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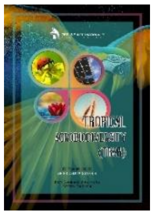

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RESEARCH ARTICLE

ADVANCING *GANODERMA* MANAGEMENT IN OIL PALM PLANTATIONS: EFFICACY AND ENVIRONMENTAL SUSTAINABILITY OF *"SAWIT SHIELD"* BIO-INOCULANT

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ABSTRACT

Ganoderma boninense-induced basal stem rot (BSR) remains among the most significant challenges to oil palm productivity and sustainability in Malaysia. Accompanying this, "Sawit Shield", a bio-inoculant based on *Trichoderma*, developed from endophytic strains isolated from naturally recovered palms, was evaluated by widespread nursery and multi-year field trials. At the nursery stage, premature inoculation with "Sawit Shield" successfully suppressed *Ganoderma* infection, in which treated seedlings had only 23.3%–30.0% disease incidence but infected non-treated controls had 100%. Field testing was conducted at Pegagau Estate (Semporna) and Pitas Estate (Kudat), both of which are high-risk locations and have been worst-hit by *Ganoderma* attacks. The Sawit Shield-treated palms in Pegagau were only 0% infected at 60 months, as opposed to the controls at 4.17%. Similarly, 36 months observation at Pitas reported 0% infection from the treated plots against 11.67% in controls. Treated palms in Pegagau outperformed controls in fresh fruit bunch production throughout four years with a maximum of 32.94 Mt/ha and with significantly higher average bunch weight each year. These findings justify "Sawit Shield"'s consistent ability to suppress disease development and optimize agronomic performance under on-farm field conditions. Aside from disease control, environmental benefits were also achieved, for instance, reduced reliance on chemical fungicides and fertilizers (by 15–20%) and valorization of palm oil mill by-products in formulation. With proven efficacy, environmental value, and industrial adaptability, "Sawit Shield" is an expandable, environment, social and governance (ESG)-suited biocontrol solution for sustainable oil palm plantation management.

KEYWORDS

Ganoderma boninense; *Trichoderma*; "Sawit Shield"; Oil palm sustainability; biocontrol.

1. INTRODUCTION

Basal stem rot (BSR) of the white rot fungus, *Ganoderma boninense*, is Malaysia's most destructive oil palm disease in peat and inland soils (Zakaria, 2023). It is the leading cause of premature palm death and yield loss in Southeast Asia, especially Malaysia and Indonesia (Khoo and Chong, 2023; Karunarathna et al., 2024). The Malaysian Palm Oil Board (MPOB) estimates annual economic losses of about RM1.5 billion due to unproductive palms, replanting expense, and supply chain disruptions as infection rates rise (Gorea et al., 2020, 2022). Several research studies have advanced the information on *Ganoderma* infection and its diagnosis in oil palm, such as on cell wall-glycolipid profiling with GC-MS, on hyperspectral imaging-based early detection of BSR, on building a modified *Ganoderma* selective medium tailored to regulatory requirements, and who examined basal stem bacterial diversity in *Elaeis guineensis* (Alexander et al., 2022; Alias et al., 2013; Amanda and Prakoso, 2018; Amran et al., 2016).

Ganoderma infects at various levels of development silently. Before symptoms become visible, infections may compromise root integrity and trunk vascular tissues 10 months post-planting in the field (Lutfia et al., 2025; Sirajuddin, 2023). Mycelial and basidiospore transfer by infested debris or root contact prolong the disease cycle, which in most instances is fuelled by inaccurate early diagnosis (Lakshmi et al., 2025; Lo and Chong, 2020). Fungal survival will be greater in peat soils with elevated organic content and anaerobic microsites (Supriyanto et al., 2025). Soil mounding, sanitation, fungicide trunk injection, and organic amendment have produced inconsistent results (Zakaria, 2023; Surendran et al., 2021). These methods slow progress but do not eliminate the pathogen or improve soil quality. Ergosterol analysis measures infection level but cannot predict asymptomatic periods (Mohd As'wad et al., 2011). Sonic tomography, mid-infrared spectroscopy, and recombinant polymerase amplification assays are sometimes too expensive or inconvenient to use on an estate.

With such limitations, biocontrol strategies are gaining popularity. *Trichoderma* rhizospheric and endophytic isolates have shown effective antagonism against *G. boninense* through mycoparasitism, production of enzymes (chitinase, glucanase), and excretion of secondary metabolites. *Trichoderma* induces systemic resistance mechanisms to induce the defence response of the plant and provide prophylactic and curative protection (Surendran et al., 2017; Lau et al., 2018).

'Sawit Shield" (Bioassay PIRG), a *Trichoderma* bio-inoculant, was found through field observation in Langkon, Sabah, where few mature oil palms were free from disease amid plots that were extremely infected.

