Detection and Management of Basal Stem Rot of Oil Palm: Classical to Modern Approaches

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Abstract

Oil palm (*Elaeis guineensis* Jacq.), also referred as 'Golden palm', is the most efficient oil-yielding perennial crop in the world. Unfortunately, basal stem rot (BSR) disease poses a major menace to the palm oil industry and hence to farmers' livelihoods. *Ganoderma*, the causal agent, has been known for almost a century and is still a growing economic concern without proper remedy. A crucial factor in managing the BSR disease is the lack of well-grounded diagnostic method(s) for early and accurate diagnosis. Rapid and early on-field detection is very essential for proactive management of BSR. Practice of curative methods in infected trees and their economic feasibility is a matter of great concern as the disease is asymptomatic till its advanced stages of infection. Integrated BSR disease management should employ all successful cultural practices control, chemical control and biological agents.

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U. B. Singh et al. (eds.), *Detection, Diagnosis and Management of Soil-borne Phytopathogens*, https://doi.org/10.1007/978-981-19-8307-8_9

Keywords

Oil palm · Basal stem rot · *Ganoderma* · Detection · Management

9.1 Introduction

Oil palm (*Elaeis guineensis* Jacq.), also referred as 'Golden palm', is world's most efficient oil-yielding perennial crop, extensively cultivated in South-East Asia. It is presumed to be originated in Africa and classified under order Arecales and family Arecaceae. Palm oil (75.45 Mt) surpasses soybean oil (60.27 Mt) and rapeseed oil (28 Mt) in terms of global vegetable oil production ranking first among the oil-yielding crops (Shahbandeh 2021). The unparalleled yield advantage of the oil palm to that of other oilseed crops in terms of seasonal long harvest and high productivity (4–6 tonnes of vegetable oil per hectare) led to expansion of oil palm cultivation in the last two decades. Oil palm is highly productive in humid tropical regions receiving high light intensity, thus extensively cultivated in Indonesia, Malaysia, Thailand, Nigeria and Colombia. Recent estimates state that oil palm occupies 19.04 million hectares of global agricultural land (0.36%) (Kushairi et al. 2018). There are two types of oils, such as palm oil and palm kernel oil, that can be extracted from mesocarp and kernel of fruits, respectively. Palm oil has worldwide demand for consumption and accounts for 15% of oil requirements of the local food industry. In addition, palm oil is exploited for biofuels, lubricants, cosmetics and other products. Palm oil is widely recognized as the healthiest oil since it is rich in phenolic antioxidants, carotene and free of trans-fatty acids and cholesterol. Cultivation of oil palm in India is also fast expanding to the tune of 3.5 lakh ha with a production of 16.33 lakh tonnes of fresh fruit bunches and 2.70 lakh metric tonnes of crude palm oil (Oil World 2020). India is one of the largest consumers of vegetable oil, and 133.5 lakh tonnes of edible oil worth Rs. 80,000 crore imported in 2020–21, with palm oil accounts for 55% of the total vegetable oil imports. India may witness a substantial increase in oil palm area and production in future in order to achieve self-sufficiency in palm oil.

The rapid expansion of oil palm cultivation in both forest and arable land is posing severe disease and pest outbreaks, threatening its commercial cultivation. Aderungboye (1977) described 32 different types of diseases and disorders in palm cultivation, emphasizing nine major diseases that greatly hamper production of palm oil. Basal stem rot (BSR), Fusarium wilt, spear rot-bud rot and sudden wither (Corley and Tinker 2003) are becoming devastating fungal diseases in the recent past. Several other diseases such as Armillaria trunk rot (*Armillaria mellea*), blast (*Pythium splendens*), Corticium leaf rot (*Corticium solani*), Marasmius bunch rot (*Marasmius palmivora*), red ring (*Rhadinaphelenchus cocophilus*) (Aderungboye 1977) and heart rot (*Phytophthora palmivora*) (Elliott and Uchida 2004) are also reported in oil palm. Of all the diseases reported in oil palm, basal stem rot disease caused by wood rotting basidiomycete, *Ganoderma* spp., is becoming the most annihilating disease in major oil palm cultivating areas of the world (Flood et al. 2005; Chong 2010).

9.2 Basal Stem Rot of Oil Palm: Phytopathological Aspects

9.2.1 Geographical Distribution and Economic Loss

BSR is categorized as most devastating disease of oil palm cultivation in the recent years (Corley and Tinker 2003; Susanto et al. 2005). It was first described by Wakefield in 1915 from Republic of Congo of West Africa. When incidence of oil palm basal stem rot was initially reported by Thompson in 1931, the disease was of negligible economic importance. Later, with the rapid extension of oil palm cultivation from 1960, the young plantations in South-East Asian countries witnessed the real and destructive impact of BSR (Turner 1981). The disease has now been reported in every oil palm-producing regions of the world, with the most severe cases occurring in Indonesia and Malaysia, the world's largest producers and exporters of palm oil. Infection with basal stem rot reduces the number and weight of fresh fruit bunch, along with the stem weight of oil palm bunches. In extreme cases, the disease has a potential to kill more than 80% of crop stands during its normal economic life and necessitates early replanting (Razak et al. 2004). In spite of the fact that it has been known for nearly a century, it continues to be a major economic problem, with annual losses ranging from RM 225 million to RM 1.5 billion (up to US$ 500 million) (Arif et al. 2011; Ommelna et al. 2012). *Ganoderma* infection has caused 80% and 50% yield losses in Malaysia and Indonesia, respectively, during the last 40 years (Chong 2010; Chong et al. 2012a; Idris et al. 2010b; Susanto et al. 2005), and it is predicted that BSR has the potential to wipe out 860,610 hectares of oil palm farms in Malaysia by 2040 (Olaniyi and Szulczyk 2020).

9.2.2 Causal Organism

Ganoderma is a basidiomycetes fungi, grouped in the sub-phylum Hymenomycetes, order Polyporales and family Ganodermataceae (Cannon and Kirk 2007). Karsten (1881) established *G. lucidum* as the single species under genus *Ganoderma*. According to Seo and Kirk (2000), currently 322 species names of *Ganoderma* are included in species Fungorum, although the number of true species may be limited to 60–80 (Moncalvo 2000). Among them, a handful of important species are *G. applanatum*, *G. australe*, *G. boninense*, *G. cupreum*, *G. lobatum*, *G. lucidum*, *G. oerstedii*, *G. platense*, *G. resinaceum*, *G. sinense*, *G. tornatum*, *G. tsugae* and *G. weberianum* (in alphabetical order) (Roberts 2004).

Although basal stem rot is known for its high disease severity and wide occurrence in oil palm, there is no general consensus on *Ganoderma* species associated with the disease. Turner (1981) identified potential association of 15 species of *Ganoderma* such as *G. boninense*, *G. applanatum*, *G. chalceum*, *G. miniatocinctum*, *G. pseudoferreu*, *G. lucidum* and *G. tornatum* with BSR, and he also believed that the sole cause of the disease could not be attributed to a single species in any given area. *G. boninense* is the major species that is highly pathogenic to oil palm (Ho and Nawawi 1986; Khairudin 1990; Moncalvo 2000) in South-East Asian countries. *G. boninense* has been reported to be more aggressive, causing yield reductions of 20–40% and/or losses of 46–67%, if infected oil palm aged 15 years followed by *G. zonatum* (moderately aggressive) and *G. miniatocinctum* (least aggressive). However, *G. tornatum* is reported to be non-pathogenic species associated with BSR (Singh 1991; Hisham 1993; Idris et al. 2001). In spite of that, *G. boninense* as the BSR real causative agent in different oil palm growing region is yet to be confirmed. In India, *G. lucidum* and *G. applanatum* are known to cause basal stem rot disease in oil palm as well as coconut (Mandal et al. 2003).

9.2.3 Host Range

BSR disease incited by *Ganoderma* spp. has got a wide host range, infecting mainly palms, forest, avenue and fruit trees belonging to 19 families, 36 genera and 48 species (Naidu et al. 1966). *Ganoderma* exhibits saprophytic and parasitic life on logs (Singh et al. 2007) and plays a significant ecological role. It acts a as good decomposer in the breaking down or delignification of hard wood as well as soft wood causing white rot. Apart from oil palm, many *Ganoderma* species have long been found to cause stem and root rot diseases in many commercial perennial crops such as coconut (*Cocos nucifera*), tea (*Camellia sinensis*) and betel nut (*Areca catechu*) (Miller et al. 2000).

9.2.4 Morphology

Ganoderma fructification produces bracket like large and woody basidiocarps. Their fruiting bodies are generally double walled, generating truncate spores (with round base and shorter tip) having yellow to brown ornamented inner layers (Adaskaveg and Gilbertson 1988). Basidiocarps are made up of hymenium (tissue that produces spores) and pileus (cap-like structure) (Seo and Kirk 2000). *G. boninense* is morphologically distinguished from other species by light coloured thin pileus with elongated basidiospores that are uniformly brown coloured. The colonies of *G. boninense* grows into undulating whitish mycelial growth on top and having dark pigmentation on the reverse side of growth media plate.

9.2.5 Taxonomy

Many attempts have been made in the past in differentiating Ganodermataceae *taxonomically* based on host specificity, geographical distribution and phenotypic characteristics such as colour and consistency of basidiocarp, shape of margin of pileus, stipitate or sessile fruiting body and size and shape of basidiospores (Adaskaveg and Gilbertson 1986; Bazzalo and Wright 1982; Pegler and Young 1973; Steyaert 1972, 1980). The colour (deep red, light yellow to white) and size of pileus and hymenium vary between different species. However, the size of the pore remains almost similar in all species of *Ganoderma*. Later, the cultural, morphological and physiological characters of mycelial state of *Ganoderma* was used for taxonomic delimitation at species level (Miller et al. 2000). Variation in morphological features under different growth conditions resulted in ambiguity in species identification of *Ganoderma* (Ryvarden 1991). This can also be interpreted from a study conducted by Mandal et al. (2009) on colony morphology and sporulation stating the morphological plasticity in different isolates of *Ganoderma* in India. As a result, molecular identification using ribosomal DNA (rDNA) region (Moncalvo 2000; Smith and Sivasithamparam 2000), intergenic spacer (IGS1) region, cultural and mating features, isozyme-based studies and cladistic methods (Seo and Kirk 2000) are exploited nowadays. However, only a limited number of taxa have been identified in this way so far.

9.2.6 Symptoms

The delayed expression of symptoms is one of the biggest obstacles in diagnosing and managing BSR disease. The initial symptoms are observed generally after 60–70% of damage to vascular tissue of the plant and consequently mortality is quick in young palms (Rees et al. 2007). The infection by *G. boninense* results in lignin degradation of xylem vessels of plants, which is expressed as water stressed wilt conditions in the palms. The earliest symptoms include multiple unfolded fronds that become chlorotic on one side with subsequent necrosis of tips in young plants. Adult palms also produce similar symptoms giving sickened yellow canopy and skirting of lower leaves (Turner 1981). Gradually, all necrotic leaves shed off, leaving twigs die back resembling stag-horn-like appearance to the palm. Under severe xylem decay on lower parts of stem, stem bleeding symptoms can also be observed. A cross-sectional view of the diseased trunk appears as rotten tissue with irregular zones and cavities representing active growth of the white mycelium. Infected roots become friable and gives desiccated appearance internally. The cortical tissue discolours to brown and peel off easily, whereas the stele turns black in colour (Singh 1991). *Ganoderma* takes at least 2–3 years to kill mature palms, whereas the young palms are killed within a short span of 6–24 months. Fructification of basidiomata at the stem base or base of leaf, or infected root during rainy seasons is a critical sign in the in situ diagnosis of the disease (Paterson 2007). In advanced stages, infected trees fall over due to high winds, leaving bole tissue within the ground or some dead palm remains erected with hollow trunks (Fig. 9.1).

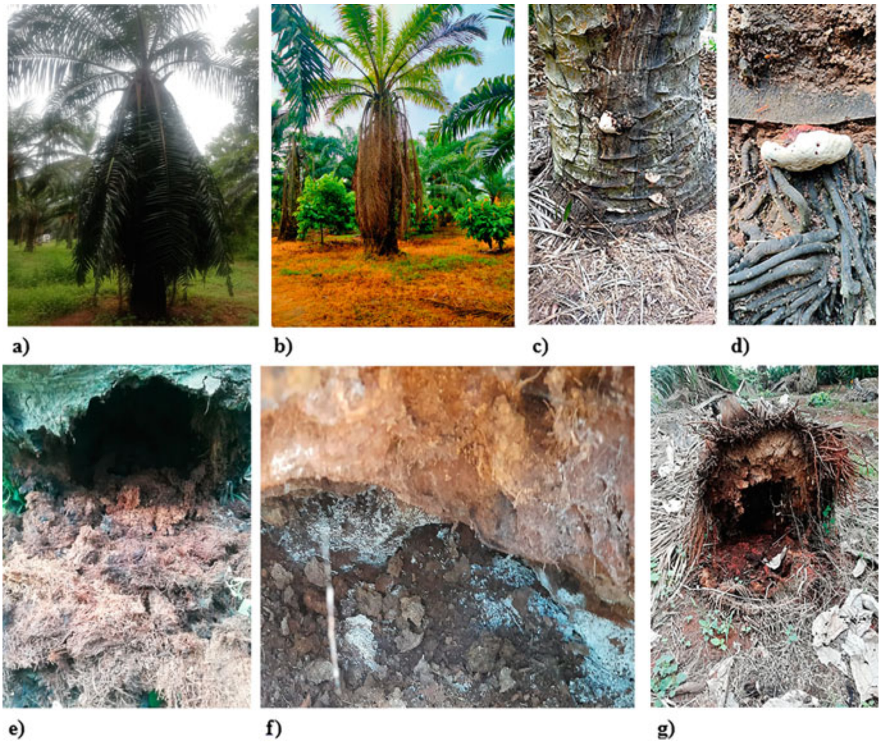

Fig. 9.1 Symptoms of basal stem rot: (**a**) snapping of old fronds at the petiole and drooping, (**b**) skirting and severe desiccation of lower leaves, (**c**) stem bleeding, (**d**) formation of basidiocarp, (**e**) internal disintegration of basal portion, (**f**) mycelial mat formation and (**g**) collapse of palm

9.2.7 Epidemiology and Favourable Conditions

Generally, wide occurrence of BSR had been reported in poorly managed and older plantations. However, in the recent past, the infection has been observed in palms regardless of plant growth stage, making it a major economic concern for oil palm growers. It is noteworthy that younger palms incited by more aggressive isolates of *Ganoderma* species when compared to older palms (Nur-Rashyeda et al. 2021). *Ganoderma* is a soil-borne pathogen and directly depends on various soil factors. Sandy soils or sandy loam soils of the coastal tracts and peat soil favour the disease development and spread. Soils having poor drainage facilities and prolonged water stagnation in rainy seasons also aggravate the disease (Latiffah and Ho 2005). Now, it is known to occur in all oil palm-cultivating soil types (Idris 1999; Khairudin and Tey 2008). Soil pH level is another important factor in determining the microbial activity and disease severity (Chong et al. 2017). High pH (Parthiban et al. 2016) as well as very low pH (Chong et al. 2017) do not favour growth of the fungus. An optimum pH range of 3.7–5.0 along with a temperature range of 27–30°C favour the fungal growth (Nawawi and Ho 1990). Interestingly, *Ganoderma* has the potential to manipulate the pH levels of the surrounding host tissue in accordance with its favourable range (Vylkova 2017). Thus, this ability of *Ganoderma* to survive and adapt in varying pH poses a serious imbalance in the soil micro-ecosystem and paves a way for other soil-borne infections. When coconut was a previous crop, early infection of *Ganoderma* was observed in 12–24 months old palm plantings (Singh 1991), and subsequently, disease progressed to 40–50% by the time they reached the age of 15 years. Similar observations were recorded for high incidence of BSR in oil palm when rubber (Ariffin et al. 1989) and pineapple were grown as the previous plantations (Ariffin et al. 1989; Rao 1990). Later, Khairudin (1993) proved the direct relationship among nature of previous crop, age of palm and BSR disease severity is inappropriate, and suggested that high disease inoculum that comes into contact with palm roots and subsequent congenial factors for disease development are more critical. Organic debris with high inoculum load left behind by previous natural forest ecosystem, infected stumps of previous trees, poor maintenance of the plantation, non-adoption of the recommended cultural operation, type of planting and poor management of irrigation and drainage are other possible reasons for severity of BSR disease.

