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REVIEW ARTICLE

Coconut phytoplasma diseases: Advances in detection and sustainable management strategies

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Abstract

Coconut palms are affected by a range of diseases, with phytoplasma-associated syndromes such as root wilt, lethal yellowing, lethal decline and Tatipaka disease posing major threats to their productivity worldwide. Phytoplasmas are wall-less, obligate phytopathogenic bacteria that infect the phloem of host plants and are primarily transmitted by phloem-feeding insect vectors belonging to families such as Cicadellidae, Fulgoridae and Psyllidae. These diseases are characterized by symptoms including yellowing, wilting, bronzing and eventual death of affected palms, leading to severe economic losses in coconut-growing regions. The molecular complexity, low titre, uneven distribution of phytoplasmas and similarity of symptoms to other stresses make detection and management particularly challenging. Recent advances have focused on the development of sensitive molecular diagnostic tools, identification of field-tolerant coconut varieties and experimental biotechnological approaches to enhance either pathogen detection or crop resistance. Biological control methods, including the use of beneficial microbes, show promise for integrated disease management. Despite some progress, sustainable and effective control remains elusive, necessitating further research into resistant cultivar development, rapid field diagnosis and innovative management strategies to safeguard global coconut cultivation.

Keywords: coconut root wilt; lethal yellowing; management; molecular analysis; phytoplasma; symptoms; tatipaka disease

Introduction

The coconut (*Cocos nucifera*), a member of the *Arecaceae* family, is known as the "king of palm" or "Kalpavriksha," meaning a tree that provides all essential life necessities. This important oilseed crop is widely grown in tropical areas across 93 countries with Indonesia, the Philippines and India being the major producers (1, 2). The total area under coconut cultivation in India is approximately 2.17 million ha as of the 2023-24 estimates. This area supports an annual production of around 27373.62 million nuts, reflecting an average productivity of 9871 nuts per ha. Karnataka is the leading coconut-producing state, accounting for approximately 6151 million nuts during 2023-24. Following Karnataka, other top coconut-producing states include Kerala, with around 5522.71 million nuts and Tamil Nadu, producing about 6092 million nuts. Andhra Pradesh ranks fourth with roughly 1707 million nuts, while West Bengal contributes approximately 421.18 million nuts. These states benefit from favourable climatic conditions and agricultural practices that support extensive coconut cultivation, with Karnataka consistently maintaining its top position in terms of production, even though ranks second in area (5.65 lakhs ha), Kerala occupying the top position with 7.66 lakhs ha area under coconut cultivation (https://coconutboard.gov.in/Statistics.aspx, 2023-24). At global level, Philippines tops the list in terms of area under coconut cultivation with 3.647 million ha, followed by Indonesia (3.374 million ha) and India (2.2 million ha). However, India tops the production list with 20376 million nuts per year, according to 2021 estimates (https://coconutboard.gov.in/Statistics.aspx) (3).

Coconut palms are susceptible to various diseases, including basal stem rot [BSR; *Ganoderma* lucidum (Curtis) Karst], bud rot (*Phytophthora palmivora* Butler), stem bleeding [*Thielaviopsis paradoxa* (de Seynes) von Hohnel], leaf blight [*Lasiodiplodia theobromae* (Pat.) Griffiths & Maubl], grey leaf spot [*Pestalotiopsis palmarum* (Cooke) Steyaert] and several phytoplasmal diseases including root wilt, lethal wilt, lethal yellowing, lethal decline, tatipaka disease, lethal yellowing, *etc.,* that have led to significant economic losses around the world (4). The phytoplasmal diseases reported across the countries, the subgroup they belong to and their vector transmission details are presented in Fig. 1 and Table 1. This review details the general characteristics of phytoplasmas, diseases caused in coconut, their vector transmissions and the management strategies adopted, challenges in phytoplasma disease management and the scope