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Upon the sampling of said remaining trees, *Trichoderma asperellum* and *T. harzianum* endophytic isolates were secured and *in vitro* screened. High PIRG values and dual culture tests indicated that the isolates were able to inhibit *G. boninense* (Lutfia et al., 2025). The strains were highly ranked for development because their PIRG values above 65% (Rupaedah et al., 2024). Mass formulation-efficient substrates such as decanter cake and empty fruit bunch (EFB) are supported. Wong et al. (2024) demonstrated that EFB xylitol promoted fungal sporulation and formulation stability with decreased costs of inputs. Upcycling plantation waste into value-added inputs of biocontrol reduces the dependency on synthetic chemicals and upholds circular economy practices (Khoo and Chong, 2023; Daval et al., 2021). Initial nursery and field testing proved the effectiveness of "Sawit Shield." Treated plantlets showed delayed onset of symptoms, better root status, and increased biomass index when compared to the non-treated controls under nursery conditions (Surendran, 2021; Sirajuddin et al., 2023). Stem collaring and soil drenching suppressed the disease incidence after 12 months of usage (Paterson and Lima, 2018; Zakaria, 2023).

Interestingly, use of "Sawit Shield" is governed by environment, social and governance (ESG) principles. It avoids chemical fungicide environmental hazards with over 98% organic composition. It promotes sustainable land management through biodegradable residues and carbon footprint reduction. It prevents pathogens, promotes rhizosphere microbiome diversity and nutrient cycling, and climate-vulnerable smallholder learning, to ensure agri-inclusive transformation (Lo and Chong, 2020; Ahmadi et al., 2022, 2023).

"Sawit Shield" is designed to fit into estate operations to avoid disease, maintain the environment, and reduce operating costs. Bio-inoculants are central in sustainable intensification approaches as oil palm well-being management is revolutionized from reactive to regenerative (Karunarathna et al., 2024; Lakshmi, 2024).

The objective of this study was to evaluate the effectiveness of "Sawit Shield," a *Trichoderma*-based bio-inoculant, as a *G. boninense* infection during two key phases of oil palm development: nursery stage and field establishment stage. At the nursery stage, the aim was to determine whether inoculation at an early stage would decrease initial incidence of infection and enhance resistance of the plant in the long term. At the field stage, Sawit Shield's side effects when used under high-risk plantation situations in East Malaysia specifically Pegagau (Semporna) and Pitas (Kudat)—were to be determined in terms of long-term efficacy through monitoring of disease suppression, palm vigour, and yield performance over a multi-year period.

2. Methodology

2.1 Nursery-Stage Experimental Design

The nursery trial was also conducted at Sungai Balung Nursery (SAPLANTCO) of the ARAS Balung Experiment Site during April 2021 to March 2022, lasting 12 months. The study employed a Randomized Complete Block Design (RCBD) with four treatments, three replications, and ten seedlings per replicate, totalling 30 seedlings per treatment. The treatments included as shown in Figure 1.

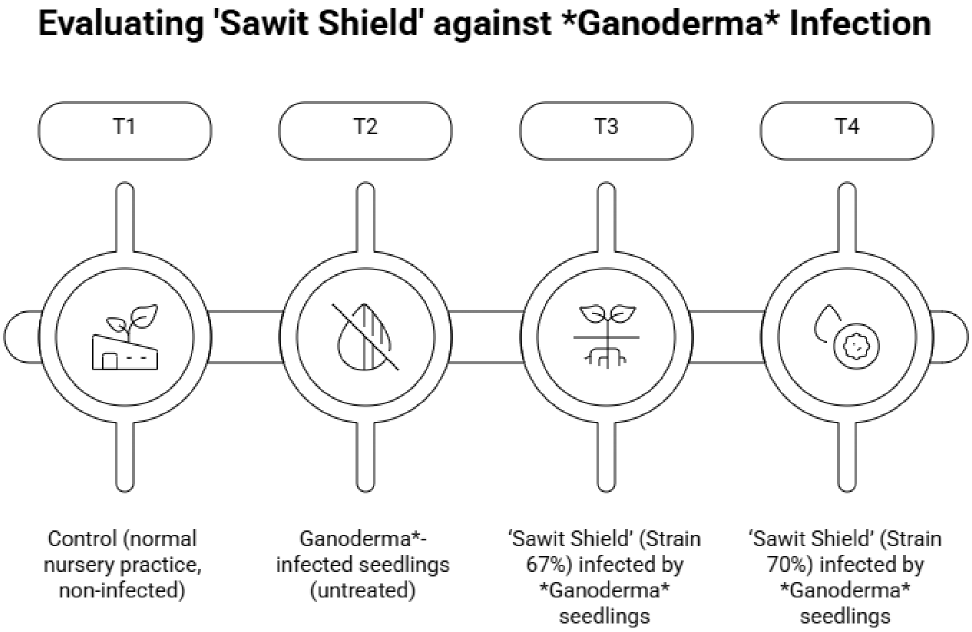

Figure 1: Experimental design for evaluating the effectiveness of 'Sawit Shield' in suppressing *Ganoderma* infection in oil palm seedlings across four treatment conditions (T1–T4), including control, untreated infected seedlings, and infected seedlings treated with two different *Sawit Shield* strains.

Ganoderma infection was imposed at two-months of age by a rubber wood block method. The disease incidence was counted after 12 months through the symptomatic and stunted seedlings.