9.2.8 Survival and Spread

Rees et al. (2009) suggested that *Ganoderma* infection cycle comprises initial biotrophic and subsequent necrotrophic phases. This is followed by the formation of melanized mycelium that results in the degradation of lignin and white rot symptoms by *G. boninense* (Adaskaveg et al. 1990). The formation of blacklines in the infected tissue transforms *Ganoderma* hyphae into thick-walled, swollen structures, which might play an important role in the perpetuation of inoculum in soil (Ariffin et al. 1989). The inoculum left by coconut (Abdullah 2000) and rubber (Flood et al. 2005) plantations, both of which contain *Ganoderma* as an endophyte, is the major primary source of inoculum for the BSR in oil palm.

The spread of BSR disease to the healthy palms occurs in two possible ways. The fungus, without a doubt, is a soil-borne pathogen but the air-borne basidiospores and secondary mycelium are speculated to be involved in its spread in the existing planation. However, there are no conclusive evidences on mode of initiation of the disease and spread of the disease in the plantations. The infection from leftover inoculum/tissue or diseased roots to healthy roots by contact is presumed to be main mode of spread of BSR disease in oil palm (Turner 1965; Flood et al. 2000). The infection from roots slowly spreads to trunk and is known to infect all kinds of tissues there onwards in advanced stages.

The idea of basidiospore's role in disease spread was put forth by Miller et al. (1995) and Ariffin et al. (1996), who reported the existence of different vegetative compatible groups and basidiomata within the same area of oil palm plantations, indicating different sources of primary inoculum. Basidiospores that can germinate and grow in non-living tissues may be the main sources for the disease dispersal (Pilotti et al. 2003; Sanderson 2005). It is recorded that 14,000 spores/min can be spread from 10 cm^2 of the fruiting body (Rees et al. 2012). The significance of basidiospores is overlooked when symptoms appear late after a long period of incubation. However, the different isolates and long infection process are the outcome of formation of dikaryotic strains from monokaryotic ones, which usually takes long time (Bridge and Utomo 2005). Basidiospores germinated by monokaryotic mycelium can colonize palm (Hasan and Flood 2003; Rees et al. 2007), but a dikaryotic heterokaryon, formed after anastomosis with a compatible mating type, is essential for potential infection and disease production. The possible little role of wind, rain and insect such as *Oryctes* beetle (Turner 1981) and larvae of the *Sufetula* spp. in dissemination of basidiospores (Genty et al. 1976) was also speculated.

9.2.9 Artificial Inoculation Methods

Due to the asymptomatic phase and slow progression of BSR in mature palms, screening cultivars resistant to BSR is an arduous task. Rubber wood blocks (RWB) method has been conventionally used as a standard method for artificial inoculation and proving Koch's postulates throughout the world. This method was also successfully deployed in roots of the seedlings (Sariah et al. 1994; Breton et al. 2006) as well as in germinated seeds (Rees et al. 2007). Alternatively, Chong et al. (2012b) achieved successful root infection with spraying of *Ganoderma* mycelial suspension onto seedling roots. However, artificial inoculation with basidiospores was not successful in initiating the disease in oil palm (Turner 1981; Ho and Nawawi 1986; Hasan et al. 2005; Cooper et al. 2011; Idris 2013). However, Lim et al. (1992) proved that spore contact through wounded tissue of fronds could cause infection. Despite its extensive usage, the RWB method is time-consuming and labour-intensive, requiring at least 6 months from preparation to disease evaluation (Chong et al. 2012a, b). Due to the long incubation period and difficulty in sterilizing RWB, contamination rate of other fungi is also quite high. Alternatively, Purnamasari et al. (2018) developed a rapid inoculation method using a root immersion technique for routinely infecting oil palm seedlings that can be used to develop resistant oil palm cultivars to *G. boninense*. In addition, Angel et al. (2021) made first report of a non-invasive tissue culture method in plantlets using a sawdust substrate for the establishment of *Ganoderma* infections.

9.3 Basal Stem Rot of Oil Palm: Detection and Diagnostic Tools

It is vital to monitor plant health and to detect infections at early stages in order to avoid disease spread and to approach appropriate management strategies. Oil palms must be assessed for disease severity and then categorized in terms of resistant and susceptible cultivars to apply pesticides cost-effectively. Early detection of BSR can extend the economic life of oil palms, although this is constrained by a number of variables. The delayed detection of BSR in oil palm is due to the fact that it is frequently misdiagnosed as *G. zonatum*, which is moderately pathogenic to oil palm, and *G. boninense* isolates have a high intraspecific diversity.

9.3.1 Manual Methods/Field Based

9.3.1.1 Based on Visual Symptoms

In the earlier days, the only way to diagnose disease was to look for symptomatic indicators in the field (Lelong et al. 2010). BSR is identified by the presence of unopened spear leaves of oil palm and basidiocarp at near soil level on the tree trunk or primary roots (Aswad et al. 2011). The most common symptom is mild to severe wilting of all leaves except the spear leaf. Other symptoms include general deterioration, reduced growth, and off-colour foliage. Symptoms of the unhealthy plant appear only after the plant becomes at least 7–16 years old (Abdullah et al. 2013).

9.3.2 Lab-Based Methods

9.3.2.1 Cultural Methods

***Ganoderma*-selective medium (GSM)**: *Ganoderma*-selective medium (GSM) developed by Ariffin and Idris (1993) could isolate the pathogen selectively from any portion of diseased tissue collected from the field, with or without surface sterilization, to assist various studies on *Ganoderma* in oil palm. Infected oil palm samples are obtained by drilling into a diseased stem at a height of about 5–10 cm above the soil surface to culture the samples on semi-selective media (Utomo and Niepold 2000).

9.3.3 Biochemical Methods

9.3.3.1 Ethylenediaminetetraacetic acid (EDTA)

It is a colorimetric technique using ethylenediaminetetraacetic acid (EDTA) to identify *Ganoderma* in oil palm (Natarajan et al. 1986; Ariffin et al. 1995; Utomo and Niepold 2000). The use of lab-based methods is limited due to their time-consuming and labour-intensive nature. These techniques may provide non-specific and inaccurate results and the necessity to bring all samples to laboratory makes them extremely unsuitable for large-scale field monitoring.

9.3.3.2 Isozyme Analysis

Isozyme analysis, such as pectinase zymograms, is used to identify palm-associated fungal isolates by producing band patterns (Bridge et al. 2000). By using polyacrylamide gel electrophoresis (PAGE) and cellulose acetate gel electrophoresis (CAGE), the isozymes of five Australian *Ganoderma* species were investigated. Pectic isozymes were found to be sufficient in distinguishing three laccate Australian species, *G. weberianum*, *Ganoderma* sp. and *G. cupreum*, but not the non-laccate *G. australe* or *G. incrassatum* (Smith and Sivasithamparam 2000).

9.3.3.3 Ergosterol Analysis

Ergosterol is a fungus-specific, primary sterol present in cell membrane of fungus, which has been found in *Ganoderma* species as well (Axelsson et al. 1995; Paterson 2006). It is absent in plants and other microbes; hence, it could be used as an effective biomarker for determining the amount of fungal biomass present (Choon et al. 2012). According to Chong et al. (2009), ergosterol is linked with the proliferation of *G. boninense* and disease severity in oil palm. The separation and characterization techniques of ergosterol from *G. boninense* mycelium are now commonly available. Thin liquid chromatography (TLC) and ultra performance liquid chromatography (UPLC) have been used to discover the ergosterol structure, which was then verified using gas chromatography combined with mass spectrometry (GC-MS) and nuclear magnetic resonance (NMR) analyses (Choon et al. 2012). The major limitation with this technique is that it cannot discriminate between the ergosterols produced by target *Ganoderma* or any other fungi present.

9.3.3.4 Altered Proteins

Infection of oil palms with *G. boninense* has been shown to alter the gene expression and protein concentrations, which can serve as an important biochemical marker in the detection process. Root proteins from both healthy and *G. boninense*-infected oil palm seedlings were examined using two-dimensional gel electrophoresis. After evaluation, proteins show a significant change in abundance under *G. boninense* infection and 21 proteins with changed abundance were discovered, which might be used as disease biomarkers (Al-Obaidi et al. 2014).

9.3.3.5 Metabolic Profiling

Plant metabolomics is a significant tool for system biology research. It has been utilized to determine the whole profile of measurable metabolites in a biological system. Plant metabolites play an essential role in host–pathogen interactions (Hu et al. 2019). Rozali et al. (2017) used a metabolomics approach to investigate the *G. boninense*-infected oil palm leaf using two-dimensional gas chromatography coupled with time-of-flight mass spectrometry (GCxGC-TOF-MS). They discovered that mannose, xylose, glucopyranose, myoinositol and hexadecanoic acid were higher in partially tolerant oil palm, whereas cadaverine and turanose were found to be more abundant in susceptible oil palm (OPLS-DA), demonstrating the differential pattern of metabolites under infected and healthy oil palms.

9.3.4 Molecular Methods

9.3.4.1 Nucleic Acid-Based Detection

Nucleic acid-based detection techniques are based on the sequence of DNA; hence, it is important to get sufficient sequencing data to use them.

1. **Molecular markers**: Molecular markers can be successfully used in biodiversity screening, phylogenetic analysis, evolutionary research (Meyer et al. 2010), geographical distribution and host–pathogen associations (Hong and Jung 2004). The following are some molecular markers used for the detection of *Ganoderma*:
   (a) Manganese-superoxide dismutase (antioxidant defence mechanism of the cell).
   (b) 18S rDNA (the small ribosomal subunit RNA: 16S in prokaryotes and 18S in eukaryotes). Analysis of nuclear 18S rDNA can be exploited to give molecular evidences for *Ganoderma*'s long-distance spread over the southern hemisphere (Moncalvo and Buchanan 2008). Furthermore, this technique has previously been used to demonstrate the diversity of wood-decaying fungi in India (Singh et al. 2013).
   (c) (Mitochondrial small subunit) mt SSU rDNA: It is recognized to be a locus that led to the division of *Ganoderma* into six monophyletic groups, indicating that complicated situations such as geographical region and pathogen–host connections, as well as phylogenetic linkages, must be examined (Hong and Jung 2004).
2. **PCR**: Polymerase chain reaction (PCR) techniques were used to amplify and detect certain DNA sequences of *G. boninense* in order to identify *Ganoderma* species (Moncalvo et al. 1995; Idris et al. 2003). To discover and identify the pathogen, researchers have used internal transcribed spacer (ITS) regions, polymerase chain reaction (PCR) amplification of ribosomal DNA, repetitive DNA polymorphism analysis and oligonucleotide hybridization to amplified ribosomal DNA (rDNA) spacers. The PCR detection approach can be used as a realistic screen for *Ganoderma* detection and identification. Two primers, PER44-123 and LR1 primer, were used to produce a 580 bp product solely for *Ganoderma* isolates and not for any other fungi (Idris et al. 2003). Similarly, Idris et al. (2010a) used multiplex polymerase chain reaction to distinguish *Ganoderma* isolates, although further tuning is required to produce convincing results.
3. **RFLP**: Using the restriction fragment length polymorphism (RFLP) approach on both highly conserved and variable ITS or rDNA sequences, it allows genetic variation investigations to be facilitated at the species level (Nusaibah et al. 2011a, b). Because ITS1 sequences have more divergent than ITS2 sequences (Moncalvo and Buchanan 2008), an experiment based on ITS1 sequences is advised. Restriction fragment length polymorphism has the benefits of combining highly conserved sequences in the ITS, 5.8S-ITS4 rDNA regions with variable sequences in the ITS regions at the species level, where the ITS has a high inter-specific variability but a very low intra-specific variability (Moritz et al. 2000).
4. **RAPD**: Random amplified polymorphic DNA (RAPD) can be modified for examining various *Ganoderma* spp. isolates. The use of RAPD-PCR and ITS sequence data yielded diverse results, with RAPD being shown to be better method for lower taxonomic level systematics that cannot be resolved using ITS sequence data. RAPD analysis indicated differences across *G. boninense* isolates even if they showed a greater degree of similarities (Zakaria et al. 2009).

Hence, RAPD can be effectively used in differentiating various *G. boninense* isolates with identical ITS sequences (Hseu et al. 1996), although it cannot provide accurate identification.

5. **AFLP**: A PCR-RFLP technique was created based on several sequential changes between pathogenic and non-pathogenic *Ganoderma* spp. Compared to RAPD and RFLP, AFLP (amplified fragment length polymorphism) is more accurate and less prone to contamination (Utomo et al. 2005).
6. **LAMP**: A nucleic acid-based gene amplification approach, known as loop-mediated isothermal amplification (LAMP), could be used to detect BSR in oil palms in the field or at remote places. It amplifies DNA under isothermal conditions with high specificity, rapidity and efficiency. The technology eliminates the necessity for the reaction to be carried out in a thermal cycler (Tomlinson and Boonham 2008). A battery-operated device has recently been developed to identify phytoplasma infections in coconut farms by combining a quick DNA extraction step of less than 2 min with the LAMP test (Dickinson 2015).
7. **DNA microarray**: DNA microarray is a detection method that makes use of the selectivity of DNA binding to complimentary sequence nucleic acids. The application of DNA oligonucleotide arrays for the sensitive and selective detection of *G. boninense* was discussed, along with the use of polymer pen lithography for the production of DNA oligonucleotide arrays. This technique can yield a clearly detectable result in the presence of the target DNA when utilized in a sandwich assay format using DNA-conjugated gold nanoparticles (Rani and Devaraj 2019).
8. **DNA biosensors**: Advances achieved in the field of molecular techniques have allowed for the introduction of a number of novel tools for the identification of BSR disease of oil palm. For the detection of *G. boninense*, an electrochemical-based DNA biosensor was devised and calibrated (Dutse et al. 2012, 2013). An interdigitated electrode (IDE)-based electrochemical biosensor for the early detection of *G. boninense* DNA was proposed by Thivina et al. (2021). The performance of IDE in combination with gold nanoparticles has been demonstrated with hybridization times ranging from 30 min to 2 h.
9. **Lateral flow assay**: LFMs (lateral flow microarrays) enable quick nucleic acid identification based on hybridization and utilization of a colorimetric signal that is clearly visible (Carter and Cary 2007). These arrays are made of a tiny lateral flow chromatography nitrocellulose membrane, hybridize rapidly with detection limits similar to microarrays, and can help laboratories save money by reducing the usage of expensive laboratory equipment. The system depends on the availability of robust and reliable host and pathogen biomarkers found using transcriptomic methods (Martinelli et al. 2015).

Although nucleic acid-based detection and molecular techniques offer an efficient and reliable tool for detection of *G. boninense*, they do suffer from few limitations such as being complex, expensive and time-consuming since these techniques necessitate the collection of samples for laboratory testing (Ishaq et al. 2014).

9.3.4.2 Protein-Based Detection Methods

1. **Immunoassay**: Immunoassays are based on the antigen–antibody interactions and were used for the detection of *Ganoderma* in culture media (Reddy and Ananthanarayanan 1984). To improve the accuracy of standard BSR disease detection methods, enzyme-linked immunosorbent assays (ELISA) and dot immuno-binding assays (DIBA) were developed (Rajendran et al. 2009). Antibodies, both monoclonal and polyclonal, have been utilized to detect pathogenic *Ganoderma* spp. The only problem is that other species of *Ganoderma* and saprophytic fungi often present on diseased oil palm roots and trunks, such as *Penicillium*, *Aspergillus* and *Trichoderma*, display cross-reactivity in the assays (Shamala et al. 2006; Idris and Rafidah 2008), but when compared to the culture-based approach GSM, ELISA-PAb demonstrates an 18% improvement in detection.

9.3.5 Remote-Based Methods

9.3.5.1 VOC Profiling

VOCs (volatile organic compounds) are biomolecules having low molecular with a high vapour pressure and low boiling point. Plants emit a variety of VOCs into their immediate environment that are important for growth, defence, communication and survival (Baldwin et al. 2006). Headspace solid-phase microextraction (HS-SPME) method paired with gas chromatography mass spectrometry (GC-MS) could detect VOCs generated from oil palm wood tissue infected by *G. boninense*. The approach was capable of sampling VOCs with good repeatability and a well-balanced VOC profile across chemical classes (Cheah et al. 2019).

