et al. (2016), however no meaningful findings were obtained. A headspace solid-phase microextraction (HS-SPME) method coupled with gas chromatography–mass spectrometry (GC–MS) was utilised to identify infection utilising volatile organic molecules (ZainolHilmi et al. 2019). The method of remote sensing was also used to identify and quantify illness (Khosrokhani et al. 2018).

12.7 *Ganoderma* as a Pathogen

Ganoderma is a natural wood rotting fungus that is encountered all over the world. As an infectious agent, it causes stem and root rots in most ecologically important plantation crops (coconut, arecanut, rubber, coffee, tea, oil palms, and so on) in the tropical regions, as well as wood rots in ornamental and natural forest trees (*Acacia, Macadamia, Populus*, and so on) in tropical and temperate regions (Palanna et al. 2012). Coleman (1911) initially recorded the breakdown of *Ganoderma* species in arecanut in India, while Butler (1913) reported the assault of *Ganoderma lucidum* on coconut palms in Karnataka in 1913, producing basal stem rot (BSR). In different

parts of India, BSR is known as Thanjavur wilt in Tamil Nadu, *Ganoderma* wilt in Andhra Pradesh, Anaberoga, bole rot or foot rot in Karnataka, and so on.

The most destructive disease in oil palms, BSR, causes substantial output losses, particularly in India's southern regions. According to estimates, basal stem rot causes annual economic losses of almost USD 0.5 billion (Jee and Chong 2015; Ahmadi et al. 2017) due to direct stand loss, reduced infected palm output, and increased replant frequency.

12.7.1 Symptomatology

Ganoderma rot is the most destructive disease of cultivated plants and trees. *Ganoderma* may infect plants from seedlings to elderly trees, although palms and forest trees between the ages of 5 and 30 are particularly vulnerable (Kandan 2003). The disease progresses slowly, with affected plants dying eventually. After many years of infection, the disease becomes apparent; nevertheless, outward disease signs are not readily apparent from the outset (Mawar et al. 2020). After several years of incubation, obvious illness signs develop at the late stage of infection, leaving little possibility of healing the afflicted plants (Bhaskaran and Ramanathan 1983). The virus may also infect immature nursery oil palms, demonstrating the disease's potential to spread from old plantations to nursery seedlings (Wong et al. 2012). *Ganoderma*, a silent killer pathogen, may infect all stages of plants and cause a gradual disease progression, although visible signs might develop late in the infection process, resulting in massive crop loss (Naher et al. 2011).

The appearance of unopened spears, yellowing, and shortening of younger fronds in oil palms indicate early disease development (Turner 1981, 1981). *Ganoderma* infects the root system first, and then spreads to the coconut trunk's basal part with reddish-brown exudation. The number of bleeding patches rises as the illness progresses. The crown portion of the coconut starts to wilt, display yellowing, and drooping of the peripheral fronds persists around the trunk at a later stage. Emerging new fronds turn yellow, shrink in size, fronds fail to unfurl correctly, and flower bunches and roots' development is slowed (Kandan et al. 2010). At a mature course of disease in oil palm, the older fronds collapse and die, and the virus spreads to the younger crown areas, resulting in lower yield output (Gorea et al. 2020). The illness causes colouring and rotting of roots, which leads to root disintegration and an alcohol odour in the ultimate stage. At the root of diseased trees, basidiocarps/sporophores/conks are formed (Wong et al. 2012). When one-half of the stem base is infected by the pathogen, foliar symptoms appear; affected trees generally die after 6–12 months of foliar infection (Turner 1981). Internally infected tissues showed a bright yellowish-brown zone linked with host cellular function of vesicular budding onto the outer membrane, signifying the generation of suberisation and lignification (Rees et al. 2009a, b).

The symptomatic manifestation can be visible at many levels, including the stem, crown, and roots.

12.7.1.1 On Stem

- The infected trees leak sticky reddish-brown exudates up to 3 metres from the base section of the stem, which is the first apparent sign.
- Bleeding patches are visible from the bottom up, and as the illness progresses, those bleeding patches expand higher.
- Up to the height of exudation, discoloration (bleeding) and internal rotting of the stem can be seen.