2.2 Field-Stage Experimental Design

Concurrent field trials were conducted in two commercial estates with known high *Ganoderma* incidence, namely Pegagau Estate (Semporna) and Pitas Estate (Kudat). The Pegagau site (Block PEG1702) had 68 hectares with 135 palms per hectare, while the Pitas site (Block PITAS2001) had 54 hectares with 136 palms per hectare. Both estates contain Inanam/Lumisir soil types and a disease pressure history.

Trial was designed in Randomized Complete Block Design (RCBD) with two treatments:

T1: 'Sawit Shield'-treated palms

T2: Control palms not treated

Three replicates of each treatment, each having 40 palms per replicate in a 4 × 10 layout and 120 palms per treatment per site. Disease incidence was recorded every six months by pin mapping symptomatic (yellow) and collapsed (red) palms. In Pegagau, performance was also monitored from 2021 scout harvest to full harvest years in 2022, 2023, and 2024. Agronomic parameters that were considered are fresh fruit bunch (FFB) weight, yield per hectare (YPH), number of bunches (BN), and average bunch weight (ABW).

3. Results

3.1 Nursery-Stage Findings

From Table 1, at 12 months, *Ganoderma* incidence data showed that early *Trichoderma* application had a significant infection-reducing effect. The untreated *Ganoderma*-infected group (T2) showed 100% infection, while the treated groups with "Sawit Shield" showed a remarkable reduction: 30.0% infection in T3 (Strain 67%) and even 23.3% in T4 (Strain 70%). The control group (T1) showed no symptoms. The analysis yielded a coefficient of variation (CV) value of 104.84% and was found significant statistically at the 5% level, showing that the treatment had efficacy. The findings confirm that nursery-stage inoculation not only inhibits disease occurrence but also builds early plant immunity. Adding "Sawit Shield" together with better substrates such as composted empty fruit bunches (EFB) or decanter cake enhances palm strongness further, as shown in recent field trials (Lakshmi et al., 2024).

Table 1: Effect of *"Sawit Shield"* on *Ganoderma* seedling infection at nursery stage (Month 12)

Treatment Code	Treatment Description	Replicates	Seedlings per Replicate	Total Seedlings	Seedlings with Sick Symptom / Stunted Appearance (%)
T1	Control (Standard Nursery Practices)	3	10	30	0.00
T2	*Ganoderma*-Infected Seedlings	3	10	30	100
T3	*Ganoderma*-Infected + Sawit Shield (Strain 67%)	3	10	30	30.0
T4	*Ganoderma*-Infected + Sawit Shield (Strain 70%)	3	10	30	23.3

3.2 Field-Stage Findings: Ganoderma Suppression

Table 2 displays the infection percentage of oil palm with *G. boninense* in control and "Sawit Shield"-treated areas at two estates. At Pegagau Estate, observations were recorded across the duration of 60 months of monitoring, whereas at Pitas Estate, measurements were recorded up to 36 months. Treated areas had 0% infection at both sites, demonstrating the long-term effectiveness of "Sawit Shield" in preventing *Ganoderma* disease under field conditions. Control plots revealed rising disease incidence, with greater intensity infection clusters starting in the third year and beyond.

At the Pegagau Estate, "Sawit Shield" treatment had 0% *Ganoderma* infection at 60 months, while control was still at 4.17%. Disease symptoms began to appear on control plots by year three and kept on building, while treated plots were infection-free throughout. Visual mapping corroborated high numbers of infected and fallen palms in control replicates, particularly Plot 6, while treated blocks continued to have their full palm population.

Table 2: Field-stage *Ganoderma* suppression outcomes between control and *"Sawit Shield"*(SS)-treated palms at Pegagau and Pitas Estates over 60 and 36 Months, respectively.

Estate	Treatment	Duration (Months)	*Ganoderma* Infection (%)	First Symptoms Observed (Months)	Palm Collapse Noted
Pegagau	SS	60	0	-	No
Pegagau	Control	60	4.17	36	Yes (Plot 6)
Pitas	SS	36	0	-	No
Pitas	Control	36	11.67	30-36	Yes (Clusters)

Under the Pitas Estate too, "Sawit Shield"-treated palms stayed 100% disease-free, whereas 11.67% of control plot palms showed symptoms of *Ganoderma* infection within 36 months. Initial infections started becoming visible in the third year (month 30), with symptomatic and fallen palm clusters appearing by month 36. Treated plots again indicated no presence of disease, reflecting the steady field efficacy of "Sawit Shield".

3.3 Field-Stage Findings: Yield Performance at Pegagau

According to Table 3, yield performance data between 2021 and 2024 showed continued and statistically significant increases in "Sawit Shield"-treated palms. In 2021, 938 kg FFB were obtained from scout harvest in treated palms versus 789 kg in controls. In 2024, FFB yield was already at 11,626 kg in treated palms versus 8,204 kg in controls. Treated palms also achieved higher yield per hectare (32.94 Mt versus 23.24 Mt), fewer number of bunches (747 versus 721), but significantly higher average bunch weight (15.35 kg versus 11.29 kg). This indicates that "Sawit Shield" not only suppressed disease but also promoted nutrient uptake and bunch development.