1. **E-nose**: A platform for VOC profiling is the electronic nose (e-nose). These systems employ a variety of specialized metal oxide sensors, each of which is selective for specific VOC classes. Individual sensors provide an impedance response when volatiles are introduced into the e-nose, which is measured and presented concurrently (Gardner and Bartlett 1994; Laothawornkitkul et al. 2008). Artificial neural network (ANN) is another accurate method for distinguishing healthy oil palms from diseased ones. By using the ANN classification algorithm and multivariate statistical analysis approaches, hand-held e-nose sensors are created, which are capable of categorizing the samples into two groups, namely infected and non-infected based on the odour (Abdullah et al. 2014).

9.3.5.2 Tomography

Mohd Shu'ud and his colleagues sought to locate *Ganoderma* in oil palm stems using tomography scans (Shu'ud et al. 2007). Tomography involves several quantity measurements of ray transmission over the object cross section (Wang 2015). Four types of tomography used for detection are described below.

1. *Electrical Capacitance Volume Tomography* (ECVT) is a technology that uses the considerable difference in permittivity values between air, soil and water to quantify soil water content. The principle of ECVT is to rebuild a 3D image using a signal from a capacitance sensor, with any changes in phase causing non-linearity in the electric field distribution. The research was executed to see the potential of electrical impedance tomography technology in early detection of BSR-infected oil palm trees. It has the advantage of identifying unhealthy and asymptomatic palms, hence reducing inoculum in the fields. As a result, it is a valuable tool for detecting basal stem rot early and implementing a disease management strategy (Arango et al. 2016).
2. *GammaScorpion* is a portable computed tomography (CT) technology that employs gamma rays and a small amount of sealed radioactive source. Without cutting the tree, it can detect BSR non-invasively and also accurately estimate the extent and location of BSR damage. Radiation detectors capture gamma-ray transmission data from a variety of angles inside the image plane, which are then utilized to reconstruct meaningful cross-sectional images (Abdullah et al. 2013).
3. *X-ray computed tomography* (CT) is a minimally invasive structural imaging technique that permits three-dimensional (3-D) reconstruction of scanned structures (Khosrokhani et al. 2016). CT is now widely used in animal sciences, mostly for cancer research, bone architecture studies, angiogenesis and small animal in vivo imaging (Hamidon and Mukhlisin 2014).
4. *Sonic tomography*: Sonic tomography image is an internal construction of a solid object generated by recording the speed differences of sonar wave transmissions and it is used to detect the presence of lesions inside the stem (Khosrokhani et al. 2016).

9.3.5.3 Microfocus X-Ray Fluorescence (μXRF)

Microfocus X-ray fluorescence (XRF) sends a micro-sized X-ray beam to a specified target for element mapping and analysis as a dispersive energy source. It is based on the fact that *Ganoderma*-infected palms had a lower rate of inorganic elements than healthy palms (Khosrokhani et al. 2016). When compared to an electronic microscope, it does not necessitate sample degradation or coating. X-ray fluorescence has been proposed as a useful sensor for detecting plant diseases (Yokhin and Tisdale 1993).

9.3.5.4 Electrical Resistance

Differential electrical resistance has been used to determine plant vigour using electrical resistance (ER) (Paysen et al. 1992). Two devices, called Shigometer and Resistograph, can measure ER and are used to diagnose faults in wood (Johnstone et al. 2010; Aziz et al. 2019).

9.3.5.5 Hyperspectral Imaging

Hyperspectral imaging sensors (HRS) have a large number of continuous spectral bands to record spectral responses of materials over a long period of time. It represents plant cell structure condition, chlorophyll pigment status, plant structural water content and other useful information. High reflectance in the near infrared and low reflectivity in the visible regions of the electromagnetic spectrum indicate healthy vegetation covering. Visible–near infrared (VIS-NIR) hyperspectral imaging was also used to detect *G. boninense* infections in palm trees that were 5 months old and had no BSR symptoms. The uninoculated and inoculated seedlings were classified with 100% accuracy using this approach (Azmi et al. 2020).

9.3.5.6 Multispectral Imaging

Sensors that capture reflected or emitted energy from a given area or item in numerous discrete bands of the electromagnetic spectrum are known as multispectral remote sensing sensors (Jensen 2006). The reflectance of BSR-infected oil palms was reduced in the NIR and greater in the RGB electromagnetic areas (Santoso et al. 2011). For detection of BSR in oil palm plantations, ground-based (Bejo et al. 2015) and spaceborne multispectral sensors (Santoso et al. 2011) could be used.

9.3.5.7 Terrestrial Laser Scanning

Terrestrial laser scanning (TLS) is a relatively recent technique that has a wide range of applications. Precision agriculture has also used it to diagnose a variety of biophysical and structural plant factors. One of the TLS uses would be the calculation of the leaf area index (LAI) (Zheng et al. 2012).

Ground-based LiDAR (Light Detection and Ranging) is an active remote sensing imaging approach for plant phenotyping that employs laser light. Using point clouds data from the TLS, a study presented a unique BSR classification technique for oil palm canopy analysis. To get a full 3D image, the TLS scanner was installed at a height of 1 m, and according to statistical research, the best single measure for early detection of BSR disease was frond number with an average accuracy of 86.67% (Husin et al. 2020).

9.3.5.8 RGB Cameras

A visible camera sensor is an imager that captures visible light (400–700 nm) and transforms it to an electrical signal before organizing it to output images and video streams. Visible cameras use light wavelengths between 400 and 700 nm, which are the same wavelengths as the human eye sees. Using visible aerial photographs (RGB-aerial photographs), a study was conducted with the goal to determine the degree of severity of *G. boninense* infection in oil palm. The resulting images could distinguish the infection severity on each individual palm with an average accuracy value of 83% (Wiratmoko et al. 2020) (Table 9.1).

Table 9.1 Summary of different types of detection and diagnosis methods for *Ganoderma*

Method type	Particulars		References
Manual method	Visual symptoms		Lelong et al. (2010); Aswad et al. (2011); Abdullah et al. (2013)
Lab-based methods	Cultural methods	Ganoderma selective medium (GSM)	Utomo and Niepold (2000)
		Ethylenediaminetetraacetic acid (EDTA)	Ariffin et al. (1995); Utomo and Niepold (2000)
Biochemical methods	Isozyme analysis		Smith and Sivasithamparam (2000)
	Ergosterol analysis		Chong et al. (2009); Choon et al. (2012)
	Altered proteins		Al Obaidi et al. (2014)
	Metabolic profiling		Rozali et al. (2017); Hu et al. (2019)
Molecular methods	Nucleic acid-based detection	Molecular markers	Hong and Jung (2004); Meyer et al. (2010)
		PCR	Idris et al. (2003); Wong et al. (2012)
		RFLP	Moritz et al. (2000); Nusaibah et al. (2011a, b)
		RAPD	Zakaria et al. (2009)
		AFLP	Utomo et al. (2005)
		LAMP	Dickinson (2015)
		DNA microarray	Rani and Devaraj (2019)
		DNA biosensors	Dutse et al. (2013); Thivina et al. (2021)
		Lateral flow assay	Martinelli et al. (2015); Ishaq et al. (2014)
	Protein-based detection	Immunoassay	Shamala et al. (2006); Idris and Rafidah (2008); Rajendran et al. (2009)
Remote-based methods	VOC profiling	E-nose	Gardner and Bartlett (1994); Laothawornkitkul et al. (2008); Abdullah et al. (2014); Tan et al. (2021)
	Tomography	Electrical Capacitance Volume Tomography (ECVT)	Arango et al. (2016)
		Gamma-ray computed tomography	Abdullah et al. (2013)
		X-ray computed tomography (CT)	Khosrokhani et al. (2016)
		Sonic tomography	Khosrokhani et al. (2016)
	Microfocus X-ray fluorescence (μXRF)		Yokhin and Tisdale (1993); Khosrokhani et al. (2016)

(continued)

Table 9.1 (continued)

Method type	Particulars		References
	Electrical resistance		Johnstone et al. (2010); Aziz et al. (2019)
	Hyperspectral imaging		Azmi et al. (2020)
	Multispectral imaging		Jensen (2006); Santoso et al. (2011); Bejo et al. (2015)
	Terrestrial laser scanning	Ground-based LiDAR	Zheng et al. (2012); Husin et al. (2020)
	RGB cameras		Wiratmoko et al. (2020)

9.4 Basal Stem Rot of Oil Palm: Integrated Disease Management Strategies

Management of BSR under field conditions is a challenging task. Although there are different management strategies, none of them give satisfactory results for managing *Ganoderma*. Slow progressing nature of BSR leads to difficulty in detection at early stages of infection. Therefore, basal stem rot disease is often detected at advanced stages and by then the infected trees may not be able to respond to any treatment given (Sapak et al. 2008). Moreover, inefficient performance of existing management strategies is attributed to the systemic infection, soil-borne nature, production of resting structures, melanized mycelium, basidiospores and pseudo-sclerotia and the ability to penetrate deeply inside palm (Bivi et al. 2010). Unfortunately, the resistant sources for combating the disease are also limited (Chong et al. 2012a, b). The curative methods are not economically feasible to save the infected trees; hence, the current management practices are aiming at reducing the incidence of BSR and delaying the progression of *G. boninense* (Azadeh et al. 2010).

9.4.1 Cultural Practices

Even if it is not possible to manage a field without pathogens (Sanderson et al. 2000), yet, a good management system by maintaining healthy stands and further prevention of various pathogen can reduce the hostile effects of a disease. Cultural practices are effective and economical for managing *G. boninense* in oil palm. These measures normally constitute eradication and reduction of the pathogen inoculums to prevent further disease spread (Khairudin 1990; Susanto et al. 2005).

9.4.1.1 Preventing the Entry of Pathogens

The entry of pathogens can be prevented easily by carefully accomplishing the harvesting process, preventing wounds in trees and improving treatment. Regular practice of paint or dressing should be followed to treat large wounds in oil palm trees.

9.4.1.2 Clean Clearing/Sanitation

Clean clearing is the most important recommendation for reducing the incidence and spread of *Ganoderma* in both existing and replanted oil palm plantations (Turner 1965; Singh 1990; Flood et al. 2000). The main goal is to clear the old-aged trees before they reach extreme susceptibility and thereby eradicate all possible inoculum that remain within an infected palm area. It is commonly implemented in two situations, from where it is apparent and at the replanting stage. Gurmit (1991) had studied that this technique gave lower disease incidence of 14% in comparison to other replanting techniques. Different practices such as ploughing, harrowing, trenching and burning are employed in this method to lower BSR incidence (Flood et al. 2000; Rees et al. 2009; Hushiarian et al. 2013). In disease prone areas of oil palm, it is often recommended that before planting of new seedlings, one round of harrowing and two rounds of ploughing should be done to finely chop the leftover roots (Flood et al. 2000). Idris et al. (2004a) described that large hole of 2 m × 2 m × 1 m of depth can be dug out for sanitation operation. Infected materials are removed, cut into pieces and left for decaying. It is generally practiced at the time of replantation. Researches show that trials up to 14–15 years sanitation, if done properly, reduced the BSR incidence or if done poorly, the inoculum helped to increase the incidence (Chung 2011). In addition to this, Khairudin (1990) showed that at different levels of BSR points in which seedlings were bait, 93% of seedlings grown around diseased stumps left in the field with 0.3 m distance, which became infected within a period of 18 months. However, open burning is prohibited in many palm oil growing countries, including Malaysia, under Air Regulation Act of 1978, which deals with the issues of air pollution. These regulatory frameworks, however, suffer from weak execution. Although it is exorbitantly expensive, this approach is practiced in many palm producing countries.

9.4.1.3 Windrows

It is a technique in which excised root tissue and fallen palm trunks are laid beside the old rows. Diseased palms are often pulverized, chipped and stacked to enhance the process of natural decomposition. This method demands less efforts than clean clearing and has been found capable in reducing losses in the successive oil palm plantation. Hashim (1991) conducted a comparative study and find out clean clearing as the most efficient way in lowering BSR incidence. Reduction in disease incidence from 27.3% in the preceding stand to 14% in the replanted stand after next 15 years was observed in plantations, followed by windrowed treatment (27.3–17.6%). This is due to the efficiency of windrowed materials to cope up with the problems of potential source of inoculum (Flood et al. 2000).

9.4.1.4 Soil Modification Practices

It is an economic practice, which is followed in almost all oil palm producing countries. It commonly involves collection of healthy soil from the adjacent areas and creation of a heap of about 75 cm height to prevent the toppling of infected palm trunk by wind. Ho and Khairuddin (1997) and George et al. (2000) in their studies found comparative economic advantage of soil mounding in controlling BSR disease. However, this method could only extend the economic life of affected palm. It could not even stop the spread of *Ganoderma*.

9.4.1.5 Surgery

In this method, excision of infected tissue is done with the help of a black-hoe blade (Singh 1991) or hand-held chisel in order to eradicate the primary source of inoculum, i.e., basidiocarp (Turner 1981). Fungicides and paints are the commonly used protectants that prevent further decay of the infected plants. Hasan and Turner (1994) showed through their study that surgery enhanced the survival and yields in case of palms. However, it is less successful due to delay in detection or an extended underground lesion that includes infectious root masses. Furthermore, surgery requires more rigorous efforts and repetition, as the revival of the infection is possible if lesions are not removed completely. Studies by Panchal and Bridge (2005) showed that if fresh cut is sealed, it would prevent the spores from coming in contact with the wound region. In addition, Ho and Khairuddin (1997) reported that surgery followed by soil mounding could decrease the loss of palm from 34% to 2% in 2 years. Surgery would extend the lifespan of the infected palms up to 2–3 years (Priwiratama et al. 2020).

9.4.1.6 Isolation Trenches

It is a common practice that is used to prevent contact between palms by digging trenches (Hasan and Turner 1998; Chung 2011) and has been found to be a more successful technique in delaying BSR occurrence for about 14 years. Trenches are created in accordance with the size and age of the trees. Generally, the diseased palm is isolated with 0.5 m wide and 1 m deep trench (Lim and Udin 2010). It is found to be a better method than clean clearing and windrowing. Sometimes drenching of chemicals in trenches is also practiced for enhancing effectiveness. However, if it is not maintained properly, or the depth of trench is not enough, it will not prevent the spread of infectious roots.

9.4.1.7 Fallowing

It is a process in which the land is left fallow for a certain period in order to reduce the disease incidence in the subsequent plantation crop. Studies were conducted by Virdiana et al. (2010) to assess the optimum time period for fallowing and the effect of other potential crop to create a balance in the environment.

9.4.1.8 Planting Legume Cover Crops (LCC)

Legumes are widely grown as cover crops in oil palm plantation areas as they have potential to fix the atmospheric nitrogen and their decomposition usually adds nitrogen for the palm. It also helps to control soil erosion and weeds (Chung 2011).

9.4.2 Nutritional Management

Nutritional status of plants plays a crucial role in disease resistance. Considering the fact, optimum nutrient uptake by the plants is essential to avoid nutritional deficiency. Mineral fertilizers have a major impact on overall plant health, and in many circumstances, they are the foremost line of defence activators against plant pest and diseases. It can also activate the disease resistance through induced defence responses including the production of different types of metabolites, toxins and lignification (Engelhard 1989). Supplementation of soil with nutrients is found to influence the susceptibility of plants towards various fungal diseases (Veresoglou et al. 2013). A balanced mineral nutrients application in the form of fertilizers can improve the plants' disease resistance in most of the cases (Usherwood 1980). In this regard, manipulation of nutrient uptake is a key approach, as all essential plant nutrients have influence on the plant health and their susceptibility to diseases (Agrios 2005). Therefore, apart from fungicide treatments, enhanced nutritional programmes (ENPs)—by employing mineral nutrients and plant hormones that are applied at seedling stage—make plants resistant to BSR disease after transplanting them in the field.

9.4.2.1 Major Nutrients

Experimental studies using macro- and microelements such as nitrogen (N), phosphorus (P) and potassium (K) have resulted in positive changes to disease status and productivity of plant, but the actual role of fertilizers in controlling BSR disease is still uncertain (Singh 1990; Chung 2011). Lately, Hasmah Mohidin (personal communication) observed that seedlings raised on peat soil in nursery showed better vegetative growth and reduction in BSR incidence when applied with a combination of primary macronutrients such as N, P_2O_5 and high K_2O at 17.37 g, 17.37 g and 41.34 g per plant, respectively. In addition to this, activities of defence-related enzymes, including chitinase, β-1,3-glucanase, PAL and POX, were found to be enhanced in the oil palm roots, thus confirming the role of macronutrients in inducing resistance against *G. boninense*. In addition, potassium modifies plant metabolism and thus limits the invasion of pathogen by inducing thicker outer wall formation in epidermal cells (Dordas 2008).