Table 1. Species and subgroups of candidatus phytoplasma affecting coconut palms

Disease	Phytoplasma species	16s RNA Subgroup	Vector	Region	Detection method	Source
Lethal yellowing	*Candidatus.* Phytoplasma *palmae*	16SrI	Not reported	America, south Africa, southeast Asia	LAMP	(5)
bronze leaf wilt	*Candidatus* Phytoplasma *noviguineense*	16SrII	Not reported	New Guinea	LAMP	(35)
Lethal yellowing	*Candidatus* Phytoplasma *palmae*	16Sr IV	Not reported	America, south Africa, south east Asia	LAMP	(6)
Lethal yellowing	*Candidatus.* Phytoplasma *palmae*	Presumably 16SrIV-A	*Heplaxius crudus*	Cuba, Belize, Haiti, Cayma Islands	PCR, Nested PCR and RFLP	(8,14)
Lethal yellowing	*Candidatus* phytoplasma *palmae*	16SrIV-A	*Cadusa* spp.	Jamaica, Florida (USA), Nevis, Saint Kitts	PCR	(36)
Coconut lethal decline	*Candidatus* Phytoplasma *palmae*	16SrIV-A & 16Sr1V-B	*Heplaxius crudus*	Mexico	RFLP	(36)
Coyol palm decline, Coconut decline	*Candidatus* phytoplasma *palmae*	16SrIV-B	-	Honduras	PCR	(36)
Tanzanian coconut lethal decline	*Candidatus* Phytoplasma *costanzaniae*	16SrIV-C	*Diastrombus mkurangai*	Kenya, Tanzania	PCR	(18)
lethal decline, Coconut leaf yellowing	*Candidatus* Phytoplasma *palmae*	16SrIV-D	-	Mexico	RLFP	(7)
Lethal yellowing	*Candidatus* Phytoplasma *palmae*	16SrIV-E	-	Mexico	Nested PCR	(22)
Yucatan coconut lethal decline	*Candidatus* Phytoplasma *palmae*	16SrIV-D & 16SrIV-C	*Heplaxius crudus*	Mexico	Nested PCR	(21,13)
Lethal yellowing	*Candidatus* Phytoplasma *palmae*	16SrIV	*Heplaxius crudus*	Americas	Cage transmission	(9,16)
Leaf wilt Disease	*Candidatus* Phytoplasma *oryzae*	16SrXI	*Stephanitis typica*, *Proutista moesta*	Sri Lanka	Nested PCR, cage transmission and RT PCR	(23)
Kerala root wilt disease	*Candidatus* Phytoplasma *oryzae*	16SrXI-B	*Stephanitis typica, Proutista moesta*, *Sophonias greeni*	India	Cage transmission, Nested PCR	(27,12)
Weligama coconut leaf wilt disease (WCLWD)	*Candidatus* Phytoplasma *oryzae*	16SrXIa	Multiple (*Kolla ceylonica, Idioscopus clypealis, Proutista moesta, Proutista* sp., *Nisia nervosa, Stephanitis typica*	Sri Lanka	PCR and RT PCR	(28,11)
Kerala root wilt disease, Areca palm yellow leaf disease	*Candidatus* Phytoplasma *cynodontis*	16SrXIVa	*Stephanitis typica, Proutista moesta*, *Sophonia greeni*	India	Nested PCR	(29, 15)
Coconut yellow decline	*Candidatus* Phytoplasma *cynodontis*	16SrXIVa	-	Malaysia	Nested PCR	(31)
Lethal yellowing disease	*Candidatus* Phytoplasma *palmicola*	16SrXXII-A	*Platacantha lutea*	Mozambique, Nigeria	PCR	(24, 10)
Awka wilt disease (AWD) or bronze leaf wilt	*Candidatus* Phytoplasma *palmicola*	16SrXXII-A	*Platacantha lutea*	Nigeria	PCR	(29)
Cape St Paul wilt disease, Côte d'Ivoire lethal yellowing	*Candidatus* Phytoplasma *palmicola*-related strain	16SrXXII-B	*Myndus adiopodoumeensis* Synare and *Diostrombus* spp.	Ghana, cote d'Ivoire	PCR and Nested PCR	(17, 33)
Coconut yellow decline	*Candidatus* Phytoplasma *malaysianum*	16SrXXXII-B	-	Malaysia	-	(19,31)
lethal yellowing disease	*Candidatus* Phytoplasma *palmicola*	16SrI, 16SrV, 16SrXII & 16SrXXII	-	Africa	RFLP	(34,20)
Côte d'Ivoire lethal yellowing	*Candidatus* Phytoplasma *asteris*	16SrI	*Nedotepa curta*	Côte d'Ivoire	Nested PCR	(28)

