Indian Phytopathology
https://doi.org/10.1007/s42360-021-00382-8

REVIEW ARTICLE

Phytophthora diseases of arecanut in India: prior findings, present status and future prospects

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Received: 16 September 2020 / Revised: 15 March 2021 / Accepted: 24 May 2021

Abstract

Phytophthora diseases are serious and often fatal in arecanut causing huge losses to farmers (50–100%) if timely and proper management measures aren't adopted. Among *Phytophthora* diseases, fruit rot disease predominantly exists in all the arecanut growing regions receiving heavy rainfall during the south-west monsoon season. The extended manifestation of pathogen causes crown and bud rot disease which prevails till November–December due to prolonged rains and congenial weather factors. The role of *Phytophthora* in causing these diseases of arecanut was established in the early 1900's and later the *Phytophthora meadii* was identified as a causal agent. Though the diseases are sporadic, their management in the field situation is a challenging task due to intense rainfall and the variability in the pathogen. The continuous heavy rainfall during the tender arecanut developmental stage, non-availability of professional climbers coupled with the absence of machinery for powerful spraying, occurrence of aggressive pathotypes and lack of *Phytophthora* resistant/tolerant arecanut varieties are the major hindrance for taking up effective disease management measures. The present review has attempted to compile the earlier findings, present status of this century-old disease, and discusses future strategies for the development of effective remedies for this serious malady of the areca palm.

Keywords Arecanut · Fruit rot · *Phytophthora meadii* · Disease management

Introduction

The plantation crop sector plays a pivotal role in supplying livelihood, nutritional security and contributes significantly to the national economy and foreign exchange owing to its domestic and global significance. It also provides direct and indirect employment to the agricultural sector, and supplies a wide range of raw materials for various rural as well as small scale industries, besides playing a pivotal role in conserving soil and ecosystem *perse* (Chowdappa et al. 2014). Among plantation crops, arecanut (*Areca catechu* L.) or beetle nut is an important crop distributed in Southern and South-East Asia including India, China, Bangladesh, Indonesia, Malaysia, Srilanka, Philippines and New Guinea etc. It supports the livelihood of millions of small and marginal farmers and traders. Even though the production of arecanut is confined in some areas, commercial products are majorly shared across the globe and approximately 700 million people regularly chew betel nut worldwide (Guo et al. 2020; Peng et al. 2015). The arecanut industry frames the monetary spine of almost six million people in India and many of them depend solely on income from arecanut for their livelihood (Rajagopal and Balasimha 2004).

Arecanut is an ancient crop and cultivated from time immemorial in India. With increased production after the 1980's, the increment in the area of arecanut is dispirited with government policies. Nevertheless, the area increased by 70% over the past two or three decades and the production boom changed. In India, arecanut is cultivated in an area of 518,000 ha with an annual production of 853,000 metric tonnes (NHB 2019). Arecanut is famous for masticatory motive and used to chew with betel leaves or as scented supari and its cultivation is mainly focused in the South-Western and North-Eastern area. The states of Karnataka, Kerala, Assam, West Bengal and Meghalaya are the principal producers and account for greater than 70% of the area and production (NHB 2019).

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Published online: 31 May 2021

Arecanut being a perennial crop is vulnerable for attack by a diverse group of insect pests, diseases and disorders throughout the year at every stage of its life. Among the many reported diseases, *Phytophthora* diseases results in partial or total crop loss in individual palms or death of the palm itself. The fungus infects the immature tender nuts, growing bud and the crown resulting in fruit, bud and crown rots respectively (Saraswathy 2004). Identification of *Phytophthora* infecting arecanut palms was started by imperial mycologist Butler (1906) about 115 years back. Later, quite a lot of systematic research has been done on *Phytophthora* diseases and their management. An attempt has been made in this article to review the work done so far on *Phytophthora* diseases of arecanut and to find out the gaps in research to identify future research stratums and priorities for effective disease management.

Occurrence and distribution of diseases

In India, fruit rot was first recorded from the erstwhile Mysore state (Butler 1906) and later from the prevailing Dakshina Kannada and Uttara Kannada districts of Karnataka and some places of Malabar and Cochin in Kerala (Coleman 1910). Further, Coleman (1910) opined that, the occurrence of the disease was increased year after year due to the raise in inoculums within the endemic regions of South India inflicting extreme economic loss. In the endemic areas of India, the disease occurs straight away after the onset of the monsoon rains and prevails till mid-August due to congenial weather conditions. Crown rot disease occurs due to extended infection of pathogen and prevails till October due to prolonged rains and congenial weather factors. Of late, the disease is said to be present in the whole arecanut growing areas which receive heavy rainfall during the southwest monsoon season (Sarma et al. 2002).

