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A Centenary Review on Leaf Rot Disease of Coconut

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Coconut leaf rot disease (LRD) has posed a significant threat to coconut palms for over a century, causing widespread foliar damage, stunted growth, and reduced yield. The disease, often associated with the complex interaction of Root (wilt) disease (RWD), has been a persistent challenge since its first reports in the early 1900s. Despite extensive research, understanding the etiological agents and developing effective management strategies remain difficult due to evolving pathogenic profiles and climate variability. This centenary review consolidates over 100 years of research on LRD, offering a comprehensive analysis of the disease's progression, and environmental influences, in coconut cultivation. It contrasts traditional management methods,

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such as cultural and chemical controls, with modern integrated disease management (IDM) approaches, including biological control agents and host resistance breeding. The review also explores the role of plant-microbe interactions, emphasizing the potential of microbial antagonists as biocontrol agents. Given the economic significance of coconuts in tropical regions, this review highlights the urgent need for region-specific disease management strategies and the development of climate-resilient coconut varieties. Additionally, it identifies research gaps and future directions to advance sustainable solutions for mitigating the impact of LRD.

Keywords: Biocontrol agents; coconut leaf rot disease; colletotrichum; host resistance; Integrated Disease Management (idm).

1. INTRODUCTION

The coconut palm (*Cocos nucifera* L.), often referred to as the "King of Palms" and "Kalpavriksha," holds significant economic and cultural value in tropical regions worldwide. It sustains the livelihoods of millions of people by providing a wide range of products, including food, beverages, cosmetics, biofuels, and industrial materials. Coconut production is particularly important in countries such as India, the third-largest coconut producer globally. In India, coconut cultivation spans 1.8 million hectares, yielding approximately 14 billion nuts annually, with the southern states of Kerala, Tamil Nadu, Karnataka, and Andhra Pradesh accounting for 92% of the total cultivation (Vasanthakumar, 2017).

However, coconut farming faces considerable challenges, primarily due to diseases that threaten the viability and productivity of coconut palms (Fig. 1). Globally, coconut palms are susceptible to various devastating diseases that impact productivity and farmers' livelihoods. These include lethal yellowing (LY), a phytoplasma-associated disease prevalent in the Caribbean, Africa, and Southeast Asia, which causes severe palm death (Gurr et al., 2016); cadang-cadang disease, caused by the coconut cadang-cadang viroid (CCCVd), resulting in leaf yellowing, stunting, and palm mortality in the Pacific and Southeast Asia (Harrison and Harrison, 2003); and bud rot, caused by *Phytophthora palmivora*, which affects terminal buds, leading to palm death in areas of high humidity such as Latin America and Southeast Asia (Ramjegathesh et al., 2022). Africa's Cape St. Paul wilt, another phytoplasma-related disease, has led to significant losses in Ghana (Yankey et al., 2018), while coconut stem bleeding, caused by *Thielaviopsis paradoxa*, induces trunk decay in Southeast Asia (Rao et al., 2023).

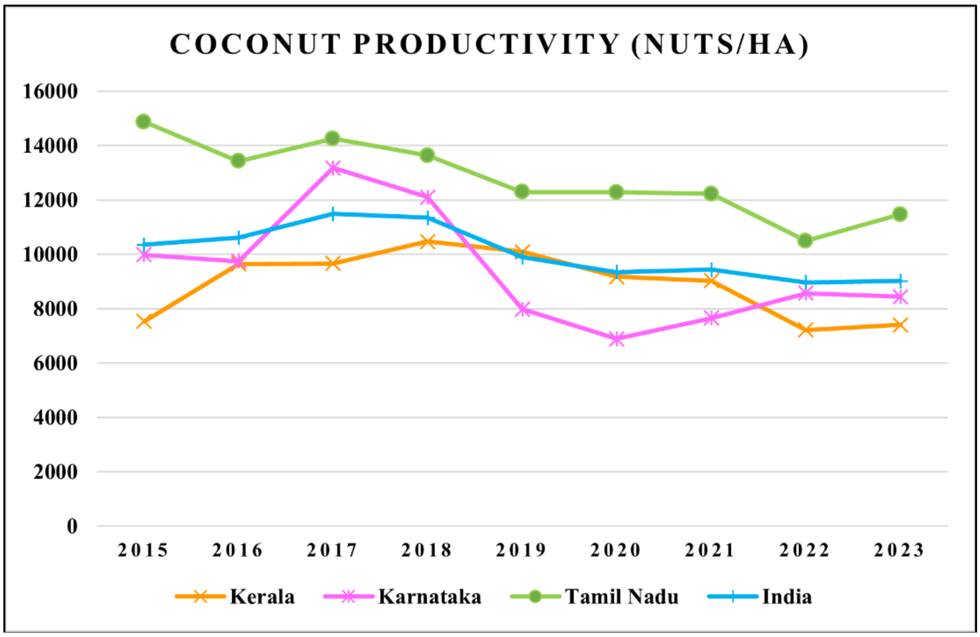

Fig. 1. The productivity status of major coconut producing states in India

In India, coconut root (wilt) disease (RWD) is prevalent, particularly in southern states, causing progressive palm decline and reduced nut production. RWD often co-occurs with coconut leaf rot disease (LRD), intensifying the damage. RWD alone has caused yield losses of up to 80% in severely affected areas, and when compounded by LRD, the economic losses are substantial. LRD, caused by a complex of fungal pathogens including *Colletotrichum gloeosporioides*, *Exserohilum rostratum*, and *Fusarium solani*, leads to necrosis, reduced photosynthetic activity, and diminished yields (Srinivasan and Gunasekaran, 1999). This disease primarily affects the spindle leaves of RWD-infected palms, and the combination of RWD and LRD can result in yield losses severely impacting smallholder farmers and commercial plantations. The spread of RWD into new regions (Fig. 2), including the districts of Erode, Tirupur, Theni, Tenkasi, Tirunelveli, Kanyakumari, and Coimbatore in Tamil Nadu, has heightened concerns about the escalating threat posed by LRD (Latha et al., 2024). This calls for proactive disease management measures to mitigate further losses. The interconnectedness of RWD and LRD underscores the urgent need for integrated strategies to safeguard coconut farming.