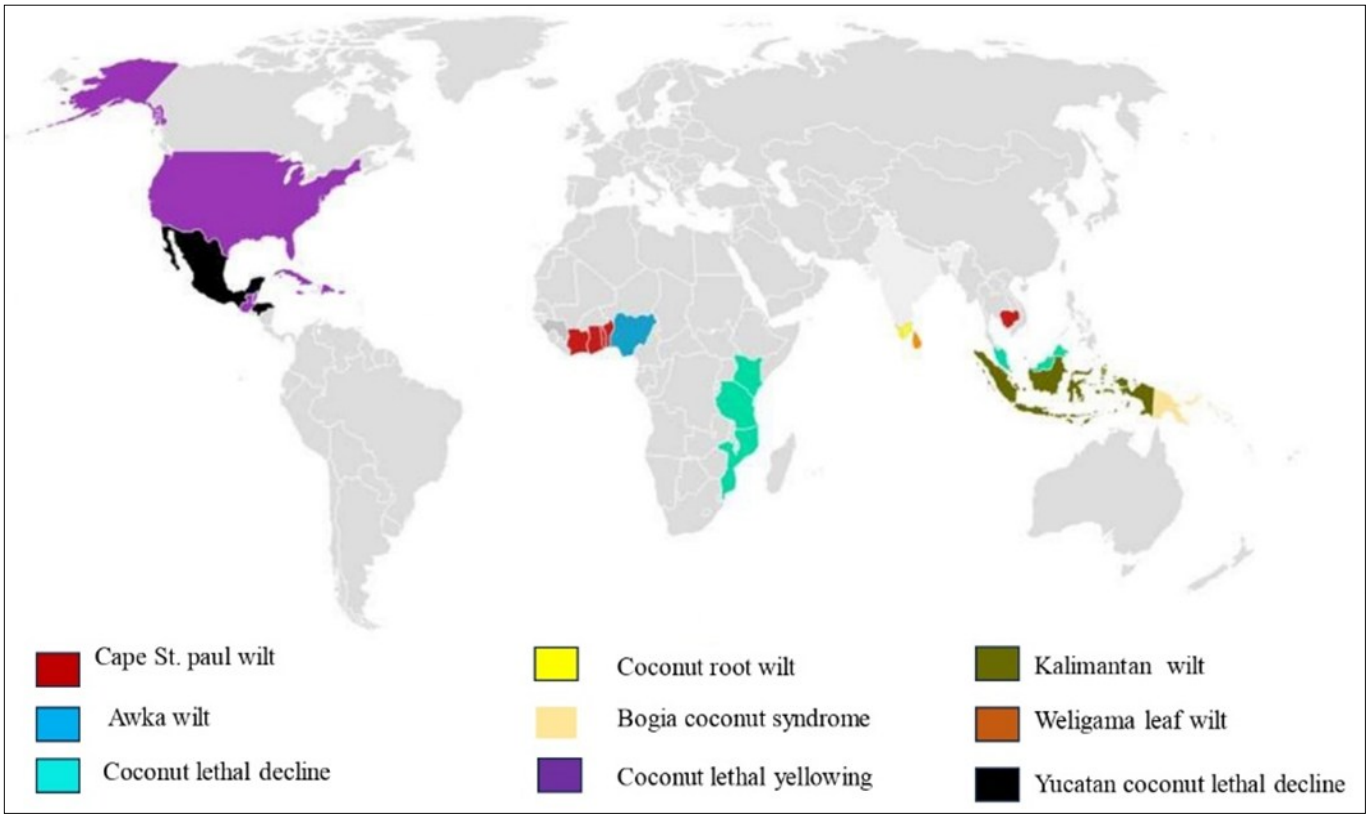

Fig. 1. Global distribution of phytoplasma diseases affecting coconut palms.

for future research.

Phytoplasma

Phytoplasma is a wall-less bacterium enclosed by a triple-layered membrane belonging to the class Mollicutes. They are obligate phytopathogenic bacteria; their survival is limited to the sieve elements of phloem tissues and cannot be cultured *in vitro*. In the absence of key metabolic genes, phytoplasmas rely heavily on their parasitic hosts for nutrient uptake and to complete their life cycle (4). Phytoplasma was first observed in the 1960s during electron microscopic studies of aster yellows disease-infected plants (5). They are small pleomorphic organisms and have been observed in many shapes and sizes, ranging from 0.1 to 2.0 mm in diameter. Phytoplasmas are previously known as mycoplasma-like organisms (MLOs) and the name was replaced by Phytoplasma and later, the interim taxonomic status of "*Candidatus* Phytoplasma" was given (3). They are usually transmitted by phloem-feeding insects of the Homoptera family and contain three types of immunodominant proteins in their membrane: immunodominant membrane protein (Imp), immunodominant membrane protein A (Idp and antigenic membrane protein (Amp) (1). The genome size of phytoplasmas ranges between 498-959 kb with a low G+C (19.9-30 %) content. Despite the limitations in their genetic compositions, phytoplasmas retain essential pathways required for DNA replication, transcription, translation and protein transport. However, they lack critical metabolic processes like protein and lipid biosynthesis, the TCA cycle and oxidative phosphorylation, which are common in free-living bacteria (8). A key element in phytoplasma survival is the Sec secretion system, which plays a crucial role in exporting proteins. This system, consisting of SecA, SecE and SecY, allows proteins to be translocated across the cell membrane. SecA acts as an ATPase and drives proteins into the membrane, while SecE and SecY form channels for export (8, 9). In addition to the Sec system, phytoplasmas utilize the YidC system, which helps them to invade the host cells. Both systems play an essential role in the pathogenicity of phytoplasmas, especially in targeting the plant phloem and the midgut of corresponding insect vectors, enabling the pathogen to spread and incite diseases (25).