9.4.2.2 Micronutrients

Micronutrients are less considered in BSR management strategies even if their involvement in plant defence activation is well known. Micronutrients such as boron (Stangoulis and Graham 2007), copper (Evans et al. 2007) and manganese (Thompson and Huber 2007) are shown to assist in controlling many plant diseases and they are closely associated with phenol synthesis in plants and have major impact on plant susceptibility to diseases (Graham 1983).

Earlier reports revealed that application of calcium nitrate was adopted to suppress the symptoms of BSR on oil palm (Sariah and Zakaria 2000). In addition, it was noticed that supplementing soil with calcium nitrate could enhance the population of *Trichoderma harzianum* and other antagonistic fungal population. These discoveries are in agreement with the findings of Nur Sabrina et al. (2012). Boron (B), copper (Cu) and manganese (Mn) were shown to reduce the disease incidence and severity in seedlings of oil palm inoculated with *G. boninense* (Bivi et al. 2014). Under glass house conditions, oil palm seedlings exhibited increased resistance against *Ganoderma* when applied with calcium (Ca) and copper (Cu) in combination. In studies conducted by Tengoua et al. (2014), double combination treatments, namely B + Mn and Cu + Mn, alleviated the disease severity in oil palm seedlings under nursery condition with reduction of 16% and 24%, respectively.

9.4.2.3 Beneficial Elements

Studies conducted by Najihah et al. (2015) revealed that the use of calcium silicate, potassium silicate, sodium silicate, silicon oxide and sodium meta-silicate reduced the severity of BSR in oil palm seedlings. Endodermal deposition of Si enhanced the cellular features by forming a mechanical barrier, hence restricting movement of pathogen into the stems. Nursery study using beneficial nutrient proved that supplementation of 1200 mg/L of SiO_2 contributed to highest BSR reduction of 53%, with less number of primary roots and bulb tissue lesions infected with the fungus. Salicylic acid (SA) is a crucial plant hormone (Raskin 1992) that is well known for activating host defence responses during pathogen infection and abiotic stress (Gautam and Singh 2009; Pieterse et al. 2009) and is an essential factor in the systemic acquired resistance (Nie 2006). Bivi et al. (2014) demonstrated that application of a combination of calcium chloride, copper-EDTA and salicylic acid (SA) has reduced the disease symptoms in BSR-infected palms. EDTA has potential to inhibit ligninolytic enzymes produced by *G. boninense* (Siddiqui et al. 2019). Calcium/copper/SA supplementation on a continuous basis can be a key approach to improve resistance in oil palm (Bivi et al. 2016). An apparent increase in lignin content was observed, which explained how resistance was induced. A new fertilizer technology, GanoCare®, that is formulated by combining powdered empty fruit bunches (EFB) and beneficial elements, was found to be effective in preventing BSR infection in oil palm (Rebitanim et al. 2020).

9.4.2.4 Soil Amendments

Soil amendments application is one of the strategies for managing *Ganoderma* in palms. Applying decomposed green manure or farmyard manure at 50 kg/palm/year in combination with 5 kg of neem cake can check the disease spread in the field (Prakasam et al. 1997). In a trial conducted, it is shown that phosphobacteria (200 g peat inoculum + 10 kg of farmyard manure) could cause significant reduction in BSR disease in coconut (Bhaskaran et al. 1994). In another study, Bhaskaran (2000) showed that supplementation of phosphobacteria (200 g in 10 kg of farm yard manure/tree/year) evidently lessened severity of the disease in coconut compared to treatments with *Azospirillum* or the VAM fungus, *Gigaspora calospora*.

9.4.3 Management of *Ganoderma* Using Chemical Fungicides

The use of chemicals tends to be a well-founded strategy for the oil palm plantations. Chemical method of management is shown to be efficient only if applied judicially. The use of fungicides requires careful consideration, and field level evaluation of the results is necessary. This method combined with soil mounding shown to be effective and the benefit-costs need reassessment.

A number of fungicides have detrimental effect on the growth of *Ganoderma*; systemic fungicides, especially those in the triazole group, were noted to be highly effective as they could penetrate and spread to different parts of the plant (Khairudin 1990; Gurmit 1991). Azoxystrobin (EC50 of 0.53 g/mL), carbendazim (EC50 of 0.026 g/mL), hexaconazole (EC50 of 0.026 g/mL) and pyraclostrobin (EC50 of 0.25 g/mL) are among the fungicides that have exhibited inhibition of *G. boninense* (in vitro) with low EC50 values (Idris et al. 2010a, b; Said et al. 2019). It was recorded that 74.4% of the hexaconazole-treated oil palms could stand alive with the production of fruit bunches up to 5 more years. In contrast, none of the untreated palms could survive the disease (Idris et al. 2010b).

9.4.3.1 Delivery Systems

Control of BSR by chemical method can be achieved only if properly applied. Application of chemical fungicides for control of soil-borne pathogens constitutes soil drenching, pressurized trunk injection or combination of both. Similarly, trunk injection method was also assessed in the field by use of systemic fungicides with the help of a pressure injector (Idris et al. 2010a). According to a study conducted by the Malaysian Palm Oil Board (MPOB), it was demonstrated that the application of hexaconazole onto infected standing palms using a trunk injector restricted the spread of *Ganoderma* infection within the palm trunk (Idris et al. 2004b; Mohammed et al. 2014). It was also recorded that cyproconazole was capable to hold up 97% of the standing palms infected with *Ganoderma*. In another field study, trunk injection treatment with carboxin–quintozene mixture was found efficient by extending the lives of about 91% of the palms by 69 months after treatment (George et al. 1996). These findings manifest promising results by confirming the restriction of the disease progression in affected palms and thus prolonging the productive life of palms.

Eradication of wood-decay fungi of tree crops using chemicals, which are normally used for soil fumigation, has shown success in field studies. Dazomet (a soil fumigant), which releases methyl isothiocyanate, was shown to move within the stem tissues of palm and thus could subsequently limit the growth of *G. boninense*. Furthermore, prophylactic spraying with dazomet was successful in eradicating the pathogen inoculum in the infected stumps, hence limiting the spread of the fungus within plantations (Idris and Maizatul 2012).

Nevertheless, the development of alternative means to manage diseases is the need of current scenario as there is an increasing concern about the ecological issues and high cost of pesticides. However, employing chemical control measures delay the spread of the disease. Additionally, inhibition of defence mechanisms in plants could be affected by the fungicidal action (Oostendorp et al. 2001).

9.4.3.2 Chitosan-Based Nano Fungicides

Recently, chitosan-based nano-fungicides have emerged as a remarkable breakthrough in enhancing the efficacy of fungicides. Such nano-delivery systems put forward controlled release characters with high potency and efficacy in delivering the fungicides at the target, compared to their counterparts (Duhan et al. 2017). It also aims to enhance uptake and reduce volatilization as well as toxicity level, thus keeping down their adverse effect on the environment (Worrall et al. 2018). In addition, chitosan is non-toxic and compatible with other bio-agents and also known for its potential to check the spread of pathogens and enhance the plant defence responses (Maluin and Hussein 2020). Chitosan-based encapsulated formulations of hexaconazole and/or dazomet can be encapsulated into the chitosan nanoparticles and it would act as an efficient antifungal agent for the control of *Ganoderma*. This new nano-formulation comprising chitosan (carrier) and hexaconazole (active ingredient) can be a better option for the management of BSR, and the results suggested the ability of these nanoparticles to persist in the crop longer than the conventional formulations. As reported in previous works, the release period of chitosan–hexaconazole nanoparticles was six times more than that of their counterpart (Maluin et al. 2019). The findings also indicated the movement of the nanoparticles in the internal parts of the stem and leaf, rather than being mobilized to the fruit. It was noticed that the crude palm oil and crude palm kernel oil were devoid of residue. Additionally, increased accumulation of the active ingredient in stem and leaf after treatment with the hexaconazole nanoparticles is ideal for enhanced bioavailability of the product for the prevention of *G. boninense*. Thus, the chitosan–hexaconazole nanoparticles offer a better platform for the effective control of BSR disease as the disease can be managed over a long period without any residue in the palm oil matrices. This is the ideal property for furnishing nano-based fungicides for basal stem rot disease management in oil palm (Maluin et al. 2019).

9.4.4 Biological Control of *Ganoderma* in Oil Palm

As the conventional control measures such as chemical, cultural and mechanical practices are found to be unsatisfactory in field conditions (Susanto et al. 2005), there is a need to switch on to alternate strategies for managing the disease to extend the productive life of the palms in the field, and it is mainly focused on biocontrol agents (BCAs). Biological control is generally the prime choice of prevention and control in the integrated disease management approach. In this era of sustainable agriculture, biological control with the use of natural enemies is a promising green tool as compared to synthetics. The biological control and growth promotion activities of these microbes could offer sustaining economic benefits for the palm oil industry. Development and exploitation of biocontrol agents mainly focus on four pivotal points: (1) biocontrol properties of the microbial agents, (2) evaluation of microbe–

plant interactions, (3) assessment of ecological and beneficial effects of the agent in the rhizosphere and (4) formulation and proper delivery of the microbial agents (Herrmann and Lesueur 2013; Miransari 2013). Studies conducted in plantation seedlings with microbial antagonists have shown remarkable results in managing BSR, but large-scale plantation-based evaluation is needed to validate the success of using BCA for the long-term control of *Ganoderma* in field condition.

A list of BCAs studied for the management of *Ganoderma* in oil palm is shown in Table 9.2. Growth promotional activities of these microbes, including enhanced root and plant development, induced resistance and solubilization of inorganic nutrients, would assist in the control of the disease (Susanto et al. 2005).

9.4.4.1 Fungal and Bacterial Antagonists

Ascomycetes

Trichoderma spp. are the commonly utilized bio-agents to combat a wide range of plant pathogenic organism, especially soil-borne pathogens. This beneficial free-living fungus has antagonistic effects on many phytopathogens and can inhibit growth and survival of pathogens by employing multiple mechanisms including mycoparasitism, antibiosis, hydrolytic enzyme production, competition and plant resistance induction (Nusaibah and Musa 2019).

Biocontrol of *G. boninense* using *Trichoderma* spp. has recorded high effectiveness and potency in controlling the pathogen in both green house and field conditions (Ilias 2000; Sariah et al. 2005; Susanto et al. 2005). Similarly, it is found to induce plant defence activation in oil palm by enhancing the production of fungal cell wall-degrading enzymes such as chitinases and glucanases (Naher et al. 2011). These two enzymes have synergistic effect on each other and adversely affect the hyphal growth of filamentous fungi (Latgé 2007). Similar defence responses have previously reported in *Ganoderma* spp. infected tissues (Siswanto and Darmono 1998). Investigations on control of *G. boninense* using *T. harzianum* in green house showed that the *T. harzianum*-treated oil palm seedlings had reduced disease incidence compared to the control (Naher et al. 2012; Izzati and Abdullah 2008; Susanto et al. 2005). *T. harzianum* solely or mixed with dried palm oil mill effluent, calcium nitrate and mycorrhizal preparation were tried out in a nursery and have showed a notable effect on the seedlings (Sariah and Zakaria 2000). Furthermore, disease suppression was reported in seedlings of oil palm treated with *T. harzianum* isolate FA1132 conidial suspension (Izzati and Abdullah 2008). This isolate showed notable antagonistic activity against *G. boninense* in trials conducted in plant house. It was also suggested that *T. harzianum* was a more efficient biocontrol agent against *G. boninense* than other species such as *T. longibrachiatum* and *T. virens* (Ilias 2000).

In addition to *Trichoderma*, many other ascomycetous fungus have been found to be parasitic on *Ganoderma* spp. From oil palm, numerous mycoparasitic ascomycetous fungi were isolated, which are capable of sporulating asexually and/or sexually on *G. boninense* (Goh et al. 2015). Out of these, *Scytalidium parasiticum* was shown to be a necrotrophic parasite on *G. boninense* and could be a possible biocontrol agent against this basidiomycetous pathogenic fungi. In the in vitro studies,

Table 9.2 Potential biocontrol agents for the control of BSR in oil palm

Bio-agent	Effects	Reference
1. *Fungus*		
Hendersonia isolate (GanoEF1)	Reduced incidence of BSR disease in nursery seedlings after 6 months of treatment	Nurrashyeda et al. (2018)
Scytalidium parasiticum	Suppressed fruiting body regeneration of *G. boninense* Reduced disease incidence and severity in nursery trials Improved seedling growth	Goh et al. (2016)
Trichoderma sp.	Growth inhibition of *G. boninense* in laboratory trials and plant growth promoting activities Delay of infection at early stages Enhance the defence response in oil palm by inducing the fungal cell wall-degrading enzymes production, including chitinases and glucanases	Hasan and Turner (1998); Ilias (2000); Sariah et al. (2005); Susanto et al. (2005) Naher et al. (2011)
Trichoderma sp. + dried palm oil mill effluent, calcium nitrate and mycorrhiza	Notable effect on disease suppression in oil palm seedlings	Sariah and Zakaria (2000)
Soil mounding + *T. harzianum*	Extended life of infected palm by 3 years in field trials	Priwiratama and Susanto (2014)
Hymenomycetes (*Pycnoporus sanguineus*, *Trametes lactinea* and *Grammothele fuligo*)	Growth inhibition of *G. boninense* under in vitro screening	Naidu et al. (2018)
Talaromyces apiculatus and *Clonostachys rosea*	Disease reduction by 4.9–60% in treated seedlings Plant growth promoting traits	Goh et al. (2020)
Scytalidium parasiticum	Reduced fruiting body regeneration and inhibited the mycelial survival of *G. boninense*. In nursery trials, reduced disease severity of *Ganoderma*	Goh et al. (2016)
2. *Bacteria*		
Burkholderia sp.	Decreased disease incidence in seed-treated plants up to 3 months in nursery	Buana et al. (2014)
Burkholderia cepacia, *Pseudomonas aeruginosa* and *Serratia marcescens*	Inhibition of *G. boninense* in nursery trials	Sapak et al. (2008); Azadeh et al. (2010)
Bacillus sp. and *Enterobacter* sp.	Reduced incidence of disease in seedlings Growth promotional activity	Suryanto et al. (2012)
3. *Actinomycetes*		
Streptomyces spp. and *Nocardiopsis* sp.	Reduced disease incidence and severity by 81.6% in seedlings Reduced severity of foliar symptoms in nursery trials	Tan et al. 2002; Ting et al. 2014; Sujarit et al. (2020)

S. parasiticum remarkably reduced fruiting body regeneration and inhibited the mycelial survival of *G. boninense*. In addition, nursery trials suggested that *S. parasiticum* was non-pathogenic on seedlings of oil palm and it could also limit infection by *Ganoderma* and thus the disease severity (Goh et al. 2016).

Basidiomycetes

Attempts to control stump infection using basidiomycetes have been made in forest trees (Roy et al. 2003). No such investigation has been done in BSR-affected oil palm. Non-pathogenic hymenomycetes, naturally found on oil palm trunk, were tested for their antagonistic activity against *Ganoderma*. Out of 25 fungi isolated, 8 appeared to be antagonists against the pathogen. Three potential antagonists including *Grammothele fuligo*, *Pycnoporus sanguineus* and *Trametes lactinea* restricted the mycelial growth of *G. boninense* with higher PIRG (percentage inhibition of radial mycelial growth) in dual culture (Naidu et al. 2018). Nonetheless, further studies are required to validate their potential use for the management of infection of *G. boninense* in field.

Actinomycetes

The actinomycetes isolated from mangrove area, including *Streptomyces* and *Micromonospora* sp., were antagonistic to *G. boninense* in oil palm, and *Streptomyces* genus has high inhibitory effect on *G. boninense* in vitro by hyphal lysis and antibiosis (Tan et al. 2002). Non-pathogenic actinomycetes such as *Nocardiopsis* sp. and *Streptomyces* spp. isolated from empty fruit bunches of oil palm were also identified as antagonists against *G. boninense* (Ting et al. 2014). Anti-*Ganoderma* activity of three *Streptomyces* species such as *S. palmae*, *S. sioyaensis* and *S. noursei* was proved in vitro, and *S. palmae* CMU-AB204^{T} isolate was found as effective inoculant, which reduced the severity of foliar symptoms and showed lowest percentage disease severity. Additionally, the treated seedlings marked highest plant vigour in terms of biomass and stem diameter (Sujarit et al. 2020). Thus, *S. palmae* could be an assuring biocontrol candidate to protect the palm trees from BSR.

