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A Review of Fungal Disease in *Hevea brasiliensis* (Willd. ex A. Juss.) Mull. Arg.: From Identification to Scientific Investigation for Control Strategies

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Abstract: Fungal diseases pose a substantial risk to the health and productivity of rubber plants (*Hevea brasiliensis* (Willd. ex A. Juss.) Mull. Arg., the primary source of natural rubber. The diverse fungal pathogens responsible for these diseases lead to significant economic losses in rubber plantations, threatening the global rubber supply. This review provides a comprehensive examination of major fungal diseases affecting rubber plants, focusing on their identification, scientific analysis, and management strategies. Conventional methods for pathogen identification, while valuable, often lack the efficiency and precision required for effective disease control. Recent advancements in molecular diagnostics, genomics, and biotechnology have greatly improved the accuracy and speed of pathogen detection, enabling more targeted and sustainable management practices. Integrated pest management, mainly through the use of disease-tolerant clones, is emerging as a viable alternative to chemical fungicides. Although chemical fungicides remain the most widely used solution due to their accessibility and effectiveness, their environmental impact and potential for resistance necessitate a shift toward sustainable practices. While biofungicides offer a more environmentally friendly option and are already in use, they are currently limited to small-scale plantations and have yet to be adopted for large-scale production. Efforts to develop resistant clones through molecular studies and advanced cloning techniques are ongoing, representing the most sustainable approach for combating fungal diseases in rubber plantations. By synthesizing current knowledge and advancements, this review underscores the pressing challenges in managing fungal diseases and the opportunities presented by innovative technologies. The findings aim to guide future research and promote the development of efficient, sustainable strategies for maintaining rubber crop health, ensuring consistent production, and safeguarding the economic stability of the rubber industry.

Keywords: Control; Disease Management; Fungal Disease; *Hevea brasiliensis*

Introduction

Rubber plants (*Hevea brasiliensis* (Willd. ex A. Juss.) Mull. Arg.) are vital to the world economy, particularly in tropical Asian countries such as Indonesia, Thailand, Malaysia, and Vietnam (Chiarelli et al., 2018; Jayathilake et al., 2023). Rubber functions as the principal source of natural rubber. An adequate supply is essential since the demand for natural rubber from rubber trees is expanding over time (Bae et al., 2020). Numerous hazards provide considerable dangers to natural rubber production, since they directly impact the

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health, yield, and sustainability of rubber trees (*Hevea brasiliensis*) and their surrounding ecosystems (Vineeth et al., 2024)

Fungal diseases represent a considerable challenge to the health and productivity of rubber plants, ultimately resulting in reduced latex production. These fungal infections can lead to a range of adverse effects, causing lower rubber output, economic losses, and lasting damage to the plants (Chen et al., 2023). Notable fungal diseases affecting rubber plants include leaf blight, root rot, powdery mildew, and leaf fall disease. Several diseases can decrease latex yield by as much as 45% (Damiri et al., 2022; Liyanage et al., 2016).

Timely and precise recognition of these diseases is crucial for efficient management and control (Cheng et al., 2024). Conventional approaches to identifying diseases, although beneficial, frequently require considerable time and have constraints in their breadth. Recent advancements in molecular biology, biotechnology, and digital imaging have broadened the array of tools for more accurate and swift identification of fungal pathogens in rubber plants. The exploration of these pathogens has illuminated their life cycles, virulence factors, and environmental interactions, enhancing our comprehension of their spread and infection in rubber trees.

In this review, we examine the major fungal diseases affecting rubber plants, focusing on their identification, scientific investigation, and the development of mitigation strategies. We explore how emerging technologies, such as genomic approaches and recent pest management systems, offer promising avenues for controlling fungal outbreaks. By highlighting both the current challenges and the advancements in fungal disease management, this article aims to provide a comprehensive overview for researchers, agronomists, and plantation workers to ensure the sustainable production of natural rubber.

Method

This paper of systematic literature review (SLR) employs the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology to ensure a thorough and transparent process. Publish or Perish tool was employed to gather relevant articles using search keywords such as "Rubber Disease Control," "Rubber Disease," and "*Hevea brasiliensis* Disease", published between 2015 and 2024. These keywords enabled the identification of highly pertinent studies. It also used references manually searched by authors to support the SLR. To enhance the comprehensiveness of the review, manual screening of reference lists from articles and review papers was also carried out. Only peer-reviewed English-language literature was included, and the PRISMA flow diagram was utilized to document each stage of the review process, from identification to inclusion (Figure 1.).