Historical data highlight the severity of the situation. Menon and Nair, (1948) estimated the annual loss due to RWD at Rs. 5.6 million, with an average yield reduction of 20%. Radha *et al.* (1962) reported yield losses of up to 70% in LRD-infected palms, with RWD alone causing losses ranging from 43% to 82%. A survey by the Central Plantation Crops Research Institute (CPCRI, 1985) indicated annual losses due to RWD at 968 million nuts, with an overall disease incidence of 26.44% in the endemic region. A subsequent survey by the Department of Agriculture, Government of Kerala, (1997) reported a disease incidence of 24.05%, attributed to improved management practices, including the removal of diseased palms and fresh planting. However, the precise estimation of yield loss due to LRD remains challenging, as the disease often occurs alongside RWD.

The management of LRD remains challenging due to its multifactorial nature, with environmental factors such as humidity, temperature, and rainfall heavily influencing disease progression. Conventional management strategies rely on chemical fungicides, but their efficacy is often limited due to environmental contamination and the development of resistance to fungal pathogens. Additionally, the persistence of LRD, particularly during the monsoon season, exacerbates management difficulties. As a result, integrated disease management (IDM) strategies which combine chemical, biological, and cultural approaches—are gaining interest. However, widespread adoption of IDM remains limited.

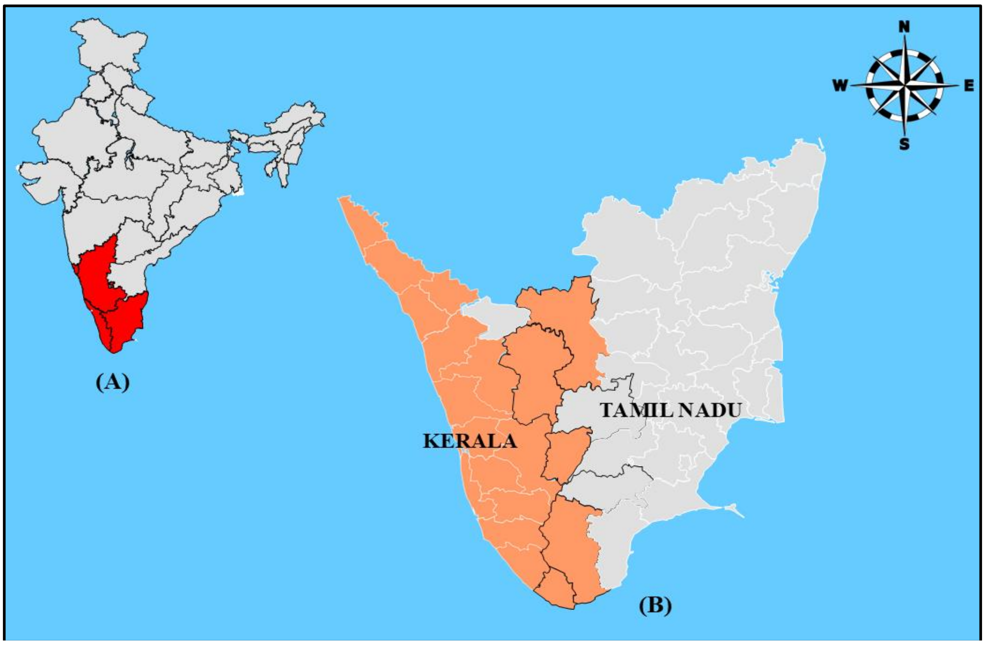

Fig. 2. (A) Root (wilt) disease detected states in India (B) Major root (wilt) affected regions in Kerala and Tamil Nadu states

This centenary review compiles 100 years of research on coconut leaf rot disease, focusing on the primary fungal pathogens, their infection mechanisms, symptomatology, and geographic distribution. It evaluates current management strategies and assesses the efficacy of chemical, biological, and cultural approaches, highlighting the limitations of each. The review aims to guide future research and contribute to the development of resilient and sustainable coconut farming systems to ensure the continued viability of this vital crop amidst evolving disease pressures.

2. PHYTOPLASMA CO-INFECTIONS

Phytoplasma infections in plants are often linked to secondary fungal and bacterial infections because these pathogens suppress the plant's immune responses, leaving them more vulnerable to opportunistic invaders. Phytoplasmas, being phloem-limited bacteria, alter the plant’s physiological and hormonal balance, weakening its natural defences and facilitating the entry and spread of other pathogens (Ray, 2024). This co-infection dynamic has been observed in several crops, resulting in increased disease severity and yield losses.