9.4.4.2 Fungal and Bacterial Endophytes

Nowadays, antagonistic endophytes are drawing attention as a promising bio-agent for plant disease control, resulting in replacement of harmful chemicals (Kobayashi and Palumbo 2000). Endophytes live asymptomatically within plants, bringing with them additional benefits such as improved crop development and health, as well as the ability to generate plant resistance through the secretion of secondary compounds and antibiotics (Zhao et al. 2015). As they colonize and move within the plant, they are suitable for the holistic control of diseases like BSR and are usually unaffected by environmental changes. Apart from *Trichoderma* spp., microbes such as *Gliocladium viridae*, *Bacillus* spp. (Susanto et al. 2005), *Burkholderia cepacia* and *Pseudomonas aeruginosa* (Sapak et al. 2008) were also studied as a promising biocontrol agent for BSR management. Shamala (2013) made the first record of endophytic *Trichoderma* isolated from oil palm with biocontrol activity towards

G. boninense. In an attempt to evaluate their competency for managing BSR disease, four endophytic fungi—a Dothidiomycetes species, *Lasiodiplodia venezuelensis*, *T. longibrachiatum*, and *T. harzianum*—were investigated. It was hypothesised that these fungi could stimulate the production of pathogenesis-related protein in the palm (Esyanti et al. 2017).

Some of the gram-negative and gram-positive endophytic bacteria can be a potential biocontrol agent against *G. boninense* pathogen of oil palm. Bacteria such as *Bacillus* spp., *Burkholderia cepacia*, *Pseudomonas aeruginosa* and *Serratia marcescens* have been recorded as possible bio-agents to control BSR disease (Zaiton et al. 2006; Bivi et al. 2010). Chitinolytic bacteria including *Bacillus* sp. and *Enterobacter* sp. could cause hyphal abnormalities in *Ganoderma* in vitro and are capable of minimizing the disease incidence in nursery seedlings. Endophytic *Bacillus subtilis* was isolated from oil palm, and it was revealed that these antagonistic isolates would limit the growth of *Ganoderma* with an inhibition of 8.13–49.38% (Nasahi et al. 2016). The effectiveness of induction of resistance by *B. subtilis* has not been evaluated well in oil palm. Other species including *B. cepacia* and *B. amyloliquefaciens* were also shown to restrict the mycelial growth of *G. boninense* in vitro (Azadeh et al. 2010; Azizah et al. 2015). *P. aeruginosa* has been reported to enhance the growth of plants by producing various growth promoting hormones such as auxin and cytokinin and also other volatile compounds including ethylene, acetonin and 2,3-butanediol (Lambrecht et al. 2000; Persello-Cartieaux et al. 2003; Ryu et al. 2003). *P. aeruginosa* was found to improve the root mass and seedling growth and was effective in controlling *G. boninense* in comparison to *B. cepacia* (Zaiton et al. 2008). Furthermore, Ramli et al. (2016) reported the effectiveness of *P. aeruginosa* in reducing the disease incidence and foliar symptom severity in treated oil palm seedlings, compared to *P. fluorescence* and *B. cepacia*.

9.4.4.3 Arbuscular Mycorrhizal Fungi (AMF)

In recent times, the usage of endophytic arbuscular mycorrhizal fungi has accelerated in the field of agriculture in an attempt to enhance yield and plant health with further advantage of restricted use of pesticides and fertilizers (Barea et al. 2002; Gianinazzi et al. 2010). AMF are symbiotic fungi of mycorrhizal origin which carry out essential ecological functions such as augment plant nutrients uptake, enhancement of plant tolerance to environmental stress and improvement of soil structure (Smith and Read 1997). AMF are found to be associated with oil palm roots and may hinder *G. boninense* (Sundram et al. 2015). Azizah (2003) recorded that oil palm seedlings treated with mycorrhiza could combat the infection by *Ganoderma*. Evaluations in nursery trials proved the efficacy of the arbuscular mycorrhizal fungi in suppression of the *Ganoderma* incidence (Priwiratama and Susanto 2014). Application of the mycorrhizal fungus, *Glomus intraradices*, restricted the disease progression of BSR, and a combination of this fungus with endophytic bacteria further improved the biocontrol potency (Sundram et al. 2015). Moreover, treatment with the mycorrhizal fungi was effective in prolonging the incubation period of the pathogen, and mycorrhizal fungal inoculants could significantly enhance the growth of the seedlings of oil palm artificially inoculated with *Ganoderma*, in terms of dry and fresh weight of seedling and leaf number (Widiastuti 2011). Thus, the use of AMF can be a promising approach for the management of BSR disease, but there is a necessity for further large-scale trials and review of their field efficacy.

9.4.4.4 Delivery Mechanism

A possible approach to deliver the biocontrol agents like endophytes is the seed enrichment. The use of microbes such as *Trichoderma* spp. and AMF is regarded as a standard operational procedure (SOP) in the production of seedlings of oil palm especially in *Ganoderma* endemic area. The dose of these microbial agents to be applied can vary based on the developmental stage of the plant. Thus, seed coating of these biocontrol agents can be a solution for the efficient transportation and delivery in the field. Even though seed coating and enrichment is a general approach in horticultural seeds, this method has not been practiced much in oil palm due to the susceptibility of the seeds to mechanical damage. The delivery of the consortium of AMF, *T. asperellum* and *E. sacchari*, followed by Carboxymethyl cellulose (CMC) coating, is likely to improve the seedling vigour of oil pam in pre-nursery stage (Jawak et al. 2018).

9.4.4.5 Challenges in Field Level Testing of Biocontrol Agents

- The use of biocontrol agent (BCA) in field conditions often faces difficulty because of susceptibility of microbes to combative environmental conditions. Various obstacles such as alteration in the rhizosphere, inability to colonize in different soil conditions, interaction with non-target organisms, genetic diversity of the pathogen, the presence of other microbes and vulnerability to climate change lead to poor performance of BCAs in field (Meyer and Roberts 2002). The use of bio-agents for field applications can be effortful due to (a) difficulty in handling and transport, (b) poor storage and (c) intricate application requisite (Vidhyasekaran et al. 1997). In addition, some fungal bio-agents produce mycotoxins that are harmful to the environment and also contaminate the economical product (palm oil). Thus, only few BCAs could be commercialized due to the instability of many of the microbes in field.
- Although the potency of BCAs for the management of BSR has proven, most of the studies are nursery-based trial without field assessments, which is a time-taking process. The effectiveness of different biocontrol agents has been investigated in nursery (Soepena et al. 2000; Izzati and Abdullah 2008; Sapak et al. 2008; Sundram et al. 2008; Suryanto et al. 2012), but a regular field evaluation needs at least 3–5 years monitoring to obtain relevant results. Hence, establishment of a shorter time scale-based effective system is required for the appraisal of biocontrol agents at the field level. Flood et al. (2000) exploited a bait seedling trial to assess the implication of inoculum intensity of *G. boninense*, in which the bait seedlings were planted adjacently to the differing inoculum intensities of the pathogen for determining the significance of removal of infected tissues while replanting. This technique comes up with benefits such as possibility of field assessment and shorter observation time.

9.4.4.6 The Concept of Biocontrol Consortium

Most of the investigations on biocontrol agents for the plant health management are focused on the application of a solitary BCA against a single pathogen. Yet, the use of a single BCA may not be efficient in all types of soils, as optimum conditions for growth and multiplication of each microbe vary. Combining multiple microbial agents has benefits over a sole biocontrol agent in controlling diseases (Lemanceau et al. 1993; Pierson and Weller 1994; Crump 1998). Thus, researchers have been trying to improve the efficacy of biocontrol by exploiting multiple biocontrol agents (Multi-BCAs). Moreover, it is obvious that the naturally happening biocontrol is the result of action of a mixed population of antagonists rather than by an individual organism. Hence, introduction of Multi-BCAs will help in expanding their mode of action for the management of pathogens with stable broad spectrum activity (Mishra et al. 2011).

Based on initial studies, a combination of *T. asperellum* and *P. aeruginosa* was selected and assessed for the control of *G. boninenese* in terms of antagonistic activity, enzymatic action and also plant growth promoting properties. Both could inhibit the mycelial growth of *G. boninense* with Percentage of inhibition radial growth (PIRG value of more than 50%. In addition, both showed positive results to IAA production and phosphate solubilization, whereas only *T. asperellum* exhibited siderophore production properties (Muniroh et al. 2019). Studies have also reported that endophytic bacteria could assist the mutualistic interaction of AMF with the host plant and encourage the defence responses against plant pathogens (Garbaye 1994; Pivato et al. 2009). This combination would offer notable benefits including enhanced chitinase production and growth promotion of plants. Even though AMF could assure protection against pathogens (Smith and Read 1997; Gianinazzi et al. 2010), picking the suitable endophytic bacteria was crucial for assessing the biocontrol potential of the consortium against *G. boninense*. Two such potential endophytic bacteria, *Burkholderia cepacia* UPMB3 and *Pseudomonas aeruginosa* UPMP3, were isolated and evaluated by Sapak et al. (2008) and found effective suppression of *G. boninense* both in vitro (Sundram et al. 2011) and in vivo studies (Sapak et al. 2008). In the previous study, it was observed that the same strains of endophytic bacteria could also increase the hyphal growth and spore germination of *Glomus clarum* BR152B and *Glomus intraradices* UT126 (Sundram et al. 2011). It was also recorded that the endophytic bacterial strains had similar activities like mycorrhizal helper bacteria (Garbaye 1994).

Other possibilities were also explored by researchers, and apart from the common endophytic microbes, two ascomycetous fungi were studied for their compatibility and potential use in the control of BSR. Plant growth promoting activity and biocontrol traits of *Clonostachys rosea* AAB0114 and *Talaromyces apiculatus* AT0115 consortium against BSR disease were evaluated in nursery. Inoculation of the consortium as well as the individual fungus brought about significant increase in both bole girth and leaf area of the seedlings after 5 months of treatment. Additionally, the treated seedlings showed considerable reduction in disease incidence compared to the control treatment. Co-inoculation of the two fungi came up with notable disease control efficiency, indicating its potential use as a biocontrol strategy against *G. boninense* (Goh et al. 2020).

9.5 Breeding for Genetic Resistance

The use of resistant planting materials would be a better option for the long-term control of BSR disease in plantations. The crucial factor in the breeding programmes for the disease resistance is the source of resistance. Sources of susceptibility and genetic resistance against *Ganoderma* have been recognized in field experiments, suggesting the reflection of genetic resistance as a component of Integrated disease management (IDM) of BSR (Idris et al. 2006; Chung 2011). Oil palms with varying genetic origins have been shown to be tolerant to *G. boninense* (Durand-Gasselin et al. 2005; Idris et al. 2004b). Franqueville et al. (2001) reported sources of genetic resistance in field studies in North Sumatra and it was further confirmed by Durand-Gasselin et al. (2005). Oil palms of Deli origin (both Indonesia and Malaysia) were appeared to be more susceptible compared to those originated from Africa (Durand-Gasselin et al. 2005), revealing the presence of possible genetic resistance. These findings point out that the enhancement of resistance of planting materials using available genetic sources could be a promising disease management strategy in BSR risk area. Breeding and selection of palms with greater lignin deposition (Casler et al. 2002) or modifying the lignin structure may be another key approach for the improvement of resistance in palms (Rees et al. 2009).

9.5.1 Genetic Engineering

Exploitation of genetic engineering tools could be a surpassing choice for the improvement of planting materials owing to their cost and time effectiveness (Sambanthamurthi et al. 2009). Enhanced expression of chitinases and glucanases to combat *Ganoderma* can be realized with the help of genetic engineering approach. In previous studies, two genes, rice chitinase (RCH10) and alfalfa glucanase (AGLU1), were employed to genetically engineer oil palm in view of resistance against *G. boninense*. Rashdan and Abdullah (2000) were able to successfully transform the oil palm through *Agrobacterium*-mediated transfer of chitinase gene against *Ganoderma*.

9.5.2 Application of Omic Technologies

9.5.2.1 Transcriptomics

The global-based gene expression analysis in oil palm in response to pathogen could be achieved through transcriptomic databases. This information available on the differential gene upregulation and expression upon oil palm–pathogen interaction is a great source for designing markers for the selection of resistance in oil palm. In contrast, the down-regulated genes during the interaction can be utilized for identification of markers linked with susceptibility, and therefore it further helps in selecting the susceptible seedlings. The use of the molecular markers at least avoids the deployment of susceptible materials to the field. Moreover, these susceptible genes would be a potential target for the gene editing approaches.

Transcriptomic analysis conducted by Tee et al. (2013) indicated involvement of defence-associated genes, encoding phenylalanine ammonia lyase (PAL), isoflavone reductase (IFR) and cinnamate 4-hydroxylase (C4H). Chong et al. (2012b) identified the accumulation of three antifungal compounds including caffeic acid, 4-hydroxybenzoic acid and phenolic acids such as syringic acid (SA) during oil palm–*Ganoderma* interaction. In another study carried out by Wulandari et al. (2018), it was shown that the EMLP1 gene was up-regulated amid the *G. boninense* infection. Faizah et al. (2019) identified 16 susceptibility response-related genes from the oil palm roots.

9.5.2.2 Proteomics

Comparative proteomic analysis during *Ganoderma* and oil palm interaction has revealed the variation in expression of defence-related proteins, including adenosine triphosphate (ATP) synthase, cysteine synthase, caffeic acid *O*-methyltransferase (COMT), caffeoyl-CoA *O*-methyltransferase (CCoAOMT), malate dehydrogenase, enolase and fructokinase, upon the progression of BSR disease (Al-Obaidi et al. 2014). Likewise, proteins associated with oxidative burst such as ascorbate peroxidase (APx), 2-Cys peroxiredoxin (Prx), APx catalase and superoxide dismutase (SOD) were also identified (Daim et al. 2015) and characterized (Caverzan et al. 2012).

9.5.2.3 Metabolomics

A wide range of metabolites can be assessed by employing metabolomics approach for phenotyping and diagnostic analysis in plants (Fernie and Schauer 2009). There have been several reports on metabolite diversity of oil palm roots with a potential role in disease resistance, including the pre-formed phytoanticipins and inducible phytoalexins (Diabaté et al. 2009). Dzulkafli et al. (2019) detected and identified chelidonic acid in the leaves of oil palm upon artificial inoculation with *G. boninense*. Syringic acid (a phenolic acid) accumulation in *Ganoderma*-infected oil palm roots indicates the possible anti-fungal activity of these compounds against the pathogen (Chong et al. 2012a, b). Furthermore, the presence of sterols and tocopherols was detected in infected oil palm roots by using gas chromatography-mass spectrometry (GC-MS) (Nusaibah et al. 2011b). In previous studies, it has been reported the resistance against vascular wilt pathogen (*Fusarium oxysporum*) in the presence of phenolic acids, and thus it suggests their role in indication of disease infection (Diabaté et al. 2009).

9.6 Conclusion

Basal stem rot caused by wood rotting basidiomycete, *Ganoderma* spp., is considered to be the deadliest disease of oil palm. For proper monitoring and early identification of disease in oil palm, more automated, objective and sensitive approaches such as artificial intelligence, multispectral imaging and sensor-based techniques may be used. Management strategies for controlling BSR in oil palm should integrate the existing and advanced technical knowledge. Different models of integrated disease management should be evaluated under large scale across plant species and ecosystems to come out with an effective package of practice. Marker-assisted early disease resistance phenotyping, histological characterization, pathogen genome and diversity analysis, and host–pathogen interaction investigations should all be included in disease resistance breeding in oil palm, in addition to traditional breeding methodologies.