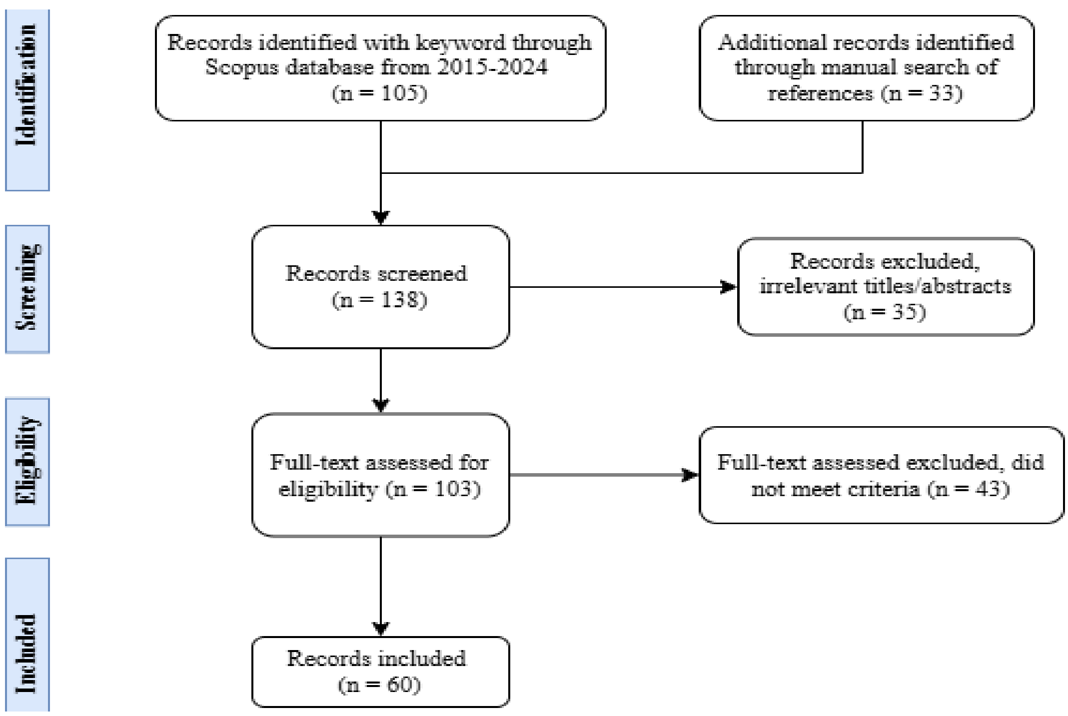

Figure 1. PRISMA methodology used to help SLR synthesis

The inclusion criteria for this review emphasized studies focusing on fungal pathogens impacting rubber plants, particularly those addressing their identification, characterization, and epidemiology. Articles exploring mitigation and management strategies, ranging from traditional methods to recent advancements in molecular biology and biotechnology, were prioritized. Studies devoid of experimental or field data or unrelated to rubber plant diseases were excluded. By adhering to these criteria, the review ensured that the selected studies were highly relevant to understanding and managing rubber plant diseases.

The analysis incorporated qualitative and quantitative findings from experimental and observational studies. Particular emphasis was placed on comparative analyses of conventional control methods and innovative technologies, such as genomics, biocontrol agents, and precision agriculture. This approach allowed for an in-depth examination of how emerging tools and methodologies contribute to improved disease management. Additionally, the review assessed the geographical distribution of fungal outbreaks and the prevalence of diseases to provide a global perspective on the challenges faced by rubber plantations.

This systematic review also integrated findings from additional journals that aligned with the theoretical framework and the initial database search results. The combination of traditional and modern approaches provided insights into the efficacy of various disease management strategies. The inclusion of recent advancements, such as molecular diagnostics and integrated pest management systems, highlighted the progress being made in the field.

Ultimately, the review aims to develop sustainable practices for managing fungal diseases in rubber plantations. By addressing the challenges posed by fungal pathogens, this study seeks to ensure consistent rubber yields and promote global efforts to enhance natural rubber production. Through the synthesis of knowledge from multiple disciplines, the review provides a comprehensive understanding of effective mitigation strategies. It offers valuable guidance for future research and practical applications in disease management.