Eventually, in the later phases of infection, the stem's basal part decays entirely. Basal stem rot, often known as the 'silent killer of palms,' is a disease in which the basal sections of the stem get infected and internal rotting may be observed where the leaves of the afflicted plant seem alive (Palanna 2016).

The fructification of the fungus (Basidiocarp) located horizontally connected to the palm stem at the base slightly above the ground level, which might be called a bracket, in the advanced stage of the illness. Bracket is initially a solid white mass that is relatively soft, but as it ages, the basidiocarp protrudes from the tree trunk and creates a shelf-like structure that is firm, semicircular and has a reddish-brown upper surface and a white undersurface (Hennessy and Daly 2007). The most significant diagnostic symptom is the formation of brackets, which can occur individually or in clusters. The illness is also known as anaberoga in palms because of the development of this structure.

12.7.1.2 On Crown

- Wilting signs, such as yellowing and drooping, are seen on the leaflets in the outermost whorls.
- Outer fronds linger for several months before shedding, and in the case of forest trees, leaf shedding is noticeable.
- Newly generated fronds are smaller and chlorotic, with a large number of unopened fronds (spear leaves) visible, flattening the crown.
- In the later stages of infection, the entire crown is blown off, leaving just the decapitated stem left.
- In the infected palm, flower development is disrupted, and button shedding is visible. In certain cases, decomposition of buds might occur, resulting in a foul odour.

12.7.1.3 On Roots

- The most common sign is severe root deterioration and death.
- Discoloration and severe rotting cause cortical tissues to disintegrate readily, and roots become liquid and exude an alcoholic odour.
- The development of new roots is also harmed, resulting in the demise of the afflicted palm. Young infected palms perish between 6 and 24 months, but developed palms might take up to 2–3 years to die (Ariffin et al. 2000).

Ganoderma induces wood rot in woody plants and white rot in hardwoods via delignification, or the breakdown of woody tissues (Peries 1974). As a result,

discoloured zones may be seen in the wood. The wood breaks down entirely, becomes soft or spongy, and eventually loses its tensile strength and dies at the advanced stage of decay.

12.7.2 Epidemiology

The occurrence of *Ganoderma* disease is mostly dependent on soil type, palm age, prior crops, climatic conditions and soil nutrition.

12.7.2.1 Soil Type

The disease is most common around the coastline, where the soil is sandy or sandy loamy in character. In lighter soils, illness incidence was higher than in heavier soils (Satyanarayana et al. 1985). Water stagnation was used by Srinivasulu et al. (2003) to prevent basal stem rot in coconuts. The growth of a hard pan in the subsoil prevents root penetration, making the palms more susceptible to *Ganoderma* infection. Several investigations also showed that oil palms planted in lateritic and inland soils had a high prevalence of BSR (Benjamin and Chee 1995).

12.7.2.2 Age of the Palm

Palms and forest trees that are 5–20 years old have a higher disease incidence than younger plants (Palanna et al. 2012).

12.7.2.3 Previous Crops

Because of the presence of inoculum on trunk tissues and stumps left behind in the field, which acts as a main source of root infection, acute outbreaks of the disease can be seen in regions where oil palms are planted followed by coconut and also when the oil palm is replanted from oil palm (Turner 1981). Oil palms that were 15 years old had a high prevalence of basal rot.

12.7.2.4 Environmental Factors

The illness incidence is seen to be higher mostly during months of March to August (Bhaskaran et al. 1985). In locations with significant rainfall and low relative humidity, the incidence of BSR was lower. The spread of BSR of coconut has a negative relationship with rainfall and the amount of rainy days (Palanna et al. 2012). The severity of the infection rises as the soil temperature rises and falls when the soil moisture rises.

12.7.2.5 Soil Nutrition

Prevalence of disease is also influenced by soil nutrition. Potash muriate and rock phosphate both increase illness incidence, but urea has the opposite effect (Singh 1991). Infected palms have lower amounts of macronutrients such as nitrogen, phosphorus, and potassium, and higher levels of magnesium than healthy palms.