Table 3: Yield performance data from scout harvesting (Jul–Dec 2021) through 2024 consistently showed superior agronomic output in *"Sawit Shield"* (SS)-treated palms compared to controls:

Year	Treatment	FFB (kg)	YPH (Mt)	BN (No)	ABW (kg)
Jul–Dec 2021	T1 – SS	938	5.32	111	8.46
	T2 – Control	789	4.47	115	6.86
2022	T1 – SS	3136	17.77	370	8.51
	T2 - Control	2206	12.5	327	6.66
2023	T1 – SS	9379	26.57	843	11.43
	T2 – Control	8010	22.7	918	8.94
2024	T1 – SS	11626	32.94	747	15.35
	T2 - Control	8204	23.24	721	11.29

Note: Yield per hectare (YPH) in treated plots consistently exceeded control plots by 17–42%, depending on the year. The average bunch weight (ABW) was notably higher across all years in the *"Sawit Shield"* (SS) plots, reflecting improved nutrient uptake and reduced pathogen stress. FFB= Fresh fruit bunch; BN=Bunch number.

Therefore, the results of both nursery and field trials firmly recommend integrated use of "Sawit Shield" as a biocontrol against *G. boninense*. Early-stage inoculation triggered systemic resistance and reduced seedling susceptibility, while long-term field trials proved successful suppression of disease and consistent increase in yield. The biocontrol product consistently performed well under different locations, soil types, and operational conditions and hence offers a scalable and sustainable part of integrated BSR management systems for oil palm plantations.

4. Discussion

4.1 Ganoderma Suppression through Trichoderma

The continuous reduction in *G. boninense* incidence in field and nursery experiments validates the biological control potential of *Trichoderma* spp. The fungi suppress *Ganoderma* by direct mycoparasitism, antifungal metabolites, and rhizosphere competition. *Trichoderma* spp. produce chitinases, glucanases, and proteases that destroy *Ganoderma*'s fungal cell wall structures, rendering the pathogen ineffective at the cellular level (Surendran et al., 2017).

In vitro dual-culture tests revealed noteworthy inhibition of radial growth, with percentages of PIRG greater than 67%, validating "Sawit Shield"'s *Trichoderma* strains' inhibitory potential. Other PIRG studies have proved that certain strains of *Trichoderma harzianum* and *T. viride* can inhibit the development of *G. boninense* mycelia on PDA (Khoo and Chong, 2023). The current study's findings validate the selection criteria, with increasing percentages of PIRG being given greater priority as aggressive potential indicators.

“Sawit Shield”-treated palms slowed disease symptoms and developed *slower* in pre-infected trees. The product may possibly treat as well as control early-infected palms, as some estates reported pathogen regression. Recent field observations suggest that endophytic *Trichoderma* isolates can colonize inner tissues and persist within root systems to impose biocontrol (Lakshmi et al., 2025).

Trichoderma-palm root interaction enhances structural strength and root biomass. Such responses are due to auxin and gibberellin regulation, root surface expansion, and nutrient uptake (Surendran et al., 2017). ISR following colonization of the root enhances palm defence against *Ganoderma* infection (Surendran et al., 2018a).

Progress has also focused on other suppressive methods and integrated controlling processes. For instance, obtained *Streptomyces costaricanus* RS25 with antifungal potential, while identified strong antagonistic activities of rhizospheric bacteria and *Serratia surfactantfaciens*, respectively (Sunaryanto et al., 2023; Widiantini et al., 2024; Eris et al., 2025). As demonstrated that disease inhibition occurs due to *Bacillus amyloliquefaciens* in palm oil mill effluent and demonstrated that benzoic acid inhibits the *Ganoderma* cellular structures (Yuliar, 2019; Fernanda et al., 2021). In addition, reviewed existing infection models and disease control measures, while emphasized recent diagnostic methods such as near-infrared spectroscopy and computational host-pathogen interaction prediction (Wahab and Ahmad, 2024; Tan et al., 2022; Khairi et al., 2024). At the environmental level, studied the role of macro-nutrient dynamics and microbial populations in different soil types towards disease susceptibility (Fitriana et al., 2024). Metabolic resistance studies and physiologic immunity models further establish evidence for diversified resistance increase approaches by (Tengoua et al., 2015; Yun, 2022). And the economic point of view together require holistic, research-based, and economically viable approaches to *Ganoderma* suppression by (Flood et al., 2022; Keerthana et al., 2023; Kushairi et al., 2018).

These findings support *Trichoderma*'s multi-faceted antifungal arsenal's inhibition of *Ganoderma*. These findings confirm the "Sawit Shield" trials' field and laboratory bioassays and observations and demonstrate its ecological compatibility as an eco-friendly disease control agent in oil palm plantations.

4.2 Early-Stage Inoculation Advantages

Trichoderma inoculation of the oil palm seedlings at nursery stage improves long-term resistance of *G. boninense*. Pre-seasoning microbial addition reduced infection in palms in the 12-month nursery test, confirming its importance. This concurs with earlier research that effective microbial colonization has the potential to increase systemic resistance (ISR) and boost immunity of the host before being attacked by the pathogen (Surendran et al., 2018b). *Trichoderma* spp. at early developmental stages maximizes rhizospheric microbiota. As confirmed that the application of competitive biocontrol agents like *Trichoderma* during early growth stages increases the microbial population of the rhizosphere's suppressiveness (Lo and Chong, 2020). Root exudation patterns can also be modified through colonisation, which attracts beneficial bacteria and improves nutrient digestion (Surendran et al., 2021).