Result and Discussion

Rubber plantations face significant challenges from various fungal diseases, which adversely affect latex production and plant health. Among these, South American Leaf Blight (SALB), powdery mildew, white root rot, abnormal leaf fall, anthracnose, *Corynespora* Leaf Fall (CLF) Disease, and *Pestalotiopsis* Leaf Fall Disease (PLFD) are some of the most prominent diseases causing considerable problems in rubber-growing regions. These diseases vary in their initial emergence, geographic distribution, and severity of impact. Table 1 provides a detailed summary of the major rubber diseases, including their initial year of observation, primary distribution areas, and the control strategies employed, ranging from chemical fungicides to integrated pest management and the development of disease-resistant clones.

South American Leaf Blight (SALB)

South American leaf blight (SALB), resulting from *Microcyclus ulei* (P. Henn.) Arx or *Pseudocercospora ulei*, significantly restricts *Hevea* cultivation in the humid tropics of the Americas (Jaimes, 2016; Rivano, 2016; Sterling & Melgarejo, 2018). According to the study by Sterling & Melgarejo (2018), SALB influences the photosynthesis rate of rubber plants, revealing a notable contrast between the clone FX 3864 (susceptible) at 88.3% and FX 4098 (moderately resistant) at 45.2% eight days post-inoculation. This phenomenon arises from reduced stomatal conductance and increased water usage in more vulnerable clones (Sterling & Melgarejo, 2018). This pertains to the first symptoms seen when the rubber plant is infected, namely a discoloration of the leaf lamina characterized by necrotic or chlorotic lesions (Sterling & Di Rienzo, 2022).

The primary technological detection of this disease was conducted by Sterling & Di Rienzo (2022), utilizing visible and near-infrared methods alongside five machine learning algorithms to detect, discriminate, and classify the SALB levels. The approach that has been adopted thus far involves utilizing resistant clones and establishing plantings in regions with minimal exposure to SALB disease (Galindo-Rodríguez et al., 2023). While recently, the disease is still controlled by chemical fungicide contain benomyl (Guyot, 2018).

Transcriptome analysis by Fang (2016) elucidated the molecular mechanisms behind rubber plants' protection against SALB disease. Genes responsible for encoding cyanogenic glycosides (CGs) in rubber leaves exhibited varying expression patterns throughout the developmental stages of leaves. While immature leaves exhibited greater vulnerability to the illness, developing leaves used their enhanced capability for cyanogenic glycoside synthesis and cyanide release to mitigate biotic stress, and mature leaves employed elevated lignin levels as a physical barrier against the infection. Furthermore, *P. ulei* infection resulted in a reduction of ethylene and jasmonic acid synthesis after 48 days in the resistant clone FX 3864 (Páez, 2015).

Powdery Mildew Disease

The disease, attributed to *Oidium heveae*, exhibits a widespread occurrence, with the extent of damage to trees being contingent upon winter patterns and clone susceptibility (Oghama et al., 2023). Temperature's influence on the germination and subsequent growth of *O. heveae* was observed. At extremely low temperatures of 10°C and notably high temperatures of 35°C, the duration of the infection exceeded that of the control group, which lasted four days (Cao, 2021). The distribution and transmission of powdery mildew disease in rubber trees are significantly influenced by climate change (Bai et al., 2022). This fungus disseminates via airborne particles, affecting not only juvenile leaves but also a range of other nascent tissues. The proliferation is facilitated by low temperatures coupled with elevated humidity levels. The symptoms observed include a surface of the leaves characterized by a layer of white spots, accompanied by shriveled leaf tips that subsequently detach (Liyanage, 2016).