12.7.3 Lifecycle of *Ganoderma* Species

Ganoderma species are soil-borne facultative parasites that thrive saprophytically on decaying roots and stumps before becoming pathogenic when appropriate substrates are available (Rees et al. 2009a, b). *Ganoderma* species have a long life cycle because the pathogen is soil-borne and may persist for a long period in the soil. They generate chlamydospores (asexual spores; *Thermophymatospora* anamorph) to live in harsh environments, which are more resistant than basidiospores and aid in disease transmission.

The major mode of infection is root-to-root contact, but secondary inoculum is found in the soil as basidiospores or chlamydospores, which can be disseminated by rain splash and wind (Wahab and Aswad 2015). The hyphae develop over the palm roots after airborne basidiospores are released from brackets and absorbed into the soil. The roots are not initially harmed; instead, the fungus utilises them to infiltrate the hardwood tissues of the trunk. Monokaryotic hyphae combine to create dikaryons, which infect tertiary roots, lower frond base and bole (causing basal stem rot), and the frond axil (causing upper stem rot). Palms receive both dikaryotic and monokaryotic mycelia from infected neighbours and basidiospores. The fungus colonises and destroys the trunk tissue after the palm is infected, eventually causing the palm to die and collapse. Within the trunk, dikaryotic mycelia continue to develop and generate sporophores on a bracket-like structure (tertiary mycelium). According to Pilotti et al. (2018), basidiospores are released for a longer period of time (5 months) and are deposited on soil surfaces or trimmed or damaged fronds on standing palms, where they are dispersed passively by rain splash and wind. These spores have a resistant structure that allows them to live in adverse conditions for prolonged periods of time, and when favourable conditions return, the spores germinate and the infection begins anew.

12.8 Integrated Disease Management

12.8.1 Cultural Practices

1. Sanitation: Trees that have been infected with the disease must be removed from the plantations. Basidiomata are removed from diseased palms and fungicidal paste is applied. Diseased tree roots should not be allowed to come into touch with healthy palms, and infected trees can be separated from healthy plants by digging trenches around them (Turner 1981; Chung 2011). Fallowing decreases disease incidence by decreasing inoculums in the soil before replanting (Virdiana et al. 2010).
2. Surgery: Because basidiospores are the most common source of infection, removing diseased tissue or basidiocarps from infected palms in plantations may be advantageous (Sanderson et al. 2000; Pilotti et al. 2018).
3. Ploughing practices: Two rounds of deep ploughing of 60 cm and one round of harrowing to break up residual roots before planting new seedlings in disease-

prone locations, provide enough moisture over the summer in plantations, prevent flood irrigation, avoid close planting, and repeat ploughings in infected fields (Rethinam 1987; Flood et al. 2000).

4. Green Manuring, Inter and cover crops: Green manure crops must be grown and ploughed in place before blooming, increasing the nutrient status of the soil and preventing soil erosion. Ailanthus and banana as inter crops are non-hosts for *Ganoderma* (Rethinam 1987). Care should be taken not to introduce legumes that are prone to *Ganoderma* infection, as well as avoid planting collateral hosts such as *Delonix regia* in close proximity.
5. Soil Amendments: By improving soil characteristics using neem cake and farm yard waste, disease incidence is reduced (Naik 2001).
6. Soil Mounding/Heaping: This method of heaping dirt around the trunk to a height of 75 cm may prolong the tree's life, but it is unsuccessful in preventing stem rot (Ho and Khairuddin 1997). However, when used in conjunction with a chemical technique, it provides better control (Mohammed et al. 2014).

12.8.2 Chemical Control

Hexaconazole can be employed to treat *Ganoderma* infection by infusing it into the wood trunk (Mohammed et al. 2014), however it hasn't been proven to be very successful (Chung 2011). Pathogen exhibits resistance to fungicides in later stages of the infection (Susanto et al. 2005). The use of benzoic and salicylic acid to immunise seedlings reduced disease growth (Surendran et al. 2018). After chizeling out the bleeding tissue, a chemical fungicide and then hot coal tar can be applied to protect the bleeding regions in the stem (Ariffin et al. 2000). Hexaconazole root feeding at three intervals of 3 months has also been proven to be beneficial. A common practice is to drench the tree trunk with Bordeaux mixture or copper oxychloride from a distance of 1.5 metres (Bhaskaran and Ramanathan 1983).