Phytoplasma transmission

Phytoplasma, being biotrophs, are highly dependent on their host plants for nutrients and survival. Phytoplasma is primarily transmitted by phloem-feeding insect vectors belonging to families such as Cicadellidae (leafhoppers), Fulgoridae (planthoppers) and Psyllidae (jumping plant lice), apart from transmission by parasitic dodder (*Cuscuta* sp.) plants, mechanical and seeds (26, 27). Insects belonging to the order Homoptera are the primary vectors for phytoplasma transmission (28). These insects suck the sap from the phloem of infected plants, allowing phytoplasma to enter the salivary glands, pass through the insect's midgut and multiply within the vectors (29, 30). When a vector feeds on an infected plant and subsequently feeds on a healthy coconut palm, it transfers the phytoplasma-containing phloem sap to the healthy palm. Recent findings have indicated the possibility of transovarial transmission of phytoplasmas, *i.e.,* transmission to the next generation through egg masses of infect vectors. Hence, the off-springs of vectors are potentially viruliferous even before feeding on an infected host plant and can transmit the phytoplasma to healthy coconut palms (31). Dodder plants act as a bridge for phytoplasma transmission between different host plants by attaching to their vascular systems. Mechanical transmission, especially through plant sap, can occur unintentionally through contaminated tools through wounds. Though less common, seed transmission has also been observed in some cases, where upon seed germination the seedlings show phytoplasma-induced disease symptoms (32). There are also evidences that phytoplasma may persist in the soil or in the roots of infected perennial plants, potentially leading to new infections when healthy plants are introduced into contaminated areas, though it is not considered a

primary transmission method (9, 30, 32).

Diseases caused by phytoplasmas in coconut

Lethal yellowing: It was first observed in the Caribbean in the late 1800s, particularly in the Cayman Islands, around 1834 and later spread to Jamaica and other areas (33). It is mainly transmitted by the planthopper *Haplaxius crudus*. Initial symptoms include drying of developing inflorescences, followed by darkening of flower cluster tips and blackening of male flowers, leading to reduced fruit production (34, 35). Infected spathes become discoloured with blackened tips and youngest leaves show water-soaked streaks leading to terminal bud rot (36). The disease progresses with yellowing of lower leaves and eventual collapse of the crown, leaving behind a trunk resembling a telephone pole (36). Over the last 50 years, LYD has devastated millions of coconut palms in the Caribbean, causing 70-80 % yield losses. The disease is associated with phytoplasmas from the 16SrIV (including 16SrIV-A, B and C) and 16SrXXII (16SrXXII-A, B) groups. The 16SrIV group prevails in the Caribbean and Americas, while 16SrXXII is more common in Africa, notably Nigeria and Ghana (37).

Kerala (root) wilt: Kerala wilt was first recorded in Travancore, Kerala, in 1874 and became prominent after the 1882 Kottayam floods (38, 39). It is a significant disease in India due to severe yield loss, reducing production from 80-100 nuts per palm to only 10-30 nuts annually. The disease, associated with the 16SrXI phytoplasma group, becomes visible 6-24 months post-infection. Symptoms include ribbing, flaccidity, yellowing, leaf necrosis, drooping, premature nut fall, leaf and crown rot and ultimately plant death (2). Leaf rot, aggravated by poor soil fertility and climatic stress, reduces the photosynthetic area and facilitates secondary infections by *Exerohilum rostratum* and *Colletotrichum gloeosporioides* (40). Root decay occurs in 12-94.4 % of infected palms (41). In young palms, RW disease disrupts flowering and reproductive development. In sandy soils common in Kerala, where nutrient and water retention are poor, symptoms are more severe, contributing to increased economic loss (42).