Candidatus Phytoplasma solani (stolbur phytoplasma) is linked to rubbery taproot disease (RTD) in sugar beet (*Beta vulgaris* L.), while *Macrophomina phaseolina* is the primary root rot pathogen. Research has explored the interaction between RTD and root rot, showing that *M. phaseolina* root rot occurs exclusively in *Ca. P. solani*-infected sugar beet. Even under conditions favorable to *M. phaseolina*, the fungus does not infect sugar beet unless the plants are first infected with phytoplasma (Duduk et al., 2023). The citrus greening disease pathogen, *Candidatus Liberibacter asiaticus*, a phloem-limited, non-cultivable bacterium, has been linked to a greening-fungus complex that causes citrus dieback. Certain fungi, such as *Colletotrichum gloeosporioides*, *Curvularia tuberculata, Diplodia natalensis*, and *Fusarium* spp., exacerbate dieback in plants that are susceptible to greening. Research indicated that seedlings impacted by greening exhibited increased vulnerability to fungal infections, resulting in significant dieback compared to healthy seedlings (Singh et al., 1971). Similarly, in coconut trees infected with *Candidatus* Phytoplasma (RWD), secondary bacterial infections like leaf rot exacerbate the plant’s decline (Ramjegathesh et al., 2012). Phytoplasmas create an environment conducive to secondary pathogen invasion by blocking the phloem and reducing the plant’s defence capabilities (Lewis et al.,2022).

Phytoplasmas manipulate plant hormonal signalling pathways, particularly those involving salicylic acid, jasmonic acid, and ethylene, which are critical in defending against both fungal and bacterial pathogens (Ray, 2024). By suppressing these pathways, phytoplasmas impair the plant’s ability to respond to secondary infections. The stress response triggered by phytoplasma infections, including reduced photosynthesis and nutrient transport, further weakens the plant and increases susceptibility to other pathogens. This creates a cascading effect where the plant is overwhelmed by multiple infections that work synergistically to reduce plant vigour and productivity.

3. ROLE OF ROOT(WILT) DISEASE (RWD)

Phytoplasma infections in coconut trees are widespread due to their long lifespan, unique vascular anatomy, and weakened defences. Coconut palms can live for over 60 years, allowing phytoplasmas to persist within the tree's phloem for extended periods, providing a reservoir for continued disease transmission. The extensive phloem network facilitates the internal spread of phytoplasmas, while the pathogens suppress the plant’s immune responses over time, making it harder for the coconut tree to fight infections (Marcone, 2023). Globally, several significant phytoplasma diseases impact coconut production. **RWD** in India, particularly in southern states, has caused major economic losses, reducing yields (Ramjegathesh et al., 2012). **LY** affects the Caribbean, Mexico, Central America, and West Africa (particularly Ghana and Tanzania), where it has decimated millions of palms (Gurr et al.,2016) **Coconut lethal decline,** a close variant, is also seen in Mozambique (Bila et al., 2015). Southeast Asia confronts dangers posed by Kalimantan wilt. Southeast Asia encounters risks posed by Kalimantan wilt (Nejat et al., 2019). These diseases are spread primarily by phloem-feeding insect vectors like planthoppers, which thrive in tropical environments. The chronic and often asymptomatic nature of phytoplasma infections, coupled with limited effective control strategies, makes them a persistent threat to global coconut production.

RWD is one of the most significant biotic stresses affecting coconut productivity in India, particularly in the southern region, where coconut is a major crop. The disease is caused by the phytoplasma *Candidatus* Phytoplasma oryzae (Manimekalai et al., 2014) and is primarily transmitted by insect vectors, notably the plant hopper (*Proutista moesta*) and the lacewing bug (*Stephanitis typica*) (Ramjegathesh et al., 2012). First documented in 1882 in the Kottayam district (Butler, 1908). RWD has since spread continuously across all eight southern districts of Kerala, from Thiruvananthapuram to Thrissur, and has appeared in isolated patches across six northern districts. Isolated cases have also been reported in Tamil Nadu, Karnataka, and Goa, posing a substantial threat to coconut cultivation in these regions (Krishnakumar et al., 2015). In the 140 years since its first detection, RWD has spread over 450-500 kilometres from the first detected location, averaging 3-4 km per year. Notably, in the last 30 years, the spread has accelerated, covering 100-120 km, and reaching the borders of Tamil Nadu and Karnataka states. This rapid spread is attributed to the increased activity of insect vectors, likely exacerbated by rising temperatures due to climate change. Over the next 50-100 years, the disease may extend across 95% of coconut-producing areas in India, potentially leading to significant yield reductions.

Typical symptoms of RWD include wilting, leaf drooping, flaccidity, ribbing, paling or yellowing, and necrosis of leaflets. Affected palms experience a reduction in the number of leaves, with successive leaves becoming smaller, shorter, and narrower, leading to stunted growth and smaller coconuts. In advanced disease stages, foliar yellowing and necrosis spread to older and younger leaves. It is noted that affected leaflets often curve along their length, resembling the ribs of mammals. The expression of symptoms varies with soil type and ecological conditions. Unopened pale yellow spindle leaflets are particularly prone to leaf rot, a key component of the RWD, which significantly reduces yield. LRD infection worsens the condition by reducing the photosynthetic area and causing palm disfiguration. Leaf rot attracts insects that cause further damage, while root rot, another major symptom, can lead to root decay depending on disease intensity. In the prebearing period, RWD delays flowering and weakens the reproductive system, resulting in smaller, underdeveloped spadixes and necrosis of spikelets (Ramjegathesh et al., 2012).

Physiological studies have shown that phytoplasma infection leads to a decrease in photosynthetic activity and various metabolic functions. Specifically, there is downregulation of chlorophyll, leaf biomass, soluble proteins, CO_2 fixation, Rubisco (Ribulose-1,5-bisphosphate carboxylase/oxygenase) activity, and nitrate reductase activity. Conversely, sugars, starch, amino acids, and total saccharides are significantly up-regulated, reflecting the altered metabolic state of the infected palms (Rao et al., 2019). The water- plant relations of infected palms have been extensively studied, revealing that RWD significantly impairs stomatal regulation, resulting in excessive transpiration (Rajagopal et al.,1986). As the disease progresses, the tree's ability to regulate water loss diminishes, causing an imbalance in the water economy of the palm. This leads to irreversible flaccidity, exacerbating the severity of LRD, as water uptake by the roots is insufficient to meet the palm's needs.