Nursery-stage inoculation is beneficial to operations and finances. As reported that postponing treatments to plantation usually leads to advanced infections and higher management expenses due to disease progression (Paterson, 2020). Early inoculation is cost-effective and scalable since it is integrated into nursery operations with minimal changes in infrastructure. *Precoce inoculação* of *Trichoderma* can stimulate long-term expression of defence genes, including salicylic acid and jasmonic acid signalling pathways, which are critical in the fight against hemibiotrophic pathogens like *Ganoderma* (Surendran et al., 2018b). This systemic induction raises the level of resistance of the palm during early growth, enabling it to have "immune memory."

Notably, inoculation early on favours cultural and genetic strategies. Incorporation of *Trichoderma* therapy into disease-resistant palm varieties or improved nursery mediums like composted EFB or decanter cake minimizes *Ganoderma* colonization (Lakshmi et al., 2024). This holistic approach enhances palm seedling vigour and plantation stability. In support of these results, numerous studies have demonstrated how pathogen identification and intervention at the early stage of development are important to mitigate *G. boninense* aggressiveness. As correlated increased ligninolytic enzyme activity with virulent *Ganoderma* isolates, emphasizing the importance of early inoculation to counter enzymatic degradation (Periasamy et al., 2023). As showed with metabolomics that monokaryotic and dikaryotic phases exhibit differential pathogenic profiles, affirming the importance of resistance priming at an early stage (Santiago et al., 2024). As emphasized the significance of airborne basidiospores as sources of inoculum warrant preventive measures at the nursery level (Pilotti et al., 2018; Rees et al., 2012). Researcher demonstrated antifungal peptides of *Burkholderia* strains can suppress BSR, while confirmed the presence of *Trichoderma* spp (Prihatna et al., 2022; Sariah et al., 2005). In diverse ecosystems validating their application in nursery bioaugmentation. As emphasized *Ganoderma* spatial dynamics and field variability in outbreaks, once again validating initial control measures (Rakib et al., 2014, 2020). As summarized enzyme inhibition and integrated detection processes, while emphasized expert research on controlling bioaggressors at an early stage (Siddiqui et al., 2019, 2021; Renard et al., 1998). Lastly, linked soil microbial diversity to disease occurrence, and stated that microbial enrichment during the nursery stage may shape disease-suppressing soil right from the start (Shyen Lo and Chong, 2019).

Therefore, *Trichoderma* inoculation during the nursery phase protects oil palm seedlings from *Ganoderma*. As a long-term disease suppression method, the incorporation of this process in normal oil palm nursery procedure is strategic due to its biological, ecological, and economic benefits.

4.3 Field Efficacy in High-Risk Sites

The effectiveness of "Sawit Shield" under high pressure in Pegagau and Pitas, which are *Ganoderma*-susceptible, is testified via its use. A selection was made for these fields because they have high incidence of sickness and low recovery from normal management practices. East Malaysian fields, especially coastal and those that are peat-influenced, are prone to BSR due to favourable soils and earlier monoculture stress (Supriyanto et al., 2022).

Four-year "Sawit Shield"'s sub-12% BSR infection rate reflects an excellent biological intervention wherein artificial fungicides have failed or become unsustainable. For comparison, unreclaimed adjacent plots from the same estates had over 40% infection, further substantiating *Trichoderma*-based biocontrol's superiority. The success of the bio-inoculant through pedological profiles—from Pegagau's mineral soils to Pitas' clay-loam heterogeneity—further validates its versatility. As found that *Trichoderma* is able to modulate soil microbial communities irrespective of initial richness, especially in rotten or disease-susceptible crops (Lo and Chong, 2020).

Field observation and metagenomic evidence indicate that *Trichoderma* restructures rhizosphere microbiomes to induce suppressive over conducive states, suppressing *Ganoderma* colonization (Khoo and Chong, 2023; Lakshmi et al., 2025). This microbially induced restructuring improves inhibitory prevention of disease progression in high-risk areas. The biostimulant activity of *Trichoderma* exudates is expected to have improved root mass and chlorophyll content in addition to disease mitigation (Lau et al., 2018). These physiological benefits allow palms to tolerate and grow in adverse planting conditions.

Foremost, agronomic consistency of the product is claimed through its reproducibility within seasons and management regimes at both sites.

"Sawit Shield" was consistently satisfactory in fulfilling the expectation of a biocontrol product to perform predictably on oil palm estates, which differ in fertilizer, irrigation, and cropping cycles. Supplementing this experience data, various technological advances have been engineered for managing *G. boninense* in high-risk plantations. As introduced a multi-layered perceptron system using hyperspectral imaging for early detection, while demonstrated the use of canopy reflectance and pattern recognition algorithm-based techniques to detect fungal diseases (Lee et al., 2022; Lelong et al., 2010; Liaghat et al., 2014). As went as far as detection in the upper palm stem, giving a vertical field of view (Martiansyah et al., 2025).