Systematic surveys were conducted from time to time to assess the intensity, extent of damage and prevalence of the disease in major arecanut ecosystem. Jose et al. (2008) analysed the distribution of fruit rot disease in five major arecanut-growing districts of Karnataka, i.e. Dakshina Kannada, Udupi, Chikkamagaluru, Shivamogga and Uttara Kannada which receive very high rainfall during monsoon season and reported fruit rot disease to the tune of 10–30%. In subsequent years, the surveys conducted by CPCRI (Anonymous 2015, 2016, 2017) indicated the occurrence of the disease severity from 5 to 28.6% and varied from garden to garden within major arecanut growing districts of Karnataka and Kerala and distributed based on the amount and pattern of rainfall. Among the disease-endemic areas, the highest incidence of fruit rot was observed in Karkala of Udupi district (41.25%) followed by Sirsi of Uttara Kannada (38.80%) districts of Karnataka (Anonymous 2014). Further, Jose et al. (2019) reported the wide spread of the disease in surveyed districts of Karnataka and Kerala due to receipt of heavy rainfall during monsoon season. From the above findings, it was concluded that-*Phytophthora* diseases of arecanut are widely distributed in major arecanut growing regions of India mainly in Karnataka, Kerala, Tamilnadu, parts of Andaman islands and Meghalaya (Fig. 1) and subsequently the occurrence of *P. meadii* was reported from different areca growing areas of Kerala and Karnataka (Dutta and Hegde 1987; Santhakumari and Hegde 1987; Saraswathy 1994).

Economic loss

Significant losses due to fruit rot (10–90%) and bud rot (15%) have been reported. Coleman (1910) reported up to 75% loss or destruction of the entire crop. Later a loss of 15–20% (Coleman and Rao 1918; Kamath 1956; Nambiar 1956), 50–90% (Koti Reddy and Anandaraj 1980) and 72–350 kg nuts/acre (Sastry and Hegde 1985a) were reported. In addition to fruit rot, hundreds of areca palms succumb to *Phytophthora* bud rot every year and a loss of about 15% (Saraswathy 1994) or 21–50 palms/acre (Sastry and Hegde 1985a) were reported. Anandaraj and Balakrishnan (1987) developed a method to assess the yield loss due to fruit rot. Chowdappa et al. (2000a) observed the extent of yield loss due to *Phytophthora* diseases depending upon locality and variety. Furthermore, Jose et al. (2008) estimated the yield loss to the tune of 10–50% due to fruit rot disease in highly vulnerable or disease-prone regions of Karnataka. Further, Jose et al. (2019) estimated the per cent yield loss by purposive method of sampling and results found that, about 34–59% yield loss had been recorded with production loss of 1,05,000 MT of arecanut.

Symptomatology

The *Phytophthora* can infect arecanut seedlings or adult palms and the symptoms can be seen on buds, spear leaf, leaf sheath, mature leaves, inflorescence and fruits, but the frequent infection appears on immature tender nuts during the monsoon season which is commonly called as "fruit rot". The infection on the bud leads to "bud rot" and on the crown region through the leaf sheath leads to complete "crown rot".

Fruit rot

Fruit rot disease is characterized by rotting and heavy shedding of immature nuts (Butler 1906). A detailed account of the disease with its causal organism was documented by