The weakened physiological state of RWD-affected palms, along with changes in the host's biochemistry, leads to a breakdown of defence mechanisms, making them more susceptible to secondary infections like LRD (Srinivasan and Gunasekaran,1999). Research consistently shows that in regions where RWD is endemic, the incidence of LRD is significantly higher. Climatic factors, particularly high humidity and rainfall, further exacerbate the spread of LRD in these areas, complicating disease management efforts. As the spread of RWD advances into new regions, it creates conducive conditions for LRD, posing a heightened risk of further disease spread. This growing geographical overlap between the two diseases presents a serious challenge for coconut farming.

4. LEAF ROT DISEASE (LRD)

LRD of coconut has been a longstanding issue in coconut cultivation, particularly in the Indian subcontinent, where it severely affects productivity. The disease was first observed in the erstwhile states of Travancore and Cochin as early as 1880 (Menon and Nair, 1948; Menon, and Nair, 1951), and its impact on coconut yield has become more pronounced over the decades due to its interaction with RWD. The relationship between LRD and RWD has been well-documented. Butler, (1908) was one of the first to describe symptoms on unopened spindles, although no pathogens were identified at that time. Further investigations by Radha and Lal

(1968) revealed that 16–40% of palms in RWD-affected areas also developed LRD, suggesting a latent infection even in palms without visible RWD symptoms. Economic losses due to the combined effects of LRD and RWD have been staggering. Menon and Nair, (1948) estimated annual losses due to RWD alone at Rs—5.6 million, with additional losses from LRD compounding the damage. It is estimated a loss of 461 million nuts annually from LRD in RWD-affected areas. The cumulative impact of these diseases has prompted numerous management studies and strategies to curb the economic damage (Srinivasan and Gunasekaran, 1999).

Several fungal pathogens have been associated with LRD, *including Colletotrichum gloeosporioides*, *Exserohilum rostratum*, and *Fusarium solani* (Srinivasan and Gunasekaran, 1996). These pathogens lead to necrosis of the spindle leaves, reducing the palm's photosynthetic capacity, which in turn impacts the yield. The progression of the disease is particularly severe in RWD-infected palms, where the fungal pathogens thrive on the weakened host. LRD is strongly influenced by environmental factors such as humidity, rainfall, and temperature. High humidity, particularly during the monsoon season, creates optimal conditions for the proliferation of fungal pathogens. Radha and Lal (1968) (Radha and Lal, 1968). reported that even palms without visible RWD symptoms could later develop LRD, suggesting that the disease complex involving both LRD and RWD needs to be studied further to understand its epidemiology fully. Additionally, climate change and shifting agricultural practices have been linked to a resurgence of LRD in certain regions, further complicating disease management (Srinivasan and Gunasekaran, 1996).

Early management strategies focused on chemical control, the shift towards integrated pest management and the use of biological controls offer a more sustainable solution. Given the complexity of the LRD-RWD phytoplasma-fungal disease complex, integrated disease management (IDM) is critical (Srinivasan et al., 2014). IDM includes early detection, vector control to prevent the spread of the phytoplasma associated with RWD, and the application of biocontrol agents for fungal pathogen management. Future research into molecular diagnostics and disease-resistant varieties is essential for mitigating the economic impact of LRD and ensuring the viability of coconut farming in the face of evolving environmental challenges.

5. SYMPTOMS AND DISEASE PROGRESSION

In palms affected by RWD, the first symptom observed is the deterioration of the spindle (unopened youngest leaf), marked by whitening and softening of the leaflets. These weakened leaflets are more susceptible to LRD, which initially appears as minute, water-soaked lesions. These lesions enlarge and coalesce, particularly on the soft, tender spindle leaflets, under high humidity, rainfall, and low temperatures, leading to extensive rotting. The disease may also extend into the spindle's interior, with rapid lesion expansion linked to infection early in spindle emergence. The tender unopened spindle leaf, with its thinner epidermal layer and high moisture content, is considered the main site of infection (Srinivasan and Gunasekaran, 1999). As the disease progresses, the infected spindle decays, attracting ants, and earwigs. A notable symptom is the sticking together of the rotten leaflet tips, which dry, turn black, and eventually fall off. The tips of the leaflets and midribs often shrivel and blacken. Rotting progresses slowly in mature leaves, leaving some basal portions symptom-free, giving the crown a fan-like appearance (Srinivasan and Gunasekaran, 1992). This fan-like appearance indicates that all leaves have contracted LRD in succession, with varying degrees of rotting (Fig. 3). In severe cases, yield declines drastically as heavily affected leaves lose their photosynthetic capacity, resulting in reduced vigor, stunted growth, and diminished fruit production. If left untreated, the palm may ultimately die.

Artificial inoculation studies by Srinivasan and Gunasekaran, (1996b) have successfully reproduced LRD symptoms similar to those observed in naturally infected palms, including lesions on the petioles, midribs, and leaf veins. Srinivasan, and Gunasekaran (1992) quantified the distribution of LRD symptoms in RWD-affected palms, finding that the inner whorls of leaves are more vulnerable to infection. Among diseased palms sampled, 24–43% exhibited symptoms throughout the crown. In certain RWD-endemic areas, the middle whorl leaves may suddenly yellow, even when the outer whorl and central shoot remain normal. In these leaves, lesions appear, coalesce, and result in severe blighting. Early diagnosis is therefore crucial for effective disease management.