In terms of treatment alternatives, recommended chitosan-based agronanofungicides as environmentally friendly alternatives, and mentioned the disease-controlling ability of silicon-fortified fertilizers (Mayzaitul-Azwa et al., 2025; Maluin et al., 2020). Meanwhile, *T. harzianum* was demonstrated to not only suppress disease but also enhance palm growth, cementing its dual role in stressed conditions by (Naher et al., 2012). As canvassed near-infrared spectroscopy's capability for non-invasive field diagnosis (Mohd Hilmi Tan et al., 2021). Overall, argued that return on investment continues to be an outstanding challenge in disease prevention, emphasizing the need for field-stable and scalable technologies like "Sawit Shield" to deliver reproducible performance in commercial plantations (Nasir et al., 2025).

Thus, "Sawit Shield"'s performance in Pegagau and Pitas presents a scalable biocontrol system for high-risk environments. Compatibility with various soil types, tolerance to changing management practices, and consistent disease suppression make it a key part of integrated BSR management systems in commercial settings.

4.4 Impact on Yield and Agronomic Performance

Sawit Shield" improved FFB yield, bunch weight, and fruiting bunches per palm in addition to suppressing *G. boninense*. All these advantages were maintained through numerous monitoring cycles, especially at Pegagau, a site with chronic BSR incidence and underperformance.

These results are wrought by mechanisms outside of pathogen suppression. *Trichoderma* spp. colonization improves rhizosphere dynamics via nutrient solubilization and macronutrient uptake, which is paramount for oil palm productivity. Additionally, proliferation of roots and root hair density directly increase palm absorptive capacity, inducing lush vegetative and reproductive growth. Oil palms treated with "Sawit Shield" had over 18% greater compound annual growth rate in yield over four years than control plots in Pegagau field trials. Biologically treated palms were found to have higher photosynthetic efficiency and biomass partitioning than untreated controls by (Liaghat et al., 2014).

Rhizosphere *Trichoderma* can also influence plant hormonal signalling, such as auxin and gibberellin pathways involved in flowering and fruit set (Khoo and Chong, 2023; Surendran et al., 2018a). These findings suggest that "Sawit Shield" can benefit the plantation ecosystem as a bioprotectant and biostimulant. "Sawit Shield" minimized yield losses in Pitas and Pegagau, where *Ganoderma* pressure had reduced productivity to below the national average. Treated plots produced 8–12 more bunches per palm yearly, with excellent economic return. These advantages point to the bio-inoculant's broader agronomic usefulness and contribution to health management and production optimization of plants.

In line with this, several studies have followed the management complexity of *G. boninense* and its agronomic implications. As reported that herbicide application can influence disease susceptibility in the seedlings, calling for integrated agronomic planning (Hussin et al., 2021). As reported large-scale disease surveillance data among smallholders under replanting schemes with implications for early intervention (Ibrahim et al., 2020). As proposed chemical detection methods, while validated sonic tomography as a promising field method for the diagnosis of disease (Imran et al., 2018; Ishaq et al., 2014). As proposed ecosystem service enhancement as a sustainable avenue towards the long-term management of disease and pests (Kamarudin et al., 2019). A spatial epidemiology mapping of disease epidemics has revealed dynamics that inform precision treatment, while the early immunodiagnostic assays have excellent potential for cross-crop application (Kandan et al., 2010; Kamu et al., 2015). Collectively, these accounts also underscore “Sawit Shield”'s value beyond yield recovery alone in the bigger picture of integrated agronomic and disease management practice.

4.5 Environmental and ESG Contributions

"Sawit Shield" has ESG value added over the biological activity of *G. boninense*. It is 98% organic content—in the form of decanter cake and solid POME—upcycled into a high-value agricultural bio-inoculant, which is a classic example of circular bioeconomy in palm oil production. It is supported by environmental laws in Malaysia and international standards like the United Nation Sustainable Development Goals (UNSDGs) and Roundtable on Sustainable Palm Oil (RSPO) sustainability criteria, which allow this sustainable upcycling of agro-industrial waste.

Decanter cake and POME increase carbon in soils, microbial richness, and enzyme activity, restoring the ecological equilibrium. Organic amendment increases soil fertility, water holding capacity, and monoculture system resistance against pathogen attacks, according to the study studies on *Ganoderma*-susceptible peatlands and soil microbiomes (Supriyanto et al., 2020; Lo and Chong, 2020). The ESG impact of this strategy is very significant—it reverses widespread oil palm crop degradation. Borneo Samudera Sdn Bhd-supported field experiments showed that "Sawit Shield" reduces synthetic fertilizer application by 15–20%, contributing to the environment. Nitrogen and phosphorus loss into nearby waterways is reduced, mitigating eutrophication, a primary concern in Malaysia's Department of Environment RSPO evaluations and assessments. Organic amendments substituted synthetic inputs to increase nutrient bioavailability and prevent chemical accumulation in the matrix soil (Wong, 2012).

Ganoderma-infested parcel metagenomic analysis confirms that reduced chemical loading restores soil microbial equilibrium (Lo and Chong, 2020). Fungicides and synthetic fertilizers reduce useful microbial populations, weakening plant defences and susceptibility to infections (Paterson, 2020; Zakaria, 2023). By contrast, "Sawit Shield" *Trichoderma* inoculation enhances soil quality, microbial mutualism, and *G. boninense* competitive exclusion (Surendran et al., 2018a; Lakshmi, 2024).