Lethal wilt: It was first noticed in 2007 without a known cause. Recently, it has been identified in Thanjavur, Pudukkottai and Thiruvarur districts of Tamil Nadu with a 1.4 % disease incidence (43). Initial symptoms include brown-black decay at the nut calyx, leading to premature nut fall within 3-5 days. This is followed by yellowing and necrosis of older fronds, eventually affecting spear leaves and growing points, resulting in crown death and yield loss within 3-5 months (44).

Tatipaka disease: It was found in Tatipaka andhra Pradesh, affects palms in sandy and heavy black soils and progressed slowly over 5 years (45). The 16SrXI phytoplasma subgroup was associated with the disease. Early symptoms include clustered, darkened, twisted leaves with chlorotic spots and loop-like lesions. Affected palms are stunted, producing shell-less, undersized nuts with poor endosperm. In advanced stages, stem tapering occurs, making palms commercially unproductive (36).

Weligama coconut leaf wilt: Emerged in the Weligama area of Sri Lanka's Matara district in 2006 and spread rapidly across the Southern Province by 2008 (46). It causes a 25-60 % reduction in nut yield and may lead to complete fruiting failure. Phytoplasmas responsible belong to the 16SrXIV group. Symptoms include flaccid, ribbed young leaves, yellowing of lower fronds (up to the 12th) and marginal drying of leaflets. Eventually, dried fronds hang and fall, while female flower production is reduced significantly (47).

Coconut yellow decline: Coconut yellow decline was first noted in Malaysia and attributed to Candidatus Phytoplasma cynodontis. It causes yellowing of foliage, inflorescence drop and nut fall (48). Symptoms, similar to LYD, include chlorosis starting at the spear leaf and spreading, followed by frond collapse and basal rot, with palm death within five months. The responsible phytoplasma is grouped under 16SrXIV (49).

Cape St. Paul wilt: This disease was reported in Ghana in 1932, initially in Cape Saint Paul, Woe. It later spread to the Western and Central regions, severely damaging the coconut industry (50). Symptoms include premature nut fall, inflorescence blackening and crown yellowing or browning progressing from older to younger fronds, eventually leading to total crown collapse (51). The disease exhibits both localized and jump-type spread patterns (52, 53).

Bogia Coconut syndrome: It reported exclusively in Papua New Guinea, is linked to phytoplasmas of the 16SrXXII-A subgroup (27). It causes yellowing of outer crown fronds, premature nut shedding and browning of fronds leading to spear decay and crown death, with a skirt-like leaf arrangement (54).

Awka wilt (or) bronze leaf wilt: It was first identified in Nigeria's Awka district in 1917 and later confirmed in 1993 as a phytoplasma -associated disease (55). Symptoms include leaf discoloration from yellow to reddish-brown, starting from leaf margins and progressing inward, along with die-back and systemic infection, evidenced by under-bark browning. A striking symptom is the persistence of green veins amid discoloured tissues (56).

Morphological characterization of phytoplasma

Morphological characterization of phytoplasma is being done using microscopic techniques. Different types of microscopy techniques have been employed to study the external and internal structure of phytoplasma such as Light microscopy uses visible light to illuminate specimens and is commonly employed to detect and visualize phytoplasmas in infected plant tissues. Various dyes such as Diene's stain, methylene green, Feulgen, thionin, toluidine and acridine are used for this purpose. For example, Diene's stain causes phytoplasma-infected phloem tissues to appear light blue under the microscope (57). Similarly, other dyes provide observable differences between infected and healthy samples. Fluorescence microscopy, which relies on the emission of light by fluorophores after they absorb specific wavelengths, offers high specificity and sensitivity, making it effective for detecting low-titer pathogens like phytoplasma. Fluoroprobes such as DAPI or SYTO13 bind to DNA in infected samples and the emitted fluorescence is visualized using a high-intensity light source (e.g., mercury or xenon lamp), excitation and emission filters and a dichroic mirror, resulting in a high-contrast image against a dark background (58).

Electron microscopy, which uses accelerated electrons for imaging, was first used by Doi et al. in 1967 to visualize phytoplasmas in thin sections of infected coconut palms (18).