Table 1. Rubber Diseases and Its Control Strategies

Rubber Diseases	Initial Year of Report	Disease Distribution	Disease Control	References
South American Leaf Blight (SALB)	1904 in Amazon, Brazil	Only in South and Central American countries	Benomyl fungicide	(Guyot, 2018)
Powdery Mildew	1918 in Java	Africa and Asia (Cambodia, India, Indonesia, Malaysia, Sri Lanka, Thailand, Vietnam, Brazil, Papua New Guinea), and Brazil	The dusting of sulfur with 5-7 days interval, RRIC102 clone cultivating	(Liyanage et al., 2016; Oghama et al., 2023)
White Root Rot	1908 in Singapore	Indonesia, India, Malaysia, Sri Lanka, Thailand, West and Central Africa	Sulfur, Fungicide (propiconazole, hexaconazole, triazoles, triadimenol, pentachloronitrobenzene, triadimefon, pentacholorophenol, phenol), *Hypocrea jecorina*, *Hypocrea virens,* and *Streptomyces* sp. TM32, co-inoculation of *Rigidoporus microspora* and *Enterobacter* sp with silicon	(Chaiharn et al., 2019; Nakaew, 2015; Ogbebor, 2015; Shabbir et al., 2020)
Abnormal Leaf Fall Disease	1905 in Sri Lanka	Thailand, Malaysia, Sri Lanka, Myanmar and Cambodia	Copper fungicides based on mineral oil, *Alcaligenes* sp. and *Pseudomonas aeruginosa*	(Abraham, 2015; Laohasakul, 2017; Deepthi et al., 2024)
Anthracnose	2015 in China	All over the world with rubber plantation	Copper fungicide, prochloraz, propiconazole, difenoconazole, the culture filtrate extract (CFE) of *S. deccanensis* QY-3, Dinactin from S*treptomyces badius* gz-8	(Cai, 2016; Gu et al., 2020; Oghama et al., 2023; Zhang et al., 2020)
Corynespora Leaf Fall (CLF) Disease	1958 in India	Asia and Africa	*Trichoderma koningiopsis*	(Lopez, 2018; Pujade-Renaud, 2019; Oghama et al., 2023)
Pestalotiopsis Leaf Fall Disease (PLFD)	1987 in Malaysia	Malaysia, Indonesia, Thailand, Cameroon	Fungicide (chlorothalonil, carbendazim, mancozeb, cuprous oxide, metataxyl, and extra nitrogen fertilizer	(Ngobisa et al., 2018; Febbiyanti & Fairuzah, 2019; Pornsuriya, 2020)

The initial identification of this disease occurred in Java, Indonesia in 1918, subsequently disseminating to various Southeast Asian nations, including Brazil, India, Malaysia, and Papua New Guinea (Cao, 2021; Liyanage, 2016). This disease was identified not only in Asia but also in other continents, specifically in the Hainan rubber planting area in 1951 (Kong et al., 2023).

The study conducted by Li (2016) demonstrated that the RRIC52 clone exhibited a high level of resistance. At the same time, Reyan 7-33-97 showed mild susceptibility to the fungus *O. heveae*, as evidenced by the presence of colonies on the leaves following 120 hours of inoculation. The qRT-PCR analysis confirmed that eight particular genes exhibited responsiveness during the infection of powdery mildew in the rubber tree clone RRIC52. These genes encompass those associated with fungal cell wall hydrolysis, ferritin proteins, immune regulation, and germin-like proteins. The expression of genes associated with powdery mildew, precisely the mildew resistance locus (Mlo) genes, showed a significant increase following the inoculation of the fungus responsible for powdery mildew on rubber. In contrast to defense genes, these particular genes enable pathogens to invade plants by inhibiting the plant's defense mechanisms (Qin, 2019).

Conventional management strategies for this disease involve the cultivation of the RRIC102 clone, recognized for its resistance, during the early winter season, alongside the application of sulfur at a rate of 9 kg/ha per rotation, conducted four times weekly. The supplementary application of nitrogen may serve as a viable alternative, as it has the potential to expedite leaf senescence, thereby mitigating the severity of the disease (Oghama et al., 2023).

White Root Rot Disease

Rigidoporus microspora is recognized as a fungal species responsible for white root disease across multiple geographical areas (Go, 2021). In Nigeria, the white root rot disease is attributed to *Rigidoporus lignosus* (Ogbebor, 2015). This disease has the potential to adversely affect the entire root system of the plant, which is crucial for the growth of rubber. The visible symptoms of this disease are characterized by white fibrous mycelium on the roots of rubber plants and alterations in leaf pigmentation leading to shoot mortality. Recently, the application of fungicides in chemical control strategies effectively addresses the issue of white root rot disease in rubber plants. The fungicides discussed encompass triazole, triadimenol, triadimefon, phenol, tebuconazole, and hexaconazole (Saidi et al., 2023).