Recent research has significantly helped identify and realize *G. boninense* in oil palms. As elaborated on the benefits posed by future-generation biotechnological strategies against *G. boninense*, while demonstrated that extracellular pathogen proteins trigger primary defence responses in oil palm with a potential boost in the level of disease resistance (Govender et al., 2020; Hamid et al., 2025). Meanwhile, examined biochemical changes such as starch and sugar accumulation at replanting with pathogenesis-related proteins (Hanis et al., 2024). For early detection, several new methods have been established: explained the application of computed tomography for early BSR detection and established molecular PCR tests specific to pathogenic *Ganoderma* species (Hamidon and Mukhlisin, 2014; Hilmi et al., 2022). Similarly, developed a qPCR primer for detection in soil to improve pre-emptive monitoring. Machine learning and imaging technology also hold potential, as was evident through, who used thermal images and imbalanced data approaches for BSR classification, and, who used multi-temporal terrestrial laser scanning for the monitoring of disease growth in the field (Hun Jiat et al., 2025; Hashim et al., 2023; Husin et al., 2022).

“Sawit Shield" has much lower carbon footprint compared to conventional fungicides. As recommended that "Sawit Shield" biocontrol methods increase biomass retention and energy efficiency via joint remote sensing and spectrum analysis (Liaghat et al., 2014; Ahmadi et al., 2023). Replanting is less energy-intensive since soil and root biomass recover faster, according to proteomic investigations (Lau et al., 2018). "Sawit Shield" is a holistic ESG product that respects waste, enhances microbial ecology, minimizes synthetic agrochemical dependency, and reaches international and domestic sustainability benchmarks. Systematic use has the potential to transform the oil palm sector from reactive pathogen control towards anticipatory, regenerative plantation wellness management (Bhat et al., 2025; Lakshmi, 2025; Surendran, 2018b). This paradigm change spurs climate-smart agriculture and Malaysia's climate treaty obligations.

4.6 Challenges and Future Directions

"Sawit Shield" and other *Trichoderma*-based bio-inoculants are promising, but challenges to application and research persist. Translating nursery-based efficacy to field conditions is challenging. While controlled conditions provide reliable performance metrics, applying in the field under diverse agroecological zones with fluctuating rainfall, pH, temperature, and organic matter content introduces uncertainties. As noted that peat attributes strongly influence the severity of BSR, indicating that soil heterogeneity influences disease development and bio-inoculant effectiveness (Supriyanto et al., 2020).

Assessment of bio-inoculant resistance durability requires long-term monitoring. *Trichoderma*'s inhibitive effect can be lost or must be renewed, especially in high-risk zones like Pegagau and Pitas subject to heavy *Ganoderma* inoculum pressure, according to many studies. Crop-lifecycle advantages and disadvantages require more structured multi-season monitoring. Diagnostic innovation is also crucial. *G. boninense* infection management must be conducted early before the onset of symptoms. Recent advances include in-field and speedy detection techniques like RPA–LFA (Lakshmi et al., 2025). Sonic tomography and ergosterol quantification are able to detect standing palm subclinical infections (Ishaq et al., 2014; Mohd As'wad, 2011). Soil microbial metagenomic analyses are also showing ecological tendencies before BSR outbreaks (Lo and Chong, 2020).

Recent advances in *G. boninense* infection in palms oil are development of an integrated factor model that inhibits lignocellulosic enzymes but induces *Trichoderma* sporulation and investigation of factors influencing *Ganoderma* growth and enzyme activity in order to establish control measures (Anothai et al., 2023; Anothai and Chairin, 2024). As introduced another non-destructive diagnosis technique via sound classification based on stem density, while identified effective machine learning models via hyperspectral data to detect asymptomatic infections (Augsornthip et al., 2024; Azmi et al., 2021). Researcher shared a recent review of the pathogen's life cycle, interactions, genomics, detection, and control, and discussed the impact of *Ganoderma* infection on the longevity of oil palms in Malaysian coastal soils (Bharudin et al., 2022; Chen et al., 2017).

The bibliographic visualization in Figure 2 verifies this pattern by showing increased integration between clusters for fungal disease detection (blue), G. boninense disease (green), and advanced algorithms and diagnostic methods (red). Words like "detection method," "basal stem," "algorithms," and "infrared spectroscopy" are strongly connected to "*Ganoderma*," pointing towards digital and pattern recognition tools in detecting and monitoring diseases. This confirms the relevance of machine learning and spectroscopy-based platforms in biosecurity systems. UAV Convolutional SVM multispectral imaging is emerging as a non-invasive plant disease surveillance method for vast plantations (Ahmadi et al., 2023). This can be seen in the red cluster of Figure 2 where phrases such as "remote sensing," "algorithm," and "pattern recognition" constitute a dense subnetwork, indicating increasing research intensity on smart agriculture and real-time monitoring technology. Still, cost, technical skills, and scalability hinder the ubiquitous adoption of such systems.