In previous studies, observed elongated DNA in extra-nuclear locations and Dienes' reagent confirmed the presence of phytoplasma. Electron microscopy showed round or oval-shaped cells distributed unevenly in vascular tissues, appearing coccoid

under UV light and measuring 250 to 500 nm, with blue pigmentation noted in sieve tubes of infected palms (59). Scanning electron microscopy (SEM) allows visualization of phytoplasma cells, primarily on the external membrane, showing small cells clinging to the inner walls of sieve tubes either singly or in clusters (60). Transmission electron microscopy (TEM), which passes electrons through thin sections, provides ultrastructural details of the phytoplasma. Leaf samples are fixed, washed, post-fixed, dehydrated, embedded in Araldite resin, sectioned, stained with uranyl acetate and Reynolds lead citrate and examined under TEM. Phytoplasmas appear pleomorphic, typically spherical to ovoid, ranging from 200 to 800 nm in diameter (60, 61).

Molecular tools for the detection and identification of phytoplasmas

Detection of phytoplasmas is challenging due to their minute size, low titer in plant tissues and inability to be cultured in artificial media under standard conditions (39). Although early studies suggested that phytoplasmas might be cultured under specific controlled environments, consistent cultivation remains difficult, hindering pathogenicity studies and slowing progress in phytoplasma research. Molecular methods, particularly polymerase chain reaction (PCR), have significantly advanced phytoplasma detection due to their high sensitivity and specificity (62). Techniques such as nested PCR, real-time PCR (qPCR) and RT-PCR, often combined with enzymatic digestion of PCR products, enable accurate identification even at low pathogen loads (63, Table 1). These methods offer rapid, reliable detection and are applicable across diverse sample types, making them invaluable in plant pathology diagnostics and research (64, 65).

Nested PCR analysis of genomic DNA from symptomatic coconut palms with specific primers targeting the 16S rRNA region in phytoplasmas showed a detection success rate of 88-100 % (12,60). Similarly quantitative PCR is an efficient method of detecting the nucleic acids which amplifies and quantifies DNA in real-time using fluorescent dyes (SYBR Green) or probes (15). To detect different phytoplasma subgroups in infected hosts, sequence-independent and sequence-specific screening techniques were used (1,26). TaqMan probe based single plex and duplex real time PCR assays targeting 16S rRNA were able to differentiate different subgroups of phytoplasmas affecting coconut palms (66,26).

Restriction Fragment Length Polymorphism (RFLP) was used to detect DNA sequence variation by enzymatic digestion and fragment separation. Banding patterns act as molecular fingerprints for phytoplasma grouping (67, 68). Universal primers amplify the 16S rRNA region and subsequent digestion with restriction endonucleases create RFLP profiles for subgroup classification (69). In recent times, loop-mediated isothermal amplification (LAMP) has emerged as the reliable and quick detection method of phytoplasmas (52). LAMP amplify the target DNA using 4-6 specific primer at isothermal conditions (70). Amplification can be verified through visual observation for turbidity development (46) or colorimetric assays (71). In 2025, LAMP and real LAMP assays were used for sensitive detection of 'Candidatus Phytoplasma asteris' in coconut (72).

Management strategies

Diseases caused by Phytoplasmas, an incurable and debilitating problem affecting coconut palms, pose a significant challenge to coconut growers. Integrated management strategies are advocated for effective control of disease outbreaks. The strategies comprise of farm quarantine, regular monitoring, cultivating resistant varieties, field sanitation (eradication of infected palms to reduce inoculum), weed management, augmentation of soil with beneficial microbes, maintaining optimum soil moisture and ensuring balanced fertilizer (primary, secondary and micronutrients) application. However, despite these efforts, the disease continues to devastate coconut plantations across the globe owing to the lack of sustainable phytoplasma management strategies. To track the pattern and extent of disease spread, aerial monitoring by drones fitted with high-resolution cameras has been introduced (73), so that preventive strategies can be introduced in areas where a possible disease outbreak would occur (2).

Host plant resistance

Certain coconut varieties have been reported to show tolerance to phytoplasmas in fields, but no genotype has been found fully resistant. Field resistance allows plants to survive long enough for profitability (73). *Kalpa Raksha*, developed from the Malayan Green Dwarf and released in 2008, grows to 4.14 m in two years and is 80 % disease-tolerant to root wilt disease. *Kalpasree*, from the Chowghat Green Dwarf, are widely grown in Kerala, reaching 4.0 m at 20 years and shows strong resistance to coconut root wilt (2). *Kalpa Sankara*, a cross between the Chowghat Green Dwarf and West Coastal Tall, was introduced in 2012, offering high yields and root wilt disease tolerance (38, 52). Hence, developing or identifying varieties or cultivars or hybrids with field tolerance will be highly helpful to mitigate the onslaught from phytoplasmas. Healthy palms in phytoplasma epidemic areas can be used to collect nuts for raising nurseries. Cultivars showing tolerance or resistance to phytoplasmas may be brought under traditional breeding programmes to impart phytoplasma tolerance to the existing high-yielding varieties. Coconut cultivars showing tolerance to phytoplasma diseases reported in different countries