Fig. 3. (A) Deterioration of the spindle leaves, (B) Rotten tips of the leaflets (C) Extensive rotting of leaves (D) fan-like appearance of crown

Rajagopal *et al.* (1986) studied the water relations of infected palms, noting that LRD significantly disrupts stomatal regulation, leading to excessive water loss and impaired water uptake, ultimately causing wilting. Phytoplasma-infected palms, such as those affected by RWD, undergo physiological changes that weaken their defence mechanisms, making them more susceptible to LRD. Increased free amino acid concentrations in tender leaves of RWD-affected palms may explain the heightened susceptibility to fungal infections (Pillai and Shanta, 1965). In palms affected by both LRD and RWD, the crown becomes disfigured, and the palm declines rapidly, necessitating further research to understand this interaction. LRD spreads through direct leaf contact, wind, or rain dispersal of spores, leading to outbreaks across plantations. Effective management strategies include timely fungicidal applications, cultural practices to reduce humidity and improve air circulation, early detection through regular monitoring, and addressing underlying RWD infections to minimize LRD risk. Chronic LRD infections result in stunted growth, poor fruit set, and palm death, highlighting the importance of integrated disease management.

6. ETIOLOGY AND PATHOGENS OF LRD

The earliest recorded isolation of a fungus associated with LRD of coconut was made by

McRae, (1916), who identified a Penicillium-like fungus from affected palms, followed by Sundararaman, 1934. Varghese 1929, strongly believed that LRD was primarily fungal in origin. Sundararaman, (1929) linked *Fusarium* spp. to coconut shoot rot, while McRae, (1916) observed *Gloeosporium* species in weakened palms. Later investigations revealed a diverse fungal complex associated with LRD, including *Helminthosporium* (*Bipolaris*), *Gloeosporium*, *Gliocladium*, *Pestalotia* (Pestalotiopsis), *Fusarium*, *Thielaviopsis paradoxa*, and *Rhizoctonia solani*. Pathogenicity tests on young coconut leaflets and central shoots showed that *Helminthosporium*, *Gloeosporium*, *Gliocladium*, and *Pestalotia* could induce rot, with *Helminthosporium* being the most virulent, causing up to 84% infection. Mixed inocula of *Helminthosporium*, *Gloeosporium*, and *Gliocladium* raised the infection rate to 93%. Helminthosporium spores are airborne, and their deposition on tender coconut leaflets, particularly in moist conditions, results in rapid germination and infection, forming brown spots that expand and coalesce within 12 hours (Srinivasan and Gunasekaran, 1999).

Histological studies by Menon, and Nair, (1951) detailed the infection process of *Helminthosporium halodes*, describing how the germinating spore forms an appressorium that penetrates the cuticle and invades the leaf's parenchymatous cells, causing disintegration of tissues. They also identified the fungi *H. halodes*, *Gliocladium roseum*, *Colletotrichum paucisetum*, and *Pestalotiopsis palmarum* as key pathogens in LRD. Similar findings were reported by Lily, (1963 & 1981), who showed that *Bipolaris halodes* preferred the youngest, most tender leaves for infection, while Radha and Lal, (1968) confirmed its pathogenicity even in palms free of RWD.

Isolations made from affected regions identified additional pathogens such as *Curvularia* sp. and *Diplodia* sp., with nematodes like *Panagrolaimus rigidus* also found in association, though they appear unrelated to LRD incidence. Biochemical studies revealed that increased phenol content and nitrogen levels in infected tissues play a role in disease expression, with the most severe infections observed in palms deficient in nutrients such as calcium and magnesium. Although earlier studies focused predominantly on *Bipolaris halodes*, later research highlighted the involvement of multiple pathogens in a fungal complex. Srinivasan and Gunasekaran (1996a) isolated *Exserohilum rostratum*, *Colletotrichum gloeosporioides*, and *Gliocladium vermoeseni*, identifying their role in LRD. Pathogenicity tests using the detached leaf method confirmed that these fungi, either alone or in combination, could induce symptoms typical of LRD, showing rapid infection and inducing 100% infection in injured tissues.

Other pathogens such as *Cylindrocladium scoparium*, *Fusarium solani*, *F. moniliforme*, *Thielaviopsis paradoxa*, and *Rhizoctonia solani* were also implicated in LRD. Profuse mycelial growth and spore masses were commonly observed on diseased tissues, and studies revealed that these fungi frequently co-existed in an associative, rather than antagonistic, relationship. *C. gloeosporioides* and *E. rostratum* were identified as the main pathogens, with *C. gloeosporioides* being particularly destructive to RWD-affected palms (Srinivasan and Gunasekaran,1999). Understanding the complex interactions among multiple fungal pathogens, environmental conditions, and coconut host factors is critical for developing effective management strategies for LRD, which significantly impacts coconut productivity worldwide.

7. EPIDEMIOLOGY

To enhance the understanding of the interaction between LRD and RWD meteorological conditions, it is important to consider that the disease complex involves multiple pathogens that co-exist and thrive under specific environmental factors, especially in palms affected by RWD. LRD is often associated with various fungal species, the most notable being *C. gloeosporioides*, *E. rostratum*, and *Fusarium* spp., each responding differently to climatic conditions. *C. gloeosporioides*, the primary pathogen of LRD during monsoon months, thrives in warm, humid environments. Studies have shown that fungal pathogens like *C. gloeosporioides* require prolonged leaf wetness and high relative humidity to sporulate and spread effectively. Humidity above 90% and temperatures around 27°C provide optimal conditions for the pathogen to infect the petioles and lamina of palms, particularly during the monsoon periods. The pathogen's activity peaks between June and December, which corresponds with the monsoon's high moisture availability. However, during the dry season, the population of *C. gloeosporioides* declines (Srinivasan and Gunasekaran, 1996).