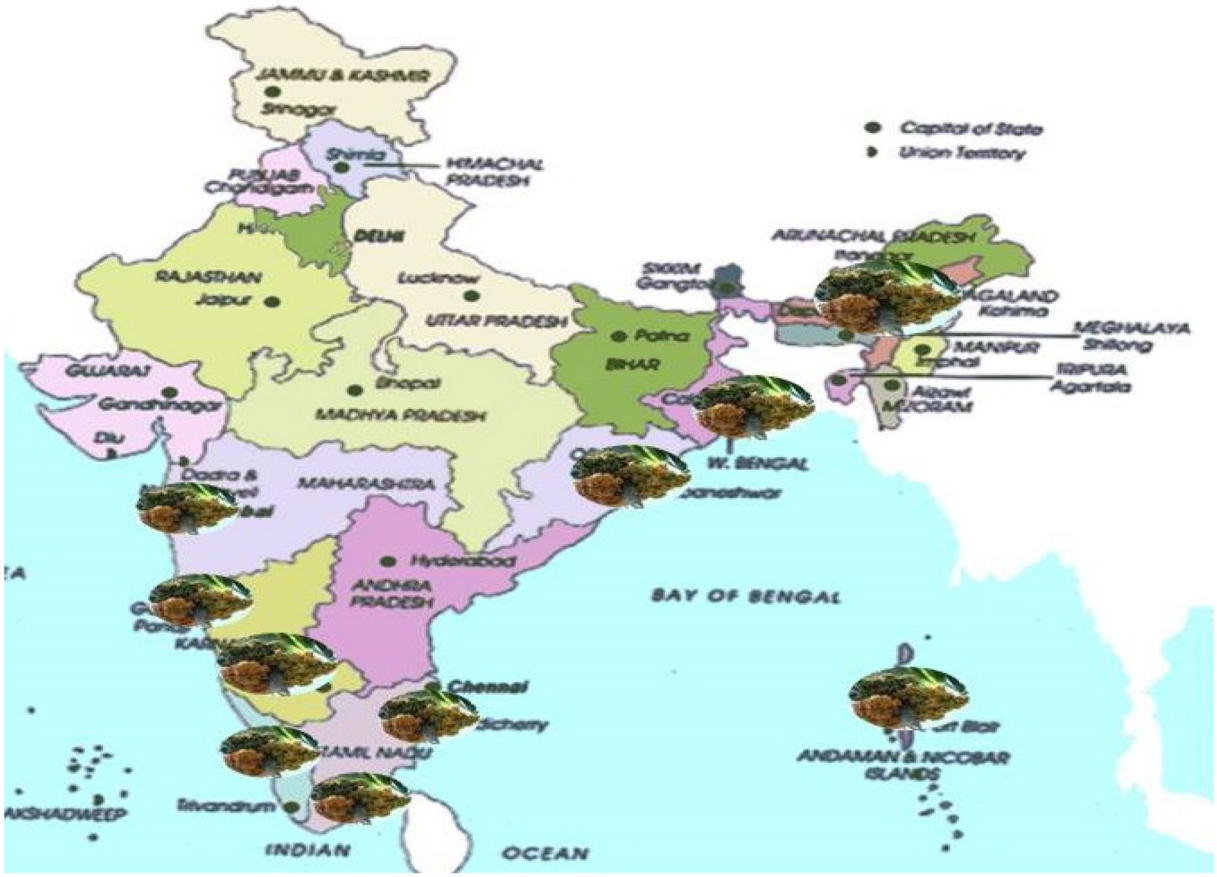

Fig. 1 Distribution of *Phytophthora* diseases of arecanut in India

Coleman (1910) in his pioneering work on fruit rot. The appearance of disease could be identified by the unusual shedding of fruits during south-west monsoon season. The symptom appears as dark green water-soaked lesions at the nut surface usually close to the perianth (Fig. 2). The pathogen makes entry to the host tissue through the stomata or epidermis. The entry is aided by the mycelium or germ tube of the germinating sporangia (Coleman 1910).

Under the laboratory conditions, the infection initiates within 18–19 h on the wounded tissues or occurs 4–5 days

Fig. 2 Symptom expression due to fruit rot disease in arecanut

after inoculation on the uninjured fruit surface (Saraswathy 1994). Fruits lose their clear natural green colour due to infection. On the infected nuts the lesion spread gradually covering the fruit surface before or after shedding and on incubation under humid conditions, develop white mycelial mat over the infected area and envelopes the entire surface of the fruit (Coleman 1910; Saraswathy 2003). In a severe case of infection fruit stalk and the axis of the inflorescence are also affected (Marudarajan 1950a; Sundararaman and Ramakrishnan 1928). Waterhouse (1974) described symptoms of fruit rot as the development of the chlorotic area with loose mycelium and luxuriant sporangia.

The infected nut shows discoloration of the kernel, reduction in weight and large vacuole. The infection occurring towards the end of south-west monsoon season may not develop the typical symptoms of fruit rot and dry up without shedding of nuts and remain mummified (Marudarajan 1950a). Fruit rot leads to quantitative and qualitative loss to the crop and the infected nuts are not suitable for chewing.

Bud rot

Bud rot could occur independently or following excessive fruit rot, where the Oomycete can grow down the bunch stalk and to the tender portion of the stem or can enter directly through the outer leaf sheath in to the tender growing point leading to crown rot (Coleman 1910). Bud rot and crown rots can occur often in fruit rot affected gardens (Sastry 1982; Sastry and Hegde 1987). Incidences of bud rot and crown rot are very sporadic compared to fruit rot. Bud rot or crown rot infection leads to death of the areca palm itself, whereas fruit rot incidence results in yield loss (Fig. 3). Every year hundreds of areca palms succumb to bud rot or crown rot and the palm treetops were killed in many gardens in the Malnad area, adjoining the Western Ghats (Venkatarayan 1932). Later, the occurrence of bud rot in a severe form from the heavy rainfall areas of Karnataka was reported (Nambiar 1949).