The conventional method to surpress this disease are the utilization of sulfur and fungicide containing propiconazole, hexaconazole, and triazoles.triadimenol, Pentachloronitrobenzene (PCNB), triadimefon, pentachlorophenol, and phenol, which are cost higher and harmful to the environment (Chaiharn et al., 2019). The treatments involving biological agents, specifically *Hypocrea jecorina* and *Hypocrea virens*, demonstrated a reduction in plant mortality rates when contrasted with the control rubber plant solely infected by *Rigidoporus lignosus*. This suggests their potential efficacy in disease management. *Hypocrea jecorina* demonstrated the most significant inhibitory effect, recorded at 79.83%, following a 24-hour inoculation with *Rigidoporus lignosus* (Ogbebor, 2015). *Streptomyces sioyaensis*, recognized for its antagonistic properties against *Rigidoporus* sp., is prevalent in soil environments. The antifungal properties exhibited, including the production of chitinase, siderophore, and indole-3-acetic acid, render it a suitable candidate for application as a biocontrol agent. Approximately 20% of white root rot disease can be mitigated through the application of the biocontrol agent *Streptomyces* sp. TM32 (Nakaew, 2015).

The study by Shabbir (2020) demonstrated that the co-inoculation of *Rigidoporus microspora* and *Enterobacter* sp., along with the incorporation of silicon, can effectively reduce both the incidence and severity of white root rot disease following 24-week infection period. Furthermore, an enhancement in plant growth was observed under greenhouse conditions. Siri-udom (2016) has identified isolates of *Muscodor vitigenus, M. equiseti,* and *M. heveae* sp. nov. obtained from healthy leaves of rubber trees, which possess the capability to produce volatile compounds, including 3-methylbutan-1-ol, 3-methylbutyl, and azulene derivatives. The application of these three compounds resulted in a significant enhancement in the survival rates of tall rubber tree seedlings, achieving an increase of up to 100% in comparison to the control group (Siri-udom, 2017).

The expression patterns of various pathogenesis-related genes in tolerant clones PB5/51 and susceptible clones RRIM600 and BPM24 in response to *R. microsporus* exhibited notable differences. The expression levels of *HbPR-2*, *HbPR-4,* and *HbPR-5* genes showed a marked increase in tolerant clones, whereas a decline was observed in susceptible clones over time (Woraathasin et al., 2017). A recent discovery concerning PR proteins highlights that the novel PR-10 protein in rubber trees is markedly expressed in reaction to infection by the white root rot fungus *R. microporus* (Longsaward et al., 2023).

Abnormal Leaf Fall Disease (ALF)

Abnormal leaf fall disease in rubber plants is caused by *Phytophthora* spp., results in a significant latex loss of up to 56% in rubber plantations across India (Krishnan, 2019). The pathogens responsible for this condition include *P. palmivora, P. botryosa, P. meadii, P. citrophthora, P. nicotianae, P. nicotianae* var. parasitica, and *P. capsici* (Sirikamonsathien et al., 2023). The infection manifests through water-soaked lesions on leaf stalks, with affected leaves transitioning from brown to black and releasing droplets of latex. Clones that are susceptible to this infection undergo severe leaf fall, resulting in a carpet-like accumulation on the soil surface (Krishnan, 2019). Copper fungicide in mineral oil is known better to control the disease development in plantation (Deepthi et al., 2024).

In order to investigate the mechanism of infection by *Phytophthora*, numerous researchers have conducted molecular analyses. The expression of the *Hevea brasiliensis* serine protease (*HbSPA*) gene in the leaves of *Nicotiana benthamiana* enhances resistance to *P. palmivora*, suggesting that *HbSPA* is involved in the plant's defense mechanisms. The semi-quantitative RT-PCR analysis results indicated a notable increase in the expression of the *Phytophthora palmivora* extracellular protease inhibitor (*PpEPI10*) gene during the interaction between *P. palmivora* and *H. brasiliensis* (Ekchaweng, 2017).

A subsequent proteomic analysis conducted by Havanapan (2016) revealed that the latex serum from BPM24 rubber clone (tolerant) exhibited elevated levels of beta-1,3-glucanase and chitinase protein accumulation in comparison to the RRIM600 clone (susceptible). The upregulation of *the HbCAT1, HbPAL,* and *HbPR1 genes* triggered by salicylic acid (SA) led to a significant reduction in disease severity, quantified at 41%. The induction of increased catalase (CAT) and peroxidase (POD) activities provided support for resistance (Deenamo, 2018).