On the other hand, *Fusarium* spp., which dominates during the dry season, exhibits different environmental conditions. These pathogens can thrive in drier conditions with lower humidity and higher temperatures, making them more aggressive from January to May. *Fusarium* spp., are known for their ability to survive in soil and plant debris, which allows them to persist even in adverse conditions and become opportunistic pathogens when conditions become more favourable during wet periods. Their presence is year-round suggesting they contribute to maintaining the disease complex during unfavorable periods. The role of *E. rostratum* is less consistent, but its occurrence is noted during periods of fluctuating humidity and temperature, although it appears to play a secondary role in the disease's progression. This pathogen's erratic pattern of infection and its moderate activity during winter months suggests that it may act as a co-pathogen, influencing disease expression in conjunction with other dominant fungi like *C. gloeosporioides* and *Fusarium* spp (Srinivasan and Gunasekaran, 1999).

Further investigation into the population dynamics of these pathogens, particularly during periods of fluctuating weather, suggests that their interactions are not just influenced by the immediate environmental conditions but also by the microclimate within palm canopies. Dense foliage and shaded conditions within palm groves can delay leaf drying and create pockets of high humidity, even during relatively dry periods. This microenvironment supports the persistence and spread of LRD pathogens, particularly *C. gloeosporioides*, which rely heavily on prolonged leaf wetness.

Recent research emphasizes the need for disease monitoring during the monsoon, as rapid pathogen resurgence can trigger severe LRD outbreaks (Latha et al.,2024, Rithesh and Radhakrishnan, 2024). Predictive models based on weather patterns help growers anticipate and manage these outbreaks with timely interventions, such as fungicides and improved airflow. Biological control agents (BCAs) like *Trichoderma* and *Pseudomonas* are also being explored to outcompete pathogens and reduce infections. Integrated strategies combining predictive modelling, BCAs, and cultural practices are becoming essential in managing LRD, particularly in economically important coconut-growing regions, offering a more effective approach to disease control.

8. INTEGRATED DISEASE MANAGEMENT STRATEGIES (IDM)

LRD of coconut is a significant problem in regions where coconut cultivation is prominent in India, leading to decreased photosynthetic area, deformity of the palm, and diminished yield. An inflorescence should ideally emerge from each leaf axil in coconut, and the quantity of female flowers, setting percentage, nut size, copra yield, oil content, and other factors are contingent upon the health of the leaf that generated the inflorescence (Koshy, 2002). Previous studies confirm that certain fungi, primarily from the fungi imperfecti group, are linked to LRD (Srinivasan and Gunasekaran, 1996). IDM is a key strategy for combating LRD, combining cultural, chemical, and biological control methods. Regular monitoring of palms for early symptoms allows timely intervention, and developing resistant or tolerant varieties provides a long-term solution. Cultural practices form the first line of defence by creating conditions unfavourable for disease development. These include removing and destroying infected debris, ensuring proper irrigation and drainage, and maintaining balanced fertilization—particularly potassium—to improve palm health and reduce disease incidence.

Farm and palm sanitation are essential for disease management. Removing and destroying diseased palms, particularly those yielding fewer nuts is recommended to reduce pathogen inoculum. In regions with chronic disease, the replanting of RWD-resistant varieties such as Kalpasree, Kalparaksha, or Kalpa Sankara is crucial for optimal palm productivity, careful selection of superior, high-yielding, disease-resistant mother palms is necessary (Krishnakumar et al., 2015). Seedlings should be selected based on early germination, vigorous growth, and disease tolerance traits. Bio-priming seedlings with *Pseudomonas fluorescens* during nursery and field planting enhances disease resistance and growth (Srinivasan, 2003).

Organic management is increasingly popular due to consumer demand for organic products. Organic fertilizers and composts enhance soil health, while plant-based extracts like neem oil offer antifungal properties. Environmental management practices, such as intercropping, promote biodiversity and reduce pathogen spread. Organic manuring, such as using 25 kg of farmyard manure or 10 kg of vermicompost enriched with *Trichoderma harzianum*, promotes beneficial microbial activity and nutrient availability, crucial for RWD-LRD affected plantations. Green manure crops like *Pueraria phaseoloides* and *Vigna unguiculata* (cowpea) further improve soil health and nutrient availability, enhancing palm productivity (Krishnakumar et al., 2015).

Adequate soil organic matter improves soil structure, nutrient availability, and microbial populations. In coconut-growing regions prone to leaching due to heavy rainfall, the application of manures is crucial. Fertilization based on soil testing, including NPK and micronutrients, along with dolomite for pH correction, ensures palm health. Mulching, proper irrigation, and soil conservation techniques help retain moisture and prevent soil erosion, particularly in sandy coastal areas vulnerable to nutrient leaching.

Breeding for resistance is a long-term strategy, with research focusing on screening varieties and using molecular markers for breeding programs. Resistant varieties, such as Kalpasree, Kalparaksha, and Kalpa Sankara, released by ICAR-CPCRI, are recommended for replanting in LRD- and root (wilt) disease (RWD)-affected zones (Thomas et al., 2018). Bio-priming seedlings with bioinoculants such as *P. fluorescens* improves seedling establishment and disease tolerance. Intercropping and high-density multispecies cropping systems (HDMSCS) maximize resource use and reduce disease severity (Thomas et al., 2010). Integrating diverse crops and recycling biomass through vermicomposting enhances farm sustainability and yields. Cash, food, and fodder crops incorporated into the system offer consistent economic returns and employment opportunities for farmers.

LRD management, particularly for palms affected by RWD, as over 99% of these palms show symptoms. Applying fungicides like hexaconazole 5 EC @ 2ml in 300 ml water or bioagents such as *P. fluorescens* and *B. subtilis* or consortia of the two bio-agents @ 50 g in 500 ml water/ helps control the disease (Krishnakumar et al., 2015). These treatments, applied during critical disease periods, reduce pathogen load and improve palm health. In conclusion, managing LRD and RWD in coconut cultivation requires an integrated approach combining cultural practices, biological controls, resistant varieties, and organic methods. This holistic strategy ensures the long-term health and productivity of coconut palms while minimizing environmental impacts and promoting sustainable farming.