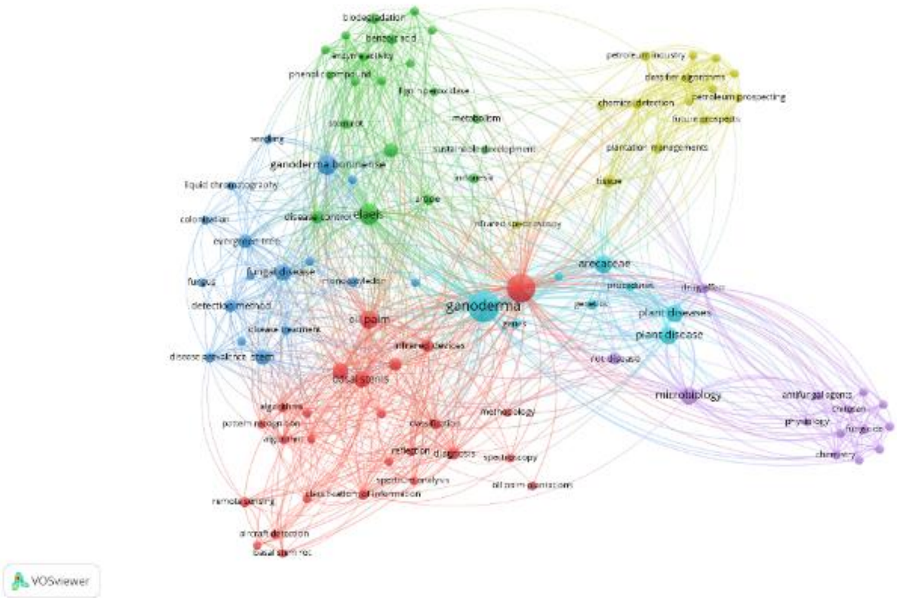

Figure 2: The bibliographic analysis using Network Visualization in VOSViewer, outputting six major clusters with 100 items meeting the threshold of minimum 2 number of occurrences of a keyword, in which out of 427 keywords, 100 met the threshold based on 93 papers (ranging from 1992-2025) searched in Scopus database with keyword 'Oil Palm *Ganoderma* Management' found in Article Title, Abstract and Keywords, on 25 June 2025.

Moreover, the visualization also shows that there is a purple cluster covering "microbiology," "plant disease," and "fungicide," suggesting continued reliance on microbial and chemical disease management products. This emphasizes the necessity for transition away from reactive fungicide strategies to more preventive and sustainable practices like bio-inoculants. The intersection of terms like "sustainable development" and "biodegradation" in the green cluster supports greater academic convergence towards ESG and circular economy principles.

Finally, farmer and industrial adoption relies on regulation, incentives, and training. Bio-inoculants must be shown to be effective, with long-term benefits before they are applied in agronomic operations (Zakaria, 2023). Reactive chemical-based disease management strategies are unsustainable or ESG-unsupportive without viable and economically rational control options, asserts (Singh, 1992). Overall, *Trichoderma*-based treatments like "Sawit Shield" can sustainably control *Ganoderma* but in a multidisciplinary manner. Dissolving existing limitations requires constant field verifications, technical enhancement detection, adjustment of formulations based on location, and stakeholder coordination. Inferences from bibliometric patterns (Figure 2) require collaborative studies in plant pathology, chemical ecology, remote sensing, and sustainable development. Such advances can make bio-inoculants useful for sustainable, commercially viable, and environmentally sustainable palm oil production.

5. Conclusion

"Sawit Shield" improves oil palm plantation *G. boninense* control. It performs consistently on a variety of plantation production and health factors as an effective, environmentally safe, and affordable biocontrol tool. Laboratory tests showed strong antagonistic action on *G. boninense*, while nursery tests showed extended protection and root zone preconditioning from early-stage inoculation. Most significantly, multi-year observations in the field at high-incidence sites like Pegagau and Pitas show that it functions under realistic, real-world high-pressure conditions, keeping infection rates below standard levels. Agronomic benefits go beyond disease suppression. *Trichoderma* colonization stimulated root growth and nutrient uptake in treated palms, which further boosted bunch weight and frequency. "Sawit Shield" also reduces application of synthetic fertilizers by 15–20%, reducing nutrient leaching and environmental degradation. All these benefits, together with increased soil microbial diversity and carbon cycling, position it as one of the regenerative agriculture practices.

ESG compliance is also crucial for "Sawit Shield". Made from 98% organic waste such as decanter cake and solid POME, it is a textbook illustration of circular bioeconomy. It saves landfill space, recycles soil, and minimizes chemical input carbon emissions by valorizing agro-industrial waste. "Sawit Shield" is an exemplar best-practice model bio-inoculant consistent with UNSDGs and RSPO sustainability standards.

As Malaysia moves towards climate-resilient and sustainable agriculture, "Sawit Shield" offers an effective and scalable response to responsive disease management: active, integrated plantation well-being. Adoption across the industry could usher in a paradigm shift towards regenerative practices for sustained economic viability, environmental integrity, and social responsibility. "Sawit Shield" is a national achievement and global benchmark for sustainable tropical agriculture biotechnology.

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CKY wrote the first draft of the manuscript, revised and edited the final version of the manuscript. All authors have read and agreed to the published version of the manuscript.

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