The utilization of endophytic bacteria, particularly *Alcaligenes* sp. and *Pseudomonas aeruginosa*, as biocontrol agents led to a significant reduction in lesions, with a decrease of 43% observed in rubber clone RRII105 and 30% in rubber clone RRIM600, both infected with P. media. The compound phenazine-1-carboxylic acid derived from *Alcaligenes* sp. EIL-2 exhibits antagonistic activity (Abraham, 2015). A study by Khompatara (2019) demonstrated a reduction in the disease index score, attributed to the induction of several enzymes, including catalase (CAT), peroxidase (POD), β-1,3-glucanase (GLU), as well as the phytoalexin scopoletin (Scp) and the signaling molecule salicylic acid (SA). Further analysis results in consistent findings, indicating that the disease severity index value remained low (0.00-11.67%) following the introduction of *Trichoderma harzianum* strains, as observed 120 days post-inoculation with *P. palmivora*. The extract from the strain comprises various compounds that impede mycelial growth and sporangium germination, specifically the 6-n-pentyl-2H-pyran-2-one compound (Promwee, 2017).

Antrachnose

Anthracnose is a disease affecting rubber plants, caused by the fungus *Colletotrichum* (Liu, 2018). Studies conducted in China indicate that the prevalence of this disease is approximately 86% across all rubber plantations. Leaves that are infected will exhibit symptoms characterized by necrotic regions on the surface, presenting as brown edges resembling mold accompanied by yellow circles (Shi et al., 2018). The disease primarily manifests at the onset of wet weather conditions, although inhibition may persist for several years (Oghama et al., 2023).

Liu (2018) demonstrated that *C. siamense* and *C. australisinense* are recognized as the primary causative agents of *H. brasiliensis* anthracnose in China, as evidenced by multi-locus phylogenetic analysis and phenotypic characteristics. Compared to previous research, which identifies the members of species complex *C. acutatum* (*C. acutatum* and *C. gloeosporioides*) as the primary agents of anthracnose disease in rubber plants in Sri Lanka through morphological, pathogenicity, and internal transcription spacer sequence analysis (Hunupolagama, 2017).

The usage of copper fungicide to infected rubber plants is subject to significant loss due to exposure to rainfall. Additional traditional approaches involve the application of manure and the removal of diseased plant parts (Oghama et al., 2023). The administration of fungicides such as prochloraz, propiconazole, and difenoconazole has demonstrated efficacy in managing the *C. gloeosporioides* and *C. acutatum* species complexes, with mean ED_{50} values of 173.341 and 151.441 mg/ml for chlorothalonil, and 0.035 and 0.040 mg/ml for prochloraz, respectively for the *C. gloeosporioides* species complex (CGSC) and *C. acutatum* complex (CASC) (Cao et al., 2017). In the interim, the management of *C. siamense* can be achieved through the application of fungicides that include fludioxonil as an active ingredient. The sensitivity to fludioxonil is governed by the *C. siamense* ATF1/CREB-activating Transcription Factor (*CsAtf1*) gene (Song, 2022).

Corynespora Leaf Fall (CLF) Disease

The necrotrophic fungi *Corynespora cassiicola* causes leaf fall disease, leading to reduced natural rubber production in Asia and Africa This condition is characterised by the formation of necrotic lesions that result in elongated fish fins on the leaf surface, subsequently leading to rapid leaf drop in rubber plants (Damiri et al., 2022).

Casiicolin is an effector that induces disease symptoms. Transcriptomic studies of the fungus *C. cassiicola* indicated that the expression of the gene encoding the cassiicolin protein was elevated during the initial phase of interaction with rubber plants. This compound exhibits toxicity to rubber plants, and its function remains unidentified (Lopez, 2018). The deletion of the Cas1 gene in the pathogen resulted in a complete loss of virulence on susceptible rubber tree clones (Ribeiro, 2019).

Largely method for this disease is adding the fungicide consist of mancozeb and carbendazim which is more effective than other fungicide (Manju et al., 2019). Research conducted by Pujade-Renaud et al. (2019) indicates that *Trichoderma koningiopsis* could act as a biocontrol agent against the pathogen *C. cassiicola* in rubber plants. The reduction in symptom occurrence and mycelial development of pathogens was observed after one week preinoculation. Multiple genes have been identified as up-regulated in the rubber clones RRII105 and GT1, specifically those encoding transcription factors (NAC, ERF, MYB, GATA, WRKY, LEA, bZIP) that modulate plant responses to stress and enhance resistance to pathogens. Furthermore, genes that encode chitinase proteins are recognized to upregulate in resistant rubber clones following infection by *C. cassiicola* (Roy, 2019).