Table 2. Phytoplasma tolerant coconut varieties

Varieties	Disease tolerance	Country	Source
Kalpasree	Kerala root wilt	India	(38)
Kalpavriksha	Kerala root wilt	India	(38)
Kalpa Sankara (a cross between the Chowghat Green Dwarf and West Coastal Tall)	Kerala root wilt	India	(35)
Green dwarf	Weligama coconut leaf wilt	Sri Lanka	(29)
Green dwarf	Root wilt disease	India	(25)
Green dwarf	Awak wilt disease	Nigeria	(54)
SGD x Vanuatu tall	Cape saint Paul Wilt Disease	Ghana	(54, 10)
Maypan hybrid	Lethal yellowing	Florida	(78)
Giant Gree (Mozambique Tall)	Lethal yellowing disease	Mozambique	(78)

are furnished in Table 2.

Cultural practices

Good agronomic or cultural practices are a must for a good harvest in any crop. Cutting down severely infected coconut palms, green manuring, following mixed cropping/inter cropping, enough watering, provision of adequate drainage facilities, balanced fertilizer application (500 g nitrogen, 300 g phosphorus, 1000 g potassium per palm applied in 2 splits during Apr- May and Sep-Oct) were some of the integrated practices recommended for phytoplasma disease management in coconut (74, 75). In addition, application of magnesium sulphate (500 g/palm/year) was recommended to control the leaf rot disease in root wilt-affected palms (52). Balanced fertilizer application is paramount to enhance plant growth and improve their ability to resist pathogen infection. Conversely, a deficiency in essential nutrients will weaken the plants, increasing their susceptibility to diseases (52).

Biological control

Biological control of diseases is the most effective and sustainable when integrated with other management practices. Plant Growth Promoting Rhizobacteria (PGPR) act as plant growth promoters through better nutrient uptake and phytohormone (auxin and cytokinin) production, in addition, support plant disease resistance through the activation of host defence mechanisms, parasitism, antibiosis and competition. PGPR strains are also reported to fix atmospheric nitrogen and aid in mineral solubilization, such as phosphorus (40). Silicate-solubilizing bacteria strengthen coconut crops by accumulating in roots and enhancing photosynthesis and stomatal regulation (76). Phosphate solubilizers like *Bacillus* spp. and *Pseudomonas* sp. prevent root rot/wilt, promote plant growth and boost the yield (25). Additionally, *Trichoderma harzianum*, combined with organic manures like vermicompost or farmyard manure, enhances soil fertility and prevents wilt disease (77, 78). In general, rhizosphere regions augmented with beneficial organisms might help the plants to overcome biological stresses under field conditions.

Chemical method

Phytoplasmas are sensitive to the tetracycline group of antibiotics *in vitro*. Hence, researchers have used oxytracycline hydrochloride (HCl) to temporarily suppress phytoplasma diseases, though this compound is primarily aimed at controlling bacterial pathogens. Oxytetracyclines are said to act on phytoplasma by suppressing their propagation and eliminating them from the infection site. Oxytetracycline HCl used on coconut palms resulted in temporary symptom relief from root (wilt) disease, but it proved ineffective in the long term, making it unsuitable for sustainable management (77, 78). Another group of scientists has reported suppression of lethal yellowing symptoms in coconut palms by preventive injection of oxytetracycline HCL antibiotic (1 g dissolved in 15 ml water) at a 4-month interval and indicated the possibility of bringing at least 50 % of the plants to the state of full remission (symptomless) from yellowing (78).

Challenges

The phytoplasmas are presumably transmitted by phloem-feeding insect vectors and therefore it's difficult to detect the pathogen and culture the organism under *in vitro* condition. In addition, the pathogen has a low titre and uneven distribution in the phloem tissues, which makes the isolation and characterization of the causative agent very difficult, as proper sampling is a prerequisite for reproducible results. The phytoplasma doesn't visualize the structures of plant tissues, thus making the traditional isolation techniques ineffective. The phytoplasma-affected palms exhibit symptoms that are like nutrient deficiencies, drought stress and even fungal infection during the initial phases. Moreover, phytoplasmas have a longer incubation time and therefore, symptoms are usually expressed after 24 months of infection, thus making the preventive strategies ineffective. Though electron microscopy provides high resolution for viewing phytoplasma, it is time-consuming, costly and demands skilled personnel. Molecular techniques such as PCR, RT-PCR and LAMP employing oligonucleotide primers are faster than SEM and TEM, but they require sophisticated laboratory equipment, in addition to technically competent molecular biologists. Till date, management of phytoplasma diseases, to a lesser extent, is achieved through inoculum reduction by destroying the infected trees, vector management and soil health improvement by balanced nutrition application and enrichment of the rhizosphere with plant growth-promoting rhizobacterial strains. However, satisfactory control of phytoplasma diseases of palms remains elusive.