12.8.3 Plant Extracts

Neem, banana rhizome extract, and *Tephrosia purpurea* root extract, according to Bhaskaran et al. (1988), exhibited *Ganoderma* suppressive effects. Glyricidia plant extract proved antifungal *in vitro* against *Ganoderma applanatum*, according to Palanna et al. (2013). Several additional plant extracts, such as *Eichhornia crassipes* against *Ganoderma lucidum* (Deepatharshini and Elango 2015), leaf extracts of *Pongamia glabra*, *Azadirachta indica* and *Prosopis julifera* (Karunanithi et al. 2007) and garlic extract (Srinivasulu et al. 2005), were shown to inhibit the fungus to varying degrees.

12.8.4 Plant Nutrition

Plant production can be improved by a proper dosage of major and minor nutrients (Singh 1990; Chung 2011). Calcium nitrate in conjunction with *Trichoderma* has been proven to be beneficial in preventing stem rot (Sariah and Zakaria 2000). Wang et al. (2017) demonstrated the protective effects of silicon in a variety of plant species against a variety of diseases, including *Ganoderma* stem rot. Potassium silicate, silicon oxide, sodium silicate, calcium silicate, and sodium meta-silicate were found to decrease *Ganoderma* incidence in oil palm by Najihah et al. (2015). Application of manganese sulphate, zinc sulphate, sulphur, and lime to the soil decreased disease incidence (Jaganathan and Ramasami 1975; Bhaskaran et al. 1985; Srinivasulu et al. 2002).

12.8.5 Host Resistance

Oil palm from Zaire and Cameroon cross has been found as a moderately resistant source (Idris et al. 2004; Durand-Gasselin et al. 2005). Tisné et al. (2017) discovered four *Ganoderma* resistance loci in oil palm, two of which controlled the onset of *Ganoderma* symptoms while the other two controlled palm tree death.

12.8.6 Biocontrol Management

Many studies have been done on *Ganoderma* biocontrol application (BCA) and several possible biocontrol agents have been discovered to be effective against the disease. Many fungal bioagents have been discovered and proven to be effective during the nursery stage, such as *Hendersonia* isolate (Nurrashyeda et al. 2018), *Scytalidium parasiticum* (Goh et al. 2016) and *Trichoderma harzianum* (Priwiratama and Susanto 2014). In a nursery trial, bacterial bio agents such as *Burkholderia* sp. (Buana et al. 2014) reduced pathogen incidence for up to 3 months. In a nursery study, *Burkholderia cepacia, Pseudomonas aeruginosa*, *and Serratia marcescens* were shown to suppress *G. boninense* by Sapak et al. (2008) and Azadeh et al. (2010). *T. harzianum* and *G. viride* outperformed *Bacillus* sp. in contrast to untreated areas. In that scenario, *T. harzianum and G. viride* had a reduced frequency of disease in treated areas (Susanto et al. 2005). As a potential defence strategy in the oil palm, *Trichoderma* sp. stimulated the synthesis of fungal-cell-wall-degrading enzymes such as glucanases and chitinases (Naher et al. 2011). As a result, as with other plant diseases, these enzymes may damage the invading fungus' cell wall, limiting illness. Arbuscular Mycorrhizal fungi (AMF) are linked with the roots of oil palm, and it has been suggested that they may resist *G. boninense* (Sundram et al. 2015). AMF competes with plant pathogens for nutrients and space, and it can also activate the plant's defence mechanism by activating siderophores, as mentioned in other plant-pathogen systems (Brundrett 2002). There have been biological control experiments using basidiomycetes to prevent stump infections in forest trees (Roy