References

Abdullah F (2000) Spatial and sequential mapping of the incidence of basal stem rot of oil palms (*Elaeis guineensis*) on a former coconut (*Cocos nucifera*). Ganoderma diseases of perennial crops, p 183

Abdullah J, Hassan H, Shari MR et al (2013) Gamma Scorpion: mobile gamma-ray tomography system for early detection of basal stem rot in oil palm plantations. Opt Eng 52(3):036502

Abdullah AH, Shakaff AM, Zakaria A et al (2014) Application Specific Electronic Nose (ASEN) for Ganoderma boninense detection using artificial neural network. In: 2014 2nd International Conference on Electronic Design (ICED). IEEE, pp 148–152

Adaskaveg JE, Gilbertson RL (1986) Cultural studies and genetics of sexuality of *Ganoderma lucidum* and *G. tsugae* in relation to the taxonomy of the *G. lucidum* complex. Mycologia 78(5): 694–705

Adaskaveg JE, Gilbertson RL (1988) Basidiospores, pilocystidia, and other basidiocarp characters in several species of the *Ganoderma lucidum* complex. Mycologia 80(4):493–507

Adaskaveg JE, Gilbertson RL, Blanchette RA (1990) Comparative studies of delignification caused by *Ganoderma* species. Appl Environ Microbiol 56(6):1932–1943

Aderungboye FO (1977) Diseases of the oil palm. PANS 23(3):305–326

Agrios GN (2005) Plant pathology. Elsevier Science, San Diego, CA

Al-Obaidi JR, Mohd-Yusuf Y, Razali N et al (2014) Identification of proteins of altered abundance in oil palm infected with *Ganoderma boninense*. Int J Mol Sci 15(3):5175–5192

Angel LP, Abu Bakar D, Sundram S (2021) A non-invasive tissue culture system for performing artificial pathogenicity assays of *Ganoderma boninense*. Australas Plant Pathol 28:1–4

Arango M, Martínez G, Torres G (2016) Advances in the interpretation of tomographic images as an early detection method of oil palm affected by basal stem rot in Colombia. Plant Dis 100(8): 1559–1563

Arif MS, Roslan A, Idris AS (2011) Proceedings of the Third MPOB-IOPRI International Seminar: Integrated Oil Palm Pests and Diseases Management. Kuala Lumpur: Convention Centre. Economics of oil palm pests and *Ganoderma* disease and yield losses.

Ariffin D, Idris AS (1993) A selective medium for the isolation of *Ganoderma* from disease tissues. In: PORIM international palm oil conference. Progress, prospects challenges towards the 21st century. (Agriculture) September 9-14 Kuala Lumpur, Malaysia (No. L-0218). PORIM

Ariffin D, Idris AS, Hassan AH (1989) Significance of the black line within oil palm tissue decayed by *Ganoderma boninense*. Elaeis 1(1):11–16

Ariffin D, Idris AS, Khairudin H (1995) Conformation of *Ganoderma* infected palm by drilling technique. In: PORIM international palm oil congress (No. L-0314). PORIM

Ariffin D, Idris AS, Marzuki A (1996) Development of a technique to screen oil palm seedlings for resistance to *Ganoderma*. In: 1995 PORIM national oil palm conference technologies in plantation (No. L-0301). PORIM

Aswad AM, Sariah M, Paterson RRM et al (2011) Ergosterol analyses of oil palm seedlings and plants infected with *Ganoderma*. Crop Prot 30(11):1438–1442

Axelsson BO, Saraf A, Larsson L (1995) Determination of ergosterol in organic dust by gas chromatography-mass spectrometry. J Chromatogr B Biomed Sci Appl 666(1):77–84

Azadeh BF, Sariah M, Wong MY (2010) Characterization of *Burkholderia cepacia* genomovar I as a potential biocontrol agent of *Ganoderma boninense* in oil palm. Afr J Biotechnol 9:3542–3548

Aziz MHA, Bejo SK, Hashim F et al (2019) Evaluations of soil resistivity in relation to basal stem rot incidences using soil moisture sensor. Pertanika J Sci Technol 27(S1):225–234

Azizah H (2003) *Ganoderma* versus mycorrhiza. Oil Palm Bull 47:6–14

Azizah SN, Mubarik NR, Sudirman LI (2015) Potential of chitinolytic *Bacillus amyloliquefaciens* SAHA 12.07 and *Serratia marcescens* KAHN 15.12 as biocontrol agents of *Ganoderma boninense*. Res J Microbiol 10(10):452

Azmi NAN, Bejo SK, Jahari M et al (2020) Early detection of *Ganoderma boninense* in oil palm seedlings using support vector machines. Remote Sens 12(23):3920

Baldwin IT, Halitschke R, Paschold A, Von Dahl CC, Preston CA (2006) Volatile signaling in plant-plant interactions: “talking trees” in the genomics era. Science 311(5762):812–815

Barea JM, Azcón R, Azcón-Aguilar C (2002) Mycorrhizosphere interactions to improve plant fitness and soil quality. Antonie Van Leeuwenhoek 81(1):343–351

Bazzalo ME, Wright JE (1982) Survey of the Argentine species of the *Ganoderma lucidum* complex. Mycotaxon, Ithaca 16(1):293–325

Bejo KS, Yusoff Y, Yusoff NSN et al (2015) Identification of healthy and BSR-infected oil palm trees using color indices. Int J Agric Biosyst Eng 9(8):786–789

Bhaskaran R (2000) Management of basal stem rot disease of coconut caused by *Ganoderma lucidum*. Ganoderma diseases of perennial crops, pp 121–126

Bhaskaran R, Rethinam P, Nambiar KKN (1994) *Ganoderma* wilt of coconut. In: Chadha KL, Rethinam P (eds) Advances in horticulture, Plantation and spice crops, part 2, vol 10. Malhotra Publishing House, New Delhi, pp 858–882

Bivi MR, Farhana MSN, Khairulmazmi A, Idris A (2010) Control of *Ganoderma boninense*: A causal agent of basal stem rot disease in oil palm with endophyte bacteria *in vitro*. Int J Agric Biol 12(6):833–839

Bivi MR, Farhana MSN, Khairulmazmi A, Idris AS et al (2014) Assessment of plant secondary metabolites in oil palm seedlings after being treated with calcium, copper ions and salicylic acid. Arch Phytopathol Plant Protect 47:1120–1135

Bivi MR, Paiko AS, Khairulmazmi A et al (2016) Control of basal stem rot disease in oil palm by supplementation of calcium, copper, and salicylic acid. Plant Pathol J 32(5):396

Breton F, Hasan Y, Lubis Z et al (2006) Characterization of parameters for the development of an early screening test for basal stem rot tolerance in oil palm progenies. J Oil Palm Res (spec.) 24–36

Bridge PD, Utomo C (2005) Papers from the Third International Workshop on *Ganoderma* Diseases of Perennial Crops, Medan, Indonesia, March 24-26, 2003. Mycopathologia 159(1): 91–179

Bridge PD, O’grady EB, Pilotti CA et al (2000) Development of molecular diagnostics for the detection of *Ganoderma* isolates pathogenic to oil palm. *Ganoderma* diseases of perennial crops, pp 225–234

Buana RFN, Wahyudi AT, Toruan-Mathius N (2014) Control activity of potential antifungal-producing *Burkholderia* sp. in suppressing *Ganoderma boninense* growth in oil palm. Asian. J Agric Res 8(5):259–268

Cannon PF, Kirk PM (eds) (2007) Fungal families of the world. CABI, Wallingford

Carter DJ, Cary RB (2007) Lateral flow microarrays: a novel platform for rapid nucleic acid detection based on miniaturized lateral flow chromatography. Nucleic Acids Res 35(10):74
Casler MD, Buxton DR, Vogel KP (2002) Genetic modification of lignin concentration affects fitness of perennial herbaceous plants. Theor Appl Genet 104:127–131
Caverzan A, Passaia G, Rosa SB et al (2012) Plant responses to stresses: role of ascorbate peroxidase in the antioxidant protection. Genet Mol Biol 35(4):1011–1019
Cheah LW, Goh YK, Goh KJ et al (2019) Electronic Nose detection of *Ganoderma boninense* Volatile Organic Compounds (VOCs) Using Direct Headspace Analysis. Trans Sci Technol 6: 334–339
Chong KP (2010) The role of phenolics in the interaction between oil palm and *Ganoderma boninense* the causal agent of basal stem rot. Doctoral dissertation, University of Nottingham
Chong KP, Rossall S, Markus A (2009) A comparison on the susceptibility of varieties AVROS, Calabar and Ekona of oil palm seedlings to *Ganoderma boninense* infection. In: Proceedings on the Science and Technology
Chong KP, Markus A, Rossall S (2012a) The susceptibility of different varieties of oil palm seedlings to *Ganoderma boninense* infection. Pak J Bot 44(6):2001–2004
Chong KP, Atong M, Rossall S (2012b) The role of syringic acid in the interaction between oil palm and *Ganoderma boninense*, the causal agent of basal stem rot. Plant Pathol 61(5):953–963
Chong KP, Dayou J, Alexander A (2017) Pathogenic nature of *Ganoderma boninense* and basal stem rot disease. In: Detection and control of *Ganoderma boninense* in oil palm crop. Springer, Cham, pp 5–12
Choon TRL, Sariah M, Mariam SMN (2012) Ergosterol from the soilborne fungus *Ganoderma boninense*. J Basic Microbiol 52(5):608–612
Chung G (2011) Management of *Ganoderma* diseases in oil palm plantations. Planter 87(1022): 325–339
Cooper RM, Flood J, Rees RW (2011) *Ganoderma boninense* in oil palm plantations: current thinking on epidemiology, resistance and pathology. Planter 87(1024):515–526
Corley RHV, Tinker PB (2003) The oil palm, 4th edn. Blackwell Publishing, Oxford. https://doi.org/10.1002/9780470750971
Crump DH (1998) Biological control of potato and beet cyst nematodes. Asp Appl Biol 52:383–386
Daim JLD, Ooi TEK, Ithnin N et al (2015) Comparative proteomic analysis of oil palm leaves infected with *Ganoderma boninense* revealed changes in proteins involved in photosynthesis, carbohydrate metabolism, and immunity and defense. Electrophoresis 36(15):1699–1710
Diabaté S, De Franqueville H, Adon B et al (2009) The role of phenolic compounds in the determination of wilt disease tolerance of oil palm (*Elaeis guineensis* JACQ)
Dickinson M (2015) Loop-mediated isothermal amplification (LAMP) for detection of phytoplasmas in the field. In: Plant pathology. Humana Press, New York, NY, pp 99–111
Dordas C (2008) Role of nutrients in controlling plant diseases in sustainable agriculture: a review. Agron Sustain Dev 28:33–46
Duhan JS, Kumar R, Kumar N et al (2017) Nanotechnology: The new perspective in precision agriculture. Biotechnol Rep 15:11–23
Durand-Gasselin T, Asmady H, Flori A et al (2005) Possible sources of genetic resistance in oil palm (*Elaeis guineensis* Jacq.) to basal stem rot caused by *Ganoderma boninense*– prospects for future breeding. Mycopathologia 159(1):93–100
Dutse SW, Yusof NA, Ahmad H et al (2012) An electrochemical DNA biosensor for *Ganoderma boninense* pathogen of the Oil palm utilizing a New ruthenium complex, [Ru(dppz) 2 (qtpy)] Cl2. Int J Electrochem Sci 7:8105–8115
Dutse SW, Yusof NA, Ahmad H, Hussein MZ et al (2013) DNA-based biosensor for detection of *Ganoderma boninense*, an Oil palm pathogen utilizing newly synthesized ruthenium complex [Ru (phen) 2 (qtpy)] 2 based on a PEDOT-PSS/Ag nanoparticles modified electrode. Int J Electrochem Sci 8(9):11048–11057

Dzulkafli SB, Othman A, Shahwan S, Nurazah Z, Abd Manaf MA, Idris AS, Amiruddin MD, Tahir NI, Ramli US (2019) Identification of chelidonic acid and asparagine in *Ganoderma boninense*-inoculated oil palm seedlings. J Oil Palm Res 31(1):53–66
Elliot ML, Uchida JY (2004) Diseases and disorders of ornamental palms. Compendium of ornamental palm diseases and disorder. APS Press, St. Paul, MN
Engelhard AW (1989) Soilborne plant pathogens: Management of diseases with macro- and microelements. APS Press, St. Paul, MN
Esyanti RR, Susanto A, Aryantha INP (2017) The chitinase activity of oil palm (*Elaeis guineensis* Jacq.) roots against fungal endophytes and pathogenic '*Ganoderma boninense*'. Plant Omics 10(5):247–251
Evans I, Solberg E, Huber DM (2007) Copper and plant disease. Mineral nutrition and plant disease, pp 177–188
Faizah R, Putranto RA, Wening S et al (2019) Differential expression of root specific genes of oil palm seedlings at early stage of *Ganoderma boninense* infection. In: IOP conference series: earth and environmental science, vol 418, No 1. IOP Publishing, p 012044
Fernie AR, Schauer N (2009) Metabolomics-assisted breeding: a viable option for crop improvement? Trends Genet 25(1):39–48
Flood J, Bridge P, Holderness M (2000) *Ganoderma* diseases of perennial crops. CABI, Wallingford
Flood J, Keenan L, Wayne S et al (2005) Studies on oil palm trunks as sources of infection in the field. Mycopathologia 159(1):101–107
Franqueville HD, Asmady H, Jacquemard JC et al (2001) Indications on sources of oil palm (*Elaeis guineensis* Jacq.) genetic resistance and susceptibility to *Ganoderma* sp., the cause of basal stem rot. In: Cutting-edge technologies for sustained competitiveness: Proceedings of the 2001 PIPOC International Palm Oil Congress, Agriculture Conference, Kuala Lumpur, Malaysia, 20–22 August 2001. Malaysian Palm Oil Board (MPOB), pp 420–431
Garbaye J (1994) Tansley review no. 76 helper bacteria: a new dimension to the mycorrhizal symbiosis. New Phytol 128(2):197–210
Gardner JW, Bartlett PN (1994) A brief history of electronic noses. Sens Actuators B Chem 18(1-3):210–211
Gautam S, Singh PK (2009) Salicylic acid induced salinity tolerance in corn grown under NaCl stress. Acta Physiol Plant 31:1185–1190
Genty P, Desmier De Chenon R, Mariau D (1976) Infestation des racines aériennes du palmier à huile par des chenilles genre Sufetula Walker. Pyralidae, Lépidoptère
George ST, Zakaria K, Chung, GF (1996) Updated results (1990-1995) on trunk injection of fungicides for the control of *Ganoderma* basal stem rot. Palm Oil Research Institute of Malaysia
George ST, Chung, GF, Zakaria K (2000) Benefits of soil mounding tall palms in a high *Ganoderma* incidence area in Lower Perak. International Planters Conference Malaysia. pp 565-576
Gianinazzi S, Gollotte A, Binet MN et al (2010) Agroecology: the key role of arbuscular mycorrhizas in ecosystem services. Mycorrhiza 20(8):519–530
Goh KM, Ganeson M, Supramaniam CV (2015) Infection potential of vegetative incompatible *Ganoderma boninense* isolates with known ligninolytic enzyme production. Afr J Biotechnol 13:1056–1066
Goh YK, Marzuki NF, Goh TK et al (2016) Mycoparasitic *Scytalidium parasiticum* as a potential biocontrol agent against *Ganoderma boninense* basal stem rot in oil palm. Biocontrol Sci Technol 26(10):1352–1365
Goh YK, Marzuki NF, Tuan Pa TNF et al (2020) Biocontrol and plant-growth-promoting traits of *Talaromyces apiculatus* and *Clonostachys rosea* consortium against *Ganoderma* basal stem rot disease of oil palm. Microorganisms 8(8):1138
Graham DR (1983) Effects of nutrients stress on susceptibility of plants to disease with particular reference to the trace elements. Adv Bot Res 10:221–276

Gurmit S (1991) *Ganoderma*-the scourge of oil palm in the coastal area. In: Proceedings of Ganoderma workshop, Bangi, Selangor, Malaysia, 11 September 1990. Palm Oil Research Institute of Malaysia, pp 7–35

Hamidon NA, Mukhlisin M (2014) A review of application of computed tomography on early detection of basal stem rot disease. Jurnal Teknologi 70(3):45–47

Hasan Y, Flood J (2003) Colonisation of rubber wood and oil palm blocks by monokaryons and dikaryons of *Ganoderma boninense*-implications to infection in the field. Planter 79(922):31–38

Hasan Y, Turner PD (1994) Research at Bah Lias Research Station on basal stem rot of oil palm. In: Proceedings of the 1st international workshop on perennial crop diseases caused by *Ganoderma*, vol 28. UPM, Serdang, Selangor

Hasan Y, Turner PD (1998) The comparative importance of different oil palm tissues as infection sources for basal stem rot in replantings. Planter 73:239–244

Hasan Y, Foster HL, Flood J (2005) Investigations on the causes of upper stem rot (USR) on standing mature oil palms. Mycopathologia 159(1):109–112

Hashim KB (1991) Results of four trials on *Ganoderma* basal stem rot of oil palm in Golden Hope Estate. In: Proceedings of the *Ganoderma* Workshop, PORIM, Selangor, Malaysia, September 1990

Herrmann L, Lesueur D (2013) Challenges of formulation and quality of biofertilizers for successful inoculation. Appl Microbiol Biotechnol 97(20):8859–8873