9. CURRENT CHALLENGES AND FUTURE DIRECTIONS

LRD of coconut remains a major challenge to cultivation, primarily caused by pathogens like *C. gloeosporioides*, *E. rostratum*, and *Fusarium solani* which show significant variability in pathogenicity and adaptation to diverse environmental conditions. Climate change exacerbates the problem, as altered temperature and rainfall patterns promote pathogen proliferation, while poor soil conditions such as inadequate drainage and nutrient imbalances further increase coconut palms' vulnerability. Traditional chemical controls are becoming less effective due to resistant pathogen strains and concerns over environmental impacts, highlighting the need for IDM strategies that combine cultural practices, biological controls, and reduced chemical use. However, implementing IDM effectively remains a challenge for many farmers due to local conditions. Breeding programs aimed at enhancing genetic resistance offer a promising long-term solution, supported by advances in molecular biology and marker-assisted selection to incorporate resistance traits into coconut varieties. Additionally, developing improved biological control agents like enhanced *Trichoderma* strains and exploring microbial consortia could increase biocontrol efficacy. Adopting climate-smart agricultural practices, maintaining soil health, and using predictive models for decision support systems are vital for managing disease in a changing climate. Collaborative efforts among researchers, extension services, and farmers are essential to advancing sustainable solutions, protecting coconut production, and supporting farmers' livelihoods.

10. CONCLUSION

LRD, closely linked to RWD, continues to threaten coconut cultivation in tropical regions. The susceptibility of RWD-affected palms to fungal pathogens such as *C. gloeosporioides*, *Fusarium solani* and *E. rostratum* highlights the complex nature between these diseases, exacerbated by environmental factors like humidity and soil degradation. Effective management of LRD requires an integrated approach, including early detection, chemical fungicides, biological controls and cultural practices to improve palm vigour. The use of copper-based fungicides, vector control, and soil health management are critical to reducing disease impact. As climate change amplifies disease pressures, adaptive strategies, such as breeding disease-resistant coconut varieties and utilizing molecular diagnostics, are vital for long-term sustainability. Collaborative efforts among researchers, extension services, and farmers will be key to managing LRD and ensuring the resilience of coconut farming.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

Bila, J., Mondjana, A., Samils, B., & Högberg, N. (2015). High diversity, expanding populations, and purifying selection in phytoplasmas causing coconut lethal yellowing in Mozambique. *Plant Pathology, 64*, 597–604. https://doi.org/10.1111/ppa.12306

Butler, E. (1908). Report on coconut palm disease in Travancore. *Agricultural Research Institute Pusa Bulletin, 9*, 23.

CPCRI. (1985). *Coconut root (wilt) disease: Intensity, production loss, and future strategy, a survey report*.

Department of Agriculture, Government of Kerala. (1997). *Coconut root (wilt) survey*.

Duduk, N., Vico, I., Kosovac, A., et al. (2023). A biotroph sets the stage for a necrotroph to play: 'Candidatus *Phytoplasma solani*' infection of sugar beet facilitated *Macrophomina phaseolina* root rot. *Frontiers in Microbiology, 14*, Article 1164035. https://doi.org/10.3389/fmicb.2023.1164035

Gurr, G. M., Johnson, A. C., Ash, G. J., et al. (2016). Coconut lethal yellowing diseases: A phytoplasma threat to palms of global economic and social significance. *Frontiers in Plant Science, 7*, Article 1521. https://doi.org/10.3389/fpls.2016.01521

Harrison, N. A., & Jones, P. (2003). Diseases of coconut. In R. C. Ploetz (Ed.), *Diseases of tropical fruit crops* (pp. 197–225). CABI Publishing.

Koshy, P. (2002). Mundkur Memorial Lecture - Root (wilt) disease of coconut. *Indian Phytopathology*, 52, 335–353.

Krishnakumar, V., Babu, M., Thomas, R. J., et al. (2015). *Root (wilt) disease of coconut – Bench to bunch strategies*. ICAR-CPCRI, Regional Station, Kayamkulam.

Latha, P., Meena, B., Sudhalakshmi, C., et al. (2024). Status of coconut root wilt disease in Tiruppur district. *Indian Coconut Journal, 66*, 15–16.

Lewis, J. D., Knoblauch, M., & Turgeon, R. (2022). The phloem as an arena for plant pathogens. *Annual Review of Phytopathology, 60*, 77–96. https://doi.org/10.1146/annurev-phyto-020620-100946

Lily, V. G. (1963). Host-parasite relations of *Helminthosporium halodes* on coconut palm. *Indian Cocon J*, 16, 149–153.

Lily, V. G. (1981). Host-parasite relations of *Bipolaris halodes* (Drechs) Shoemaker on the coconut palm. *Indian Cocon J*, 11, 1–4.

Manimekalai, R., Soumya, V. P., Nair, S., et al. (2014). Molecular characterization identifies 16SrXI-B group phytoplasma ('Candidatus *Phytoplasma oryzae*'-related strain) associated with root wilt disease of coconut in India. *Scientia Horticulturae, 165*, 288–294. https://doi.org/10.1016/j.scienta.2013.11.031

Marcone, C., Valiunas, D., Salehi, M., et al. (2023). Phytoplasma diseases of trees. In *Forest Microbiology* (pp. 99–120). Elsevier.

McRae, W. (1916). Communication to the Dewan of Cochin. In K. P. V. Menon & U. K. Nair (1948). The leaf rot disease of coconuts in Travancore and Cochin. *Indian Cocon J*, 1, 33–39.