Pestalotiopsis Leaf Fall Disease (PLFD)

Recently, Indonesia has been affected by a disease known as *Pestalotiopsis* leaf fall disease, which is attributed to the fungus *Pestalotiopsis*. The initial identification of this disease occurred in Indonesia in 2016, specifically in North Sumatra, and it has since disseminated to various other regions (Febbiyanti & Fairuzah, 2019). This outbreak has been documented to affect rubber plantations in Malaysia in the years 1987 and 2003 (Damiri et al., 2022). The manifestations of this disease include the presence of necrotic spots on the foliage, yellowing of the leaf veins, and an accelerated rate of leaf abscission as the severity of the disease increases. The noticeable decline in Indonesia's economy can be attributed to a significant reduction in canopy area, estimated at 75-90%, alongside a decrease in latex production, reaching as high as 45% (Febbiyanti & Fairuzah, 2019).

The implementation of fungicides, fogging techniques, and the application of fertilizers are strategies employed to enhance the resistance of rubber plants against fungal infections. The systemic fungicide 2x carbendazim demonstrated increased activity of β-1,3-glucanase, chitinase, and peroxidase in comparison to the control, thereby inducing disease resistance. This was evidenced by the absence of phytotoxicity, such as chlorosis, necrosis, or leaf blight, as indicated by chlorophyll content (Thaochan et al., 2020). The application of nitrogen fertilizer at a rate 25% above the recommended dosage, along with an increase in potassium fertilizer, resulted in a canopy density enhancement of 5% and 6%, respectively (Febbiyanti & Fairuzah, 2019).

The investigation into morphological and molecular characteristics of ITS sequences, as presented by Kusdiana (2021), identified *Pestalotiopsis microspore* as the causative agent of leaf fall. This contrasts with the findings of Darojat et al. (2023), who identified the *Neopestalotiopsis* sp. fungus molecularly in rubber plants exhibiting similar symptoms of leaf fall in Indonesia. The impact of the disease's severity is significantly shaped by the co-infection of *Pestalotiopsis* alongside other fungal species. In Thailand, another Asian nation, *Neopestalotiopsis cubana* and *Neopestalotiopsis micarum* have been linked to a newly identified leaf fall disease affecting rubber plants (Pornsuriya et al., 2020). There is a suspicion regarding the potential existence of a fungal complex responsible for PLFD. The findings of the research indicated that the fungal isolates Lasiodiplodia theobromae, *Colletotrichum conoides*, and *Neopestalotiopsis surinamensis* were the main contributors to lesion formation on the leaves, with respective contributions of 83%, 69%, and 57% (Hadi Ismail et al., 2024).

Numerous limitations were identified in the application of recent technologies, such as substantial costs and detrimental effects on the environment (Thaochan et al., 2020). Clones exhibiting resistance to this disease may be utilized during the breeding phase. The understanding of molecular mechanisms can facilitate the development of novel clones exhibiting resistance to pathogens responsible for PLFD. Utilizing the detached leaf assay method, it was observed that clones IRR112 and RRIC100 exhibited lesions measuring less than 10 mm at 7 days post-inoculation with *Neopestalotiopsis* sp. (Darojat et al., 2023).

Conclusion

Hevea brasiliensis is a vital commodity for the global economy, with tropical Asian countries such as Indonesia, Thailand, Malaysia, and Vietnam playing significant roles in the natural rubber supply chain. However, the cultivation of natural rubber faces substantial challenges due to fungal diseases such as leaf blight, powdery mildew, anthracnose, white root rot, and leaf fall. These diseases significantly impact latex production and plant health, leading to economic losses and threatening the sustainability of rubber plantations.

Currently, chemical fungicides remain the most widely used method for managing these fungal diseases due to their ease of availability and immediate effectiveness. Although trials involving environmentally friendly biofungicides have shown promise, these alternatives have not yet been adopted on a larger scale. To address this, recent advancements in disease management strategies, including genomic approaches, molecular biology, and biocontrol agents, offer encouraging pathways to sustainable solutions.

By integrating innovative technologies and fostering ongoing research, stakeholders can reduce dependence on chemical fungicides and promote long-term ecological balance. Addressing the challenges posed by fungal pathogens enables agronomists, plantation managers, and local communities to improve disease prevention, mitigation, and control. These efforts ultimately support consistent rubber yields, safeguard the economic viability of the rubber industry, and contribute to sustainable natural rubber production worldwide.

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