Hisham K (1993) Basal stem rot of oil palm caused by *Ganoderma boninense*: an update. In: Jalani B (ed) Proceedings of 1993 PORIM International Palm Oil Congress- Agriculture. Palm Oil Research Institution Malaysia, Kuala Lumpur, pp 739–749

Ho CT, Khairuddin H (1997) Usefulness of soil mounding treatments in prolonging productivity of prime-aged Ganoderma infected palms. Planter 73(854):239–244

Ho YW, Nawawi A (1986) Isolation, growth and sporophore development of *Ganoderma boninense* from oil palm in Malaysia. Pertanika 9(1):69–73

Hong SG, Jung HS (2004) Phylogenetic analysis of *Ganoderma* based on nearly complete mitochondrial small-subunit ribosomal DNA sequences. Mycologia 96(4):742–755

Hseu RS, Wang HH, Wang HF et al (1996) Differentiation and grouping of isolates of the *Ganoderma lucidum* complex by random amplified polymorphic DNA-PCR compared with grouping on the basis of internal transcribed spacer sequences. Appl Environ Microbiol 62(4): 1354–1363

Hu Z, Chang X, Dai T et al (2019) Metabolic profiling to identify the latent infection of strawberry by *Botrytis cinerea*. Evol Bioinform 15:1176934319838518

Hushiarian R, Yusof NA, Dutse SW (2013) Detection and control of *Ganoderma boninense*: strategies and perspectives. SpringerPlus 2(1):1–12

Husin NA, Khairunniza-Bejo S, Abdullah AF et al (2020) Application of Ground-Based LiDAR for Analysing oil palm canopy properties on the occurrence of Basal Stem Rot (BSR) disease. Sci Rep 10(1):1–16

Idris AS (1999) Basal Stem Rot (BSR) of oil palm (*Elaeis guineensis* Jacq.) in Malaysia: factors associated with variation in disease severity. Dissertation, University of London

Idris AS (2013). http://www.mpob.gov.my/. Accessed 25 Sept

Idris AS, Maizatul S (2012) Stump treatment with dazomet for controlling Ganoderma disease in oil palm. MPOB TS Inf Ser 107:615–616

Idris AS, Rafidah, AR (2008) Polyclonal antibody for detection of *Ganoderma*. MPOB Information Series, MPOB TT, (405)

Idris AS, Ariffin D, Watt TA et al (2001) Distribution of species of *Ganoderma* basal stem rot of oil palms in relation to the environmental conditions in peninsular Malaysia. Cutting-edge technologies for sustained competitiveness: Proceedings of the PIPOC International Palm Oil Congress, Agriculture Conference, 2001. MPOB, Kuala Lumpur, pp 385–94

Idris AS, Ariffin D, Basri MW et al (2003) PCR technique for detection of *Ganoderma*. pp 202

Idris AS, Ismail S, Ariffin D (2004a) Innovative technique of sanitation for controlling *Ganoderma* at replanting. MPOB Information Series 213(4)

Idris AS, Kushairi A, Ismail S et al (2004b) Selection for partial resistance in oil palm progenies to *Ganoderma* basal stem rot. J Oil Palm Res 16(2):12–18
Idris AS, Kushairi D, Ariffin D et al (2006) Technique for inoculation of oil palm germinated seeds with *Ganoderma*. MPOB Inf Ser 314:1–4
Idris AS, Rajinder S, Madihah AZ et al. (2010a) Multiplex PCR-DNA kit for early detection and identification of *Ganoderma* species in oil palm. MPOB Inf Ser MPOB TS, p 73
Idris AS, Arifurrahman R, Kushairi A (2010b) Hexaconazole as a preventive treatment for managing *Ganoderma* in oil palm. MPOB TS Information Series. p 75
Ilias GNM (2000). *Trichoderma pers.* ex fr. and its efficacy as a biological control agent of basal stem rot of oil palm (*Elaeis guineensis* Jacq.). Doctoral dissertation, Universiti Putra Malaysia
Ishaq I, Alias MS, Kadir J et al (2014) Detection of basal stem rot disease at oil palm plantations using sonic tomography. J Sustain Sci Manag 9(2):52–57
Izzati MZ, Abdullah F (2008) Disease suppression in Ganoderma-infected oil palm seedlings treated with *Trichoderma harzianum*. Plant Prot Sci 44(3):101–107
Jawak G, Widajati E, Palupi ER et al (2018) Oil palm seed coating with enriched *Trichoderma asperellum* (T13) to suppress infection of *Ganoderma boninense* Pat. Jurnal Perbenihan Tanaman Hutan 6(2):121–132
Jensen JR (2006) Remote sensing of the environment an earth resource perspective: low price edition. Pearson Education, New Delhi
Johnstone D, Moore G, Tausz M et al (2010) The measurement of wood decay in landscape trees. Arboric Urban For 36(3):121–127
Karsten PA (1881) Enumeratio Boletinearum et Polyporearum Fennicarum, systemate novo dispositarum. Revue mycologique, Toulouse (in Latin) 3(9):16–19
Khairudin H (1990) Basal stem rot of oil palm: incidence, etiology and control. Master of Agriculture Science thesis, Universiti Pertanian Malaysia, Selangor, Malaysia
Khairudin H (1993) Ganoderma disease of oil palm. In: Workshop on plantation management update 29:418–423
Khairudin H, Tey CC (2008) An overview of the current status of Ganoderma basal stem rot and its management in a large plantation group in Malaysia. Planter 84:469–482
Khosrokhani M, Khairunniza-Bejo S, Pradhan B (2016) Geospatial technologies for detection and monitoring of *Ganoderma* basal stem rot infection in oil palm plantations: a review on sensors and techniques. Geocarto Int 33(3):260–276
Kobayashi DY, Palumbo JD (2000) Bacterial endophytes and their effect on plant and uses in agriculture. In: Bacon CW, White JF Jr (eds) Microbial endophytes. Marcel Dekker, New York, pp 199–233
Kushairi A, Loh SK, Azman I et al (2018) Oil palm economic performance in Malaysia and R & D progress in 2017. J Oil Palm Res 30(2):163–195
Lambrecht MY, Okon A, Broek V et al (2000) Indole-3-acetic-acid: a reciprocal signaling molecule in bacteria-plant interaction. Trends Microbiol 8:298–300
Laothawornkitkul J, Moore JP, Taylor JE et al (2008) Discrimination of plant volatile signatures by an electronic nose: a potential technology for plant pest and disease monitoring. Environ Sci Technol 42(22):8433–8439
Latgé JP (2007) The cell wall: a carbohydrate armour for the fungal cell. Mol Microbiol 66(2): 279–290
Latiffah Z, Ho YW (2005) Morphological characteristics and somatic incompatibility of *Ganoderma* from infected oil palm from three inland estates. Malays J Microbiol 1(2):46–52
Lelong CC, Roger JM, Brégand S et al (2010) Evaluation of oil-palm fungal disease infestation with canopy hyperspectral reflectance data. Sensors 10(1):734–747
Lemanceau P, Bakker PAHM, De Kogel WJ et al (1993) Antagonistic effect of nonpathogenic *Fusarium oxysporum* Fo47 and Pseudobactin 358 upon pathogenic *Fusarium oxysporum* f.sp. *dianthi*. Appl Environ Microbiol 59:74–82

Lim KH, Udin W (2010) Management of *Ganoderma* in peat soil in Indonesia. In: Proceedings of the second international seminar on oil palm diseases: advances in *Ganoderma* research and management, Yogyakarta, Indonesia, vol 31

Lim T, Chung G, Ko W (1992) Basal stem rot of oil palm caused by *Ganoderma boninense*. Plant Pathol Bull 1(3):147–152

Maluin FN, Hussein MZ (2020) Chitosan-based agro-nanochemicals as a sustainable alternative in crop protection. Molecules 25(7):1611

Maluin FN, Hussein MZ, Yusof NA et al (2019) Preparation of chitosan–hexaconazole nanoparticles as fungicide nanodelivery system for combating *Ganoderma* disease in oil palm. Molecules 24(13):2498

Mandal PK, Hymavathi K, Jayanthi M, Babu MK (2003) Cross infectivity study of *Ganoderma lucidum* isolates from coconut to oil palm and their diversity study by RAPD and AFLP. Int J Oil Palm Res 3:57–60

Mandal PK, Satyavani V, Babu MK (2009) Studies on colony morphology and sporulation of *Ganoderma* isolates, causing basal stem rot disease of oil palm. Int J Oil Palm 6(1):43–48

Martinelli F, Scalenghe R, Davino S et al (2015) Advanced methods of plant disease detection. A review. Agron Sustain Dev 35(1):1–25

Meyer SL, Roberts DP (2002) Combinations of biocontrol agents for management of plant-parasitic nematodes and soilborne plant-pathogenic fungi. J Nematol 34(1):1

Meyer A, Todt C, Mikkelsen NT et al (2010) Fast evolving 18S rRNA sequences from Solenogastres (Mollusca) resist standard PCR amplification and give new insights into mollusk substitution rate heterogeneity. BMC Evol Biol 10(1):1–12

Miller RNG, Holderness M, Bridge PD et al (1995) Isozyme analysis for characterization of *Ganoderma* strains from south-east Asia 1. EPPO Bull 25(1-2):81–87

Miller RNG, Holderness M, Bridge PD (2000) Molecular and morphological characterization of *Ganoderma* in oil palm plantings. In: Flood J, Bridge PD, Holderness M (eds) Ganoderma diseases of perennial crops. CABI Publishing, Wallingford, pp 159–182

Miransari M (2013) Soil microbes and the availability of soil nutrients. Acta Physiol Plant 35(11): 3075–3084

Mishra DS, Gupta AK, Prajapati CR, Singh US (2011) Combination of fungal and bacterial antagonists for management of root and stem rot disease of soybean. Pak J Bot 43(5):2569–2574

Mohammed CL, Rimbawanto A, Page DE (2014) Management of basidiomycete root-and stem-rot diseases in oil palm, rubber and tropical hardwood plantation crops. Forest Pathol 44(6): 428–446

Moncalvo JM (2000) Systematics of *Ganoderma*. In: Flood J, Bridge PD, Holderness M (eds) Ganoderma diseases of perennial crops. CAB International, Wallingford, pp 23–45

Moncalvo JM, Buchanan PK (2008) Molecular evidence for long distance dispersal across the Southern Hemisphere in the *Ganoderma applanatum-australe* species complex (Basidiomycota). Mycol Res 112(4):425–436

Moncalvo JM, Wang HH, Hseu RS (1995) Phylogenetic relationships in *Ganoderma* inferred from the internal transcribed spacers and 25S ribosomal DNA sequences. Mycologia 87(2):223–238

Moritz G, Delker C, Paulsen M, Mound LA, Burgermeister W (2000) Modern methods for identification of Thysanoptera. EPPO Bull 30:591–593

Muniroh MS, Nusaibah SA, Vadamalai G, Siddique Y (2019) Proficiency of biocontrol agents as plant growth promoters and hydrolytic enzyme producers in *Ganoderma boninense* infected oil palm seedlings. Curr Plant Biol 20:100–116

Naher L, Ho C-L, Tan SG, Yusuf UK, Abdullah F (2011) Cloning of transcripts encoding chitinases from *Elaeis guineensis* Jacq. and their expression profiles in response to fungal infections. Physiol Mol Plant Pathol 76(2):96–103

Naher L, Yusuf UK, Siddiquee S, Ferdous J, Rahman MA (2012) Effect of media on growth and antagonistic activity of selected *Trichoderma* strains against *Ganoderma*. Afr J Microbiol Res 6(48):7449–7453

Naidu GVB, Kumar SNS, Sannamarappa M (1966) Anabe roga, *Ganoderma lucidum* (Leys) Karst on arecanut palm: a review and further observations. J Mysore Hortic Soc 1(3):14–20
Naidu Y, Siddiqui Y, Rafii MY et al (2018) Inoculation of oil palm seedlings in Malaysia with white-rot hymenomycetes: Assessment of pathogenicity and vegetative growth. Crop Prot 110: 146–154
Najihah NI, Hanafi MM, Idris AS et al (2015) Silicon treatment in oil palms confers resistance to basal stem rot disease caused by *Ganoderma boninense*. Crop Prot 67:151–159
Nasahi C, Widiantini F, Yulia E et al (2016) Isolation and detection of potential endophytic actinobacteria in controlling stem rot disease in oil palm plants (*Ganoderma boninense* Pat.). In: Joko T (ed) Proceedings of the national seminar on plant disease control environmentally friendly II, 2016. Indonesian Phytopathol Association, Yogyakarta
Natarajan S, Bhaskaran R, Shanmugan N (1986) Preliminary studies to develop techniques for early detection of Thanjavur wilt in coconut. Indian Coconut J 17(3):3–6
Nawawi A, Ho YW (1990) Effect of temperature and pH on growth pattern of *Ganoderma boninense* from oil palm in peninsular Malaysia. Pertanika 13(3):303–307
Nie X (2006) Salicylic acid suppresses Potato virus Y isolate N: O induced symptoms in tobacco plants. Phytopathology 96:255–263
Nur Sabrina AA, Sariah M, Zaharah AR (2012) Suppression of basal stem rot disease progress in oil palm (*Elaeis guineensis*) after copper and calcium supplementation. Pertanika J Trop Agric Sci 13–24
Nurrashyeda R, Semanb IA, Zairunc MA et al (2018) Biocontrol of basal stem rot (BSR) disease of oil palm using endophytic fungus, *Hendersonia* sp. Int J Pure Appl Math 118(24):1–22
Nur-Rashyeda R, Idris AS, Rusli MH et al (2021) Fungicide application for the control of Ganoderma Upper Stem Rot (USR) disease in oil palm. MPOB Information Series. ISSN 1511-7871
Nusaibah SA, Musa HA (2019) Review report on the mechanism of *Trichoderma* spp. as biological control agent of the basal stem rot (BSR) disease of *Elaeis guineensis*. *Trichoderma*-the most widely used fungicide, p 79
Nusaibah SA, Latiffah Z, Hassaan A (2011a) ITS-PCR-RFLP analysis of *Ganoderma* sp. infecting industrial crops. Pertanika 34(1):83–91
Nusaibah SA, Akmar SNA, Pauzi MZ et al (2011b) Detection of phytosterols in *Ganoderma boninense*-infected oil palm seedlings through GC-MS analysis. J Oil Palm Res 23:1069–1077
Oil World (2020) Oil World Annual 2020 ISTA Mielke GmbH, Hamburg. http://www.oilworld.de
Olaniyi ON, Szulczyk KR (2020) Estimating the economic damage and treatment cost of basal stem rot striking the Malaysian oil palms. Forest Policy Econ 116:102163
Ommelna BG, Jennifer AN, Chong KP (2012) The potential of chitosan in suppressing *Ganoderma boninense* infection in oil-palm seedlings. J Sustain Sci Manag 7(2):186–192
Oostendorp M, Kunz W, Dietrich B et al (2001) Induced disease resistance in plants by chemicals. Eur J Plant Pathol 107(1):19–28
Panchal G, Bridge PD (2005) Following basal stem rot in young oil palm plantings. Mycopathologia 159(1):123–127
Parthiban K, Vanitah R, Jusoff K, Nordiana AA, Anuar AR, Wahid O, Hamdan AB (2016) GIS mapping of basal stem rot disease in relation to soil series among oil palm smallholders. Am J Agric Biol Sci 11:2–12
Paterson RRM (2006) *Ganoderma*– a therapeutic fungal biofactory. Phytochemistry 67(18): 1985–2001
Paterson RRM (2007) *Ganoderma* disease of oil palm- A white rot perspective necessary for integrated control. Crop Prot 26(9):1369–1376
Paysen TE, Narog MG, Zavala MA (1992) Monitoring electrical resistance in canyon live oak using a Shigometer. Symposium on ecology and management of oak and associated woodlands: perspectives in the southwestern United States and New Mexico. Symposium, 1992, Sierra Vista, AZ. p 199-203

Pegler DN, Young TWK (1973) Basidiospore form in the British species of *Ganoderma* Karst. Kew Bull:351–364

Persello-Cartieaux F, Nussaume L, Robaglia C (2003) Tales from the underground: molecular plant-rhizobacteria interactions. J Plant Cell Environ 26:189–199

Pierson EA, Weller DM (1994) To suppress Take-all and improve the growth of wheat. Phytopathology 84(1):940–947

Pieterse CMJ, Reyes AL, Ent SVD, Wees SCMV (2009) Networking by small molecule hormones in plant immunity. Nat Chem Biol 5(5):308–316