et al. 2003). But on the other hand, no similar research has yet been done on BSR-infected oil palm trunks. Naidu et al. (2015) identified 25 white rot hymenomycetes from healthy oil palm, and eight of them showed a combative reaction against *G. boninense. G. boninense* was successfully combated by actinomycetes isolated from empty fruit bunches of oil palms. *Streptomyces violaceorubidus, Nocardiopsis* sp., *and Streptomyces* sp. were discovered, with 91.4%, 86.4% and 69.1% inhibition, respectively (Ting and Jioe 2016). Conflicts with non-target organisms, rhizosphere variation decreasing effectiveness, failure to colonise diverse types of soil, susceptibility to climate, difficulty competing with large populations of other microbes, and the target pathogen's genetic diversity can all cause BCA failures (Vidhyasekaran et al. 1997; Meyer and Roberts 2002). Draz-M, a formulation of an arbuscular mycorrhiza that prolongs the productivity of 25-year-old infected oil palms and improves their oil output by 42% and 68%, is one of the products in the market (Sariah and Zakaria 2000). *Trichoderma koningii* has also been developed for commercial usage in Sumatra as a field preventative or curative therapy (Soepena et al. 2000).

Indian origin *Trichoderma* spp. such as *T. hamatum, T. harzianum, T. longibrachiatum, T. viride, T. polysporum,* and *T. virens, Pseudomonas flourescens,* and *Bacillus subtilis* have all been found to be hostile to the pathogen. *T. hamatum, T. longibrachiatum, T. virens, T. polysporum, and T. harzianum* are efficient in suppressing *G. lucidum* (Bhaskaran et al. 1985; Srinivasulu et al. 2002) and *G. applanatum* (Srinivasulu et al. 2005). Naik et al. (2008) developed Talc-based formulations of *Pseudomonas* and *Trichoderma* combined with neem cake that was effective in treating the illness. Surulirajan et al. (2014) found that *T. viride* talc formulation (200 g/palm/year), neem cake, and TNAU (Tamil Nadu Agricultural University) microbial consortia were all highly useful. Depending on the rhizosphere populations of the biocontrol agents, Karthikeyan et al. (2006) advised using antagonists every 3 months.

12.9 Conclusion and Future Prospects

Ganoderma species have become economically important as a source of bioactive chemicals, a decomposer of forest wood, and a perennial tree plant pathogen. *Ganoderma* species are widespread in tropical regions, causing basal stem rot in plantation crops such as coconut, arecanut, and oil palm (Singh 1991; Ariffin et al. 2000; Flood et al. 2000; Pilotti 2005), as well as disease and wood rots in ornamental and forest trees in tropical and temperate areas (Singh 1991; Ariffin et al. 2000; Flood et al. 2000). Remarkably, *Ganoderma lucidum* is now regarded as one of the most commonly utilised medicinal mushrooms in the world (Rios et al. 2012). In the globe, it is an economically and pharmacologically significant restorative fungus. Traditional taxonomic approaches have been ineffective in creating a stable taxonomy for the group, and they are unhelpful in characterising individual strains. Traditional techniques of identifying wood-decay fungus from dying trees are challenging due to morphological differences across various populations of this

species. In researching these macrofungi, there are taxonomic ambiguities due to a lack of unifying criteria. The use of a polyphasic approach to taxonomy and characterisation is urgently needed to resolve nomenclature ambiguities. *Ganoderma* also possesses medical benefits, and the biologically active chemicals responsible for these capabilities can possibly be investigated and confirmed. Because the taxa are so diverse, bioprospecting for various economic properties is critical. Because the majority of these qualities are found in papers, they must be industrially utilised, and tested goods must be appropriately commercialised. Because *Ganoderma* is a slow-growing mushroom, prospective strains of these helpful species that can develop at a quicker pace must be discovered, and the efficient strains or species must be preserved in appropriate Culture collections. Effective management techniques for *Ganoderma* wilt and stem rot are still missing, and these procedures are primarily undertaken in economically significant hosts, despite the fact that the disease is more widespread in forest ecosystems. Since a result, the focus should be on testing effective control strategies, as failing to do so would result in significant economic losses for farmers in the near future, and there is still time to improve efficient early detection systems. There is also a scarcity of data on *Ganoderma* spp. productions of volatile organic compounds (VOCs).

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