Future prospects

Safeguarding coconut palms against infectious phytoplasmas often presents a significant challenge to growers as well as researchers. The absence of phytoplasma-resistant coconut varieties or hybrids makes the plant protection task very difficult. Hence, the coconut breeders must reorient their research activities towards developing Phytoplasma-resistant or at least field-tolerant coconut varieties or hybrids for commercial cultivation. Tetracycline antibiotic was tried for the management of phytoplasma diseases of coconut, but it offered only a short-term solution for the problem. Hence, chemical management is not sustainable under field conditions. Therefore, for the sustainable management of phytoplasma diseases like root wilt, enrichment of root zone with microbial consortia including PGPR and biofertilizers and balanced nutrition (comprising primary, secondary and micronutrients) was tried by the plant protection scientists of Tamil Nadu Agricultural University and recorded some encouraging results in terms of emergence of new crown leaves and inflorescence from treated root wilt infected palms (unpublished results). These studies reiterate the potential lying with the exploitation of beneficial microbes for the management of pathogenic organisms colonising the rhizosphere region. However, there is a long way to go in developing a complete package of practices for the management of phytoplasma diseases.

Owing to the recent advancements in molecular biology techniques, the researchers all over the world are trying the exploit the genetic manipulation techniques for the management of phytoplasma diseases. One such technology is RNA interference (RNAi), wherein short homologous nucleotide gene sequences are used to suppress the expression of critical genes in the phytoplasmas responsible for their pathogenicity and thereby making them avirulent. Another promising technology is the CRISPR-Cas9, which is a powerful gene-editing technology used to make precise changes in the target DNA. This technology can be used to develop crop varieties with agronomically desired traits like disease tolerance, improved yield, drought resistance, etc.

Early diagnosis is very crucial for the timely management of diseases in any crop; hence, being a perennial crop, coconut is not an exception. Our surveillance studies during 2022-2024 in the coconut root wilt-infected districts of Tamil Nadu, India, showed the expression of root wilt symptoms even in young palms of 1-2 years old (unpublished data). These observations necessitate the planting of phytoplasma-free coconut seedlings, though the seed transmission of root wilt phytoplasma is not reported. Hence, the development of reliable methods for faster and early detection of phytoplasmas in coconut nurseries and fields is highly essential. Immunoassays using antisera developed against phytoplasmas is a potential approach for quick and real-time detection *in vivo*. Differentially expressed proteins in the phytoplasma-infected palms may be identified and purified to develop phytoplasma-specific monoclonal or polyclonal antibodies for use in immunoassays. Another interesting area to work is the development of biosensors, which are devices widely used in medicine, environmental biology and the food industry to monitor the prevalence of diseases, pollutants and contaminants by detecting the biological signals that are converted into optical or electrical signals. Hence, the volatile compounds or biological signals emanating from phytoplasma-infected palms could be sensed with the biosensors and compared with those of signals from healthy palms to demarcate healthy and infected seedlings in nurseries or older coconut palms in fields.

Conclusion

The management of phytoplasma-induced diseases in coconut remains a significant challenge due to the pathogen's complex biology, inefficient detection, lack of resistant varieties and the elusive nature of its transmission vectors. Current management is largely limited to destruction of infected palms, vector control and cultural practices, none of which offer lasting solutions. Emerging biotechnological tools, such as genomic editing and molecular diagnostics, offer new hope for developing resistant cultivars and achieving earlier, more accurate detection. Field tolerance in certain coconut varieties and the use of beneficial microbes in the rhizosphere have shown some promise, but integrated, sustainable disease management packages are still under development. Future research should prioritize breeding for resistance, advancing rapid detection techniques and exploring biological and genetic interventions to mitigate the devastating impact of phytoplasma diseases on global coconut cultivation.

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Authors' contributions

All authors contributed equally to the preparation and writing of the original draft and approved the final version of the manuscript. MS developed and framed the manuscripts. SM, GK, SV and MA contributed through supervision, critical evaluation and refinement of the manuscript.

Compliance with ethical standards

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