Pilotti CA, Sanderson FR, Aitken EAB (2003) Genetic structure of a population of *Ganoderma boninense* on oil palm. Plant Pathol 52(4):455–463

Pivato B, Offre P, Marchelli S, Barbonaglia B, Mougel C, Lemanceau P, Berta G (2009) Bacterial effects on arbuscular mycorrhizal fungi and mycorrhiza development as influenced by the bacteria, fungi, and host plant. Mycorrhiza 19(2):81–90

Prakasam V, Valluvaparidasan V, Raguchander T et al (1997) Field crop disease. AE Publication, Coimbatore

Priwiratama H, Susanto A (2014) Utilization of fungi for the biological control of insect pests and *Ganoderma* disease in the Indonesian oil palm industry. J Agric Sci Technol A 4(2A):103–111

Priwiratama H, Prasetyo AE, Susanto A (2020) Incidence of basal stem rot disease of oil palm in converted planting areas and control treatments. In: IOP conference series: earth and environmental science, vol. 468, No. 1. IOP Publishing, p 012036

Purnamasari MI, Agustina D, Prihatna C, Suwanto A (2018) A rapid inoculation method for infection of *Ganoderma* in oil palm. Int J Oil Palm 1(1):1–9

Rajendran L, Kandan A, Karthikeyan G et al (2009) Early detection of *Ganoderm*a causing basal stem rot disease in coconut plantations. J Oil Palm Res 21(6):627–635

Ramli NR, Mohamed MS, Seman IA et al (2016) The potential of endophytic bacteria as a biological control agent for *Ganoderma* disease in oil palm. Sains Malaysiana 45(3):401–409

Rani MJ, Devaraj D (2019) Microarray data classification using multi objective genetic algorithm and SVM. In: 2019 IEEE international conference on intelligent techniques in control, optimization and signal processing (INCOS). IEEE. pp 1–3

Rao AK (1990) Basal stem rot (*Ganoderma*) in oil palm smallholdings. In: Ariffin D, Jalani S (eds) Proceedings of the *Ganoderma* workshop. Palm Oil Research Institute of Malaysia, pp 113–131

Rashdan MM, Abdullah R (2000) Agrobacterium-mediated transformation of chitinase into oil palm (*Elaeis guineensis* J.). In: Proceedings of the 10th Scientific Meeting of Malaysian Kuala Lumpur: society for molecular biology and biotechnology, p 47

Raskin I (1992) Salicylate, a new plant hormone. J Plant Physiol 99:799–803

Razak AJ, Ahmad H, Ramdhan K et al (2004) Mechanical trunk injection for control of *Ganoderma*. MPOB Information Series. MPOB TT No. 215

Rebitanim NA, Hanafi MM, Idri AS et al (2020) GanoCare® improves oil palm growth and resistance against *Ganoderma* basal stem rot disease in nursery and field trials. Biomed Res Int 2020:3063710. https://doi.org/10.1155/2020/3063710

Reddy MK, Ananthanarayanan TV (1984) Detection of *Ganoderma lucidum* in betelnut by the fluorescent antibody technique. Trans Br Mycol Soc 82(3):559–561

Rees RW, Flood J, Hasan Y et al (2007) Effects of inoculum potential, shading and soil temperature on root infection of oil palm seedlings by the basal stem rot pathogen *Ganoderma boninense*. Plant Pathol 56:862–870

Rees RW, Flood J, Hasan Y et al (2009) Basal stem rot of oil palm (*Elaeis guineensis*); mode of root infection and lower stem invasion by *Ganoderma boninense*. Plant Pathol 58(5):982–989

Rees RW, Flood J, Hasan Y et al (2012) *Ganoderma boninense* basidiospores in oil palm plantations: evaluation of their possible role in stem rots of *Elaeis guineensis*. Plant Pathol 61(3):567–578

Roberts LM (2004) Australian *Ganoderma*: identification, growth and antibacterial properties. Doctoral dissertation, Environment and Biotechnology Centre, School of Engineering and Science, Swinburne University of Technology

Roy G, Laflamme G, Bussières G, Dessureault M (2003) Field tests on biological control of *Heterobasidion annosum* by *Phaeotheca dimorphospora* in comparison with *Phlebiopsis gigantea*. For Pathol 33(2):127–140

Rozali NL, Yarmo MA, Idris AS et al (2017) Metabolomics differentiation of oil palm (*Elaeis guineensis* Jacq.) spear leaf with contrasting susceptibility to *Ganoderma boninense*. Plant Omics 10(02):45–52

Ryu CM, Hu CH, Reddy MS et al (2003) Different signaling pathways of induced resistance by rhizobacteria in *Arabidopsis thaliana* against two pathovars of *Pseudomonas syringae*. J New Phytol 160:413–420

Ryvarden L (1991) Genera of polypores: nomenclature and taxonomy. Synopsis fungi, p 5

Said NU, Omar DZ, Nasehi AB, Wong MY (2019) Pyraclostrobin suppressed Ganoderma basal stem rot (BSR), promoted plant growth and induced early expression of beta-1, 3-glucanase in oil palm (*Elaeis guineensis*). J Oil Palm Res 31:248–261

Sambanthamurthi R, Singh R, Kadir APG et al (2009) Opportunities for the oil palm *via* breeding and biotechnology. In: Breeding plantation tree crops: Tropical species. Springer, New York, NY, pp 377–421

Sanderson FR (2005) An insight into spore dispersal of *Ganoderma boninense* on oil palm. Mycopathologia 159(1):139–141

Sanderson FR, Pilotti CA, Bridge PD (2000) Basidiospores: their influence on our thinking regarding a control strategy for basal stem rot of oil palm. *Ganoderma* diseases of perennial crops, pp 113–119

Santoso H, Gunawan T, Jatmiko RH et al (2011) Mapping and identifying basal stem rot disease in oil palms in North Sumatra with QuickBird imagery. Precis Agric 12(2):233–248

Sapak Z, Meon SA, Ahmad ZA (2008) Effect of endophytic bacteria on growth and suppression of *Ganoderma* infection in oil palm. Int J Agric Biol 10:127–132

Sariah M, Zakaria H (2000) The use of soil amendments for the control of basal stem rot of oil-palm seedlings. *Ganoderma* diseases of perennial crops:89–99

Sariah M, Hussin MZ, Miller RNG et al (1994) Pathogenicity of *Ganoderma boninense* tested by inoculation of oil palm seedlings. Plant Pathol 43(3):507–510

Sariah M, Choo CW, Zakaria H et al (2005) Quantification and characterisation of *Trichoderma* spp. from different ecosystems. Mycopathologia 159(1):113–117

Seo GS, Kirk PM (2000) Ganodermataceae: nomenclature and classification. *Ganoderma* diseases of perennial crops, pp 3–22

Shahbandeh (2021). https://www.scribbr.com/apa-examples/website/

Shamala S (2013) First report: isolation of endophytic Trichoderma from oil palm (*Elaeis guineensis* Jacq.) and their *in vitro* antagonistic assessment on *Ganoderma boninense*. J Oil Palm Res 25(3):368–372

Shamala S, Chris D, Sioban O et al (2006) Preliminary studies on the development of monoclonal antibodies against mycelia of *Ganoderma boninense*, the causal pathogen of basal stem rot of oil palm. Malays J Microbiol 2(1):30–34

Shu'ud MM, Loonis P, Seman IA (2007) Towards automatic recognition and grading of *Ganoderma* infection pattern using fuzzy systems. T Eng Comput Technol 19:1–6

Siddiqui Y, Surendran A, Fishal EMM (2019) Inhibition of lignin degrading enzymes of *Ganoderma* spp.: an alternative control of basal stem rot disease of oil palm. Int J Agric Biol 3:523–530

Singh G (1990) *Ganoderma* - The scourge of the oil palm in the coastal areas. In: Proceedings of *Ganoderma* workshop. PORIM, Bangi, Selangor, pp. 113-131

Singh G (1991) *Ganoderma* - The scourge of the oil palm in the coastal areas. The Planter 67:421–444

Singh RP, Verma RC, Arora RK et al (2007) Medicinal mushrooms of Uttaranchal with reference to *Ganoderma, Auricularia* and *Cordyceps sinensis*. In: Rai RD, Singh SK, Yadav MC, Tewari RP (eds) Mushroom biology and biotechnology. Mushroom Society of India, Solan, pp 322–324

Singh SK, Doshi A, Pancholy A, Pathak R (2013) Biodiversity in wood–decay macro–fungi associated with declining arid zone trees of India as revealed by nuclear rDNA analysis. Eur J Plant Pathol:1–10

Siswanto, Darmono TW (1998) Chitinase and β-1,3-glucanase activities against *Ganoderma* sp. in oil palm. Biotechnology Research Unit for Estate Crops, Bogor, pp 104–114

Smith SE, Read DJ (1997) Mycorrhizal symbiosis, 2nd edn. Academic Press, London

Smith BJ, Sivasithamparam K (2000) Internal transcribed spacer ribosomal DNA sequence of five species of *Ganoderma* from Australia. Mycol Res 104(8):943–951

Soepena H, Purba RY, Pawirosukarto S (2000) A control strategy for basal stem rot (*Ganoderma*) on oil palm. *Ganoderma* diseases of perennial crops, pp 83–88

Stangoulis J, Graham R (2007) Boron and plant disease. In: Mineral nutrition and plant disease American Phytopathological Society (APS) Press. pp 207–214

Steyaert RL (1972) Species of *Ganoderma* and related genera mainly of the Bogor and Leiden Herbaria. Pers Mol Phylogeny Evol Fungi 7(1):55–118

Steyaert RL (1980) Study of some *Ganoderma* species. Bulletin du Jardin botanique national de Belgique/Bulletin van de Nationale Plantentuin van België, pp 135–186

Sujarit K, Pathom-aree W, Mori M et al (2020) *Streptomyces palmae* CMU-AB204T, an antifungal producing-actinomycete, as a potential biocontrol agent to protect palm oil producing trees from basal stem rot disease fungus, *Ganoderma boninense*. Biol Control 148:104307

Sundram S, Abdullah F, Ahmad ZAM et al (2008) Efficacy of single and mixed treatments of *Trichoderma harzianum* as biocontrol agents of *Ganoderma* basal stem rot in oil palm. J Oil Palm Res 20:470–483

Sundram S, Meon S, Seman IA et al (2011) Symbiotic interaction of endophytic bacteria with arbuscular mycorrhizal fungi and its antagonistic effect on *Ganoderma boninense*. J Microbiol 49(4):551–557

Sundram S, Meon S, Seman IA et al (2015) Application of arbuscular mycorrhizal fungi with *Pseudomonas aeruginosa* UPMP3 reduces the development of *Ganoderma* basal stem rot disease in oil palm seedlings. Mycorrhiza 25(5):387–397

Suryanto D, Wibowo RH, Siregar EBM et al (2012) A possibility of chitinolytic bacteria utilization to control basal stems disease caused by *Ganoderma boninense* in oil palm seedling. Afr J Microbiol Res 6(9):2053–2059

Susanto A, Sudharto PS, Purba RY (2005) Enhancing biological control of basal stem rot disease (*Ganoderma boninense*) in oil palm plantations. Mycopathologia 159(1):153–157

Tan CJ, How KC, Loh-Mia PP et al (2002) Bioactivity of selected actinomycetes against *Ganoderma boninense*. Asia-Pac J Mol Biol Biotechnol 10:119–125

Tan MISMH, Jamlos MF, Omar AF, Dzaharudin F, Chalermwisutkul S, Akkaraekthalin P (2021) *Ganoderma boninense* disease detection by near-infrared spectroscopy classification: a review. Sensors 21(9):3052

Tee SS, Tan YC, Abdullah F et al (2013) Transcriptome of oil palm (*Elaeis guineensis* Jacq.) roots treated with *Ganoderma boninense*. Tree Genet Genomes 9(2):377–386

Tengoua FF, Hanafi MM, Idris AS (2014) Effect of micronutrients-enriched fertilizers on basal stem rot disease incidence and severity on oil palm (*Elaeis guineensis* Jacq.) seedlings. Am J Appl Sci 11(10):1841–1859

Thivina V, Hashim U, Gopinath SCB, Ayoib A, Nordin NKS, Uda MNA, Uda MA (2021) Distinct detection of *Ganoderma boninense* on metal oxides-gold nanoparticle composite deposited interdigitated electrode DNA sensor. J Phys Conf Ser 2129(1):012050

Thompson IA, Huber DM (2007) Management and plant disease. In: Mineral nutrition and plant disease. American Phytopathological Society, St. Paul

Ting ASY, Hermanto A, Peh KL (2014) Indigenous actinomycetes from empty fruit bunch compost of oil palm: evaluation on enzymatic and antagonistic properties. Biocatal Agric Biotechnol 3(4):310–315

Tomlinson J, Boonham N (2008) Potential of LAMP for detection of plant pathogens. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources 3(066):1–7
Turner PD (1965) The incidence of *Ganoderma* disease of oil palm in Malaysia and its relation to previous crop. Ann Appl Biol 55:417–423
Turner PD (1981) Oil palm diseases and disorders. Oxford University Press, Kuala Lumpur, p 298
Usherwood NR (1980) The effects of potassium on plant disease. In: Potassium for agriculture: a situation analysis. Potash and Phosphate Institute, Atlanta, pp 151–164
Utomo C, Niepold F (2000) Development of diagnostic methods for detecting *Ganoderma*-infected oil palms. J Phytopathol 148(9-10):507–514
Utomo C, Werner S, Niepold F (2005) Identification of *Ganoderma*, the causal agent of basal stem rot disease in oil palm using a molecular method. Mycopathologia 159(1):159–170
Veresoglou SD, Barto EK, Menexes G et al (2013) Fertilization affects severity of disease caused by fungal plant pathogens. Plant Pathol 62(5):961–969
Vidhyasekaran P, Rabindran R, Muthamilan M et al (1997) Development of a powder formulation of *Pseudomonas fluorescens* for control of rice blast. Plant Pathol 46(3):291–297
Virdiana I, Hasan Y, Aditya R et al (2010) Testing the effects of oil palm replanting practices (windrowing, fallowing and poisoning) on incidence of *Ganoderma*. Proc IOPC, p 7
Vylkova S (2017) Environmental pH modulation by pathogenic fungi as a strategy to conquer the host. PLoS Pathog 13(2):e1006149
Wang M (ed) (2015) Industrial tomography: systems and applications. Elsevier
Widiastuti H (2011) Effect of arbuscular mycorrhizal fungi and *Trichoderma* inoculation on growth of oil palm seedling inoculated with *Ganoderma* sp. Bioscience and Biotechnology (ICBB), p 57
Wiratmoko D, Jatmiko RH, Yusuf MA et al. (2020) Using visible spectral-index as alternative methods for identifying levels of *Ganoderma boninense* infection. In: IOP conference series: earth and environmental science, vol. 500, No. 1. IOP Publishing, p 012067
Wong L, Bong CFJ, Idris AS (2012) Ganoderma species associated with basal stem rot disease of oil palm. Am J Appl Sci 9(6):879–885
Worrall EA, Hamid A, Mody KT et al (2018) Nanotechnology for plant disease management. Agronomy 8(12):285
Wulandari YRE, Felicia F, Arifin AR et al (2018) EgMLP1 gene expression in oil palm ramet infected with *Ganoderma boninense*. Int J Oil Palm 1(2):71–78
Yokhin B, Tisdale RC (1993) High-sensitivity energy-dispersive XRF technology Part 1: overview of XRF technique, Am Lab, 36G
Zaiton S, Sariah M, Zainal Abidin MA (2006) Isolation and characterization of microbial endophytes from oil palm roots: Implication as biocontrol agents against *Ganoderma*. The Planter 82:587–597
Zaiton S, Sariah M, Ahmad ZAM (2008) Effect of endophytic bacteria on growth and suppression of *Ganoderma boninense* infection in oil palm. Int J Agric Biol 10:127–132
Zakaria L, Ali NS, Salleh B et al (2009) Molecular analysis of *Ganoderma* species from different hosts in Peninsula Malaysia. J Biol Sci 9(1):12–20
Zhao L, Xu Y, Lai XH et al (2015) Screening and characterization of endophytic *Bacillus* and *Paenibacillus* strains from medicinal plant *Lonicera japonica* for use as potential plant growth promoters. Braz J Microbiol 46:977–989
Zheng G, Moskal LM, Kim SH (2012) Retrieval of effective leaf area index in heterogeneous forests with terrestrial laser scanning. IEEE Trans Geosci Remote Sens 51(2):777–786