Menon, K. P. V., & Nair, U. K. (1948). The leaf rot disease of coconut in Travancore and Cochin. *Indian Coconut Journal, 1*, 33–39.

Menon, K. V., & Nair, U. K. (1951). Scheme for the investigation of the root and leaf diseases of the coconut palm in South India. *Indian Cocon J*, 5, 5–19.

Nejat, N., Sijam, K., Abdullah, S. N. A., et al. (2009). Phytoplasmas associated with disease of coconut in Malaysia:

Phylogenetic groups and host plant species. *Plant Pathology, 58*, 1152–1160. https://doi.org/10.1111/j.1365-3059.2009. 02153.x

Pillai, N. G., & Shanta, P. (1965). Free amino-acids in coconut palms affected by root (wilt) disease. *Current Sci*, 636–637.

Radha, K., & Lal, S. B. (1968). Some observations on the occurrence of leaf rot disease of coconut and associated factors. *Jakarta*.

Radha, K., Sahasranaman, K. N., & Menon, K. P. V. (1962). A note on the yield of coconut in relation to rainfall and leaf rot and root (wilt) diseases. *Indian Coconut Journal, 16*, 3–11.

Rajagopal, V., Patil, K. D., & Sumathykuttyamma, B. (1986). Abnormal stomatal opening in coconut palms affected with root (wilt) disease. *Journal of Experimental Botany, 37*, 1398–1405. https://doi.org/10.1093/jxb/37.9.1398

Ramjegathesh, R., Karthikeyan, G., Rajendran, L., et al. (2012). Root (wilt) disease of coconut palms in South Asia – an overview. *Archives of Phytopathology and Plant Protection, 45*, 2485– 2493. https://doi.org/10.1080/03235408.2012.729772

Ramjegathesh, R., Rajendran, L., Karthikeyan, G., & Raguchander, T. (2022). Coconut (*Cocos nucifera* Linn.) diseases and management strategies. In *Diseases of horticultural crops* (pp. 73–96). Apple Academic Press.

Rao, G. P., Manimekalai, R., Kumar, M., et al. (2019). Host metabolic interaction and perspectives in phytoplasma research. In A. Bertaccini, K. Oshima, M. Kube, & G. P. Rao (Eds.), *Phytoplasmas: Plant pathogenic bacteria - III* (pp. 201–226). Springer Singapore.

Rao, V. G., Neeraja, B., Rao, N. B. V. C., et al. (2023). The biological control of stem bleeding disease caused by *Thielaviopsis paradoxa* in coconut. *Journal of Environmental and Financial Accounting, 18*, 370–376. https://doi.org/10.48165/jefa.2023.18.02.28

Ray, R. V. (2024). Effects of pathogens and disease on plant physiology. In P. Agrios (Ed.), *Plant Pathology* (pp. 63–92). Elsevier.

Rithesh, L., & Radhakrishnan, N. V. (2024). Productivity concerns and management challenges in coconut farming. *Indian Cocon J*, 66, 26–29.

Singh, G. R., Raychaudhuri, S. P., & Kapoor, I. J. (1971). Interaction of fungi, pathogen in producing citrus die-back. *Citrograph, 57*, 27–28.

Srinivasan, N. (2003). Efficacy of *Pseudomonas fluorescens* against leaf rot in root (wilt) affected coconut palms. *Indian Phytopathology*, 56, 210–211.

Srinivasan, N., & Gunasekaran, M. (1992). An appraisal of symptom expression in coconut due to leaf rot disease. *Indian Cocon J*, 23, 2–7.

Srinivasan, N., & Gunasekaran, M. (1996). Incidence of fungal species associated with leaf rot disease of coconut palms in relation to weather and the stage of lesion development. *Annals of Applied Biology*, 129, 433–449. https://doi.org/10.1111/j.1744-7348.1996. tb05766.x

Srinivasan, N., & Gunasekaran, M. (1996). Pathogenicity of prevalent fungi associated with leaf rot disease of coconut. *Indian Cocon J*, 27, 2–4.

Srinivasan, N., & Gunasekaran, M. (1999). Coconut leaf rot disease complex: A review. *Cord, 15*, 34. https://doi.org/10.37833/cord.v15i01.323

Srinivasan, N., Chandramohanan, R., Bharathi, R., et al. (2014). Development of technology and popularization of biological control agents for integrated management of coconut leaf rot disease. *CORD*, 27, 13. https://doi.org/10.37833/cord.v27i1.123

Sundararaman, S. (1929). Administrative report of the Government Mycologist. Report of the Department of Agriculture, Madras Presidency for the official year, Coimbatore, India.

Thomas, G. V., Krishnakumar, V., Maheswarappa, H. P., & Palaniswami, C. (2010). Coconut based cropping/farming systems. *Central Plantation Crops Research Institute*, Kasaragod.

Thomas, R. J., Shareefa, M., & Nair, R. V. (2018). Varietal resistance in coconut. In V. Krishnakumar, P. K. Thampan, & M. A. Nair (Eds.), *The coconut palm (Cocos nucifera L.) - Research and development perspectives* (pp. 157–190). Springer Singapore.

Varghese, M. K. (1934). Disease of the coconut palm. Department of Agriculture and Fisheries, Travancore.

Vasanthakumar, V. C. (2017). Production loss due to monsoon deficiency. *Indian Coconut Journal, 60*, 5–13.

Yankey, E. N., Bila, J., Rosete, Y. A., et al. (2018). Phytoplasma diseases of palms. In G. P. Rao, A. Bertaccini, N. Fiore, & L. W. Liefting (Eds.), *Phytoplasmas: Plant pathogenic bacteria - I* (pp. 267–285). Springer Singapore.

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