The disease occurs in the course of south-west monsoon season and fresh infection during November onwards becomes severe due to subsequent cooler months (Marudarajan 1950a). Bud rot is characterized by rotting of developing buds and the encompassing tissues. The preliminary symptom seen is the yellowing of the spear leaf. The affected spindle loses its natural green colour and in the advanced stages turn to yellow and can be drawn out with a gentle pull. As a result of the speedy spread of contamination to the bottom of adjoining leaves, these leaves additionally end up yellow, droop and drop off leaving a bare stem. Colonization of the infected portions by secondary organisms converts it into a slimy mass, which would emit a disagreeable odour (Coleman 1910).

Fig. 3 Symptom expression due to bud rot disease on arecanut

Crown rot

In the case of crown rot, infection initiates from the bottom of an outer maximum leaf sheath or the stalk ends of infected areca bunches or developing inflorescence and slowly spread to the internal tissues of the stem. The first symptom seen is yellowing of the outermost leaf sheath followed by the inner portion of affected sheath exhibiting water-soaked lesions (Fig. 4) and later the infection spreads to the soft portion of the stem and the growing bud ensuing in yellowing of the leaves, rotting of the internal tissues of the crown and finally death of the palm (Sarma and Murthy 1971).

Etiology

The earliest description of the pathogen causing fruit rot was by Sydow and Butler (1907) who described the pathogen as *Phytophthora omnivore* de Bary. Coleman (1910) named it as *P. omnivore* var. *arecae*. Pethybridge (1913) observed that the fungus was quite different from *P. omnivore* and renamed it as *P. arecae* Peth. Later, *P. palmivora* (Das and Cheeran 1986) and *P. meadii* Mc Rae (Sastry and Hegde 1985a, b, 1987) were reported to cause fruit rot in parts of Kerala, Siddapura, Sirsi, and Yallapur areas of

Fig. 4 Symptom expression due to crown rot disease on arecanut

North Kanara district of Karnataka. The delimitation of *P. arecae and P. palmivora* remains an area of debate with conflicting conclusions cited in the literature but it has been reported that *P. palmivora* isolated from cocoa and coconut does not infect arecanut (Chowdappa et al. 2003a, b). *P. meadii*, has been reported as the incitant of fruit rot of arecanut in Uttara Kannada and Shimoga districts of Karnataka (Saraswathy 1993) and this fungus has also been reported as the causal agent of abnormal leaf fall of rubber and fruit rot of cardamom (Sarma et al. 2002). Based on detailed morphological and ITS-RFLP analysis of 63 isolates of *Phytophthora* derived from the different locality of arecanut growing areas, it was established that *P. meadii as* the causal organism associated with fruit rot disease of arecanut in India and there was no evidence of the occurrence of *P. arecae* (Chowdappa et al. 2001). In addition to dominant species *P. meadii*, *P. hevea* also been reported (Chowdappa et al. 2003a, b; Prathibha et al. 2020).

Morphology of *Phytophthora meadii*

The pathogen produces various kinds of morphological structures during their sexual and asexual life cycle which are responsible for disease development and spread in an epidemic manner. Hence, a better understanding of phenotypic characters of pathogen enables to know the variability in pathogen population, thereby helps in the development of effective management strategies.

Asexual phase

The Oomycete produces coenocytic mycelium that becomes septate on ageing and reproduces asexually through sporangia and chlamydospores. The mycelium is inter and intracellular, occasionally branched with a diameter of 8–9 mm in *P. arecae* (Coleman 1910). The pathogen grows and sporulates better on steamed cornmeal agar (Tucker 1931). The mycelium of *P. meadii* is copiously branched with a diameter ranging from 5–6 mm without distinct hyphal swelling (Saraswathy 1994; Sastry and Hegde 1987; Waterhouse 1974).

Phytophthora database shows that, the pathogen produces sporangia that are either terminal or lateral; papillate, occasionally with two papillae; caducous (pedicel 10–20 µm); ellipsoid or elongated, obpyriform, occasionally spherical, often distorted into lobed or hourglass shapes; on the fruit they are 33–67 µm long × 14–28 µm wide (average 48 × 21 µm) and in water 20–44 µm long × 16–29 µm wide (average 32 × 23 µm). The length-breadth ratio varies from 1.3 to 2.0 (Waterhouse 1974); 1.4–1.7 Oudemans and Coffey (1991). Sporangia are produced sympodially on branched sporangiophores that are 10–20 µm long.

Sporangiophores in *P. arecae* are irregularly branched, sympodial or mostly sympodial without any hyphal swellings. The deciduous sporangia are ellipsoidal, obturbinate, nearly spherical, papillate without double apieces and not distorted and are borne laterally and intercalary. The sporangial measurements varied from 20.6 × 30.1 µm to 43.3 × 71 µm or 40–50 × 35–40 µm and maximum 70 × 48 µm and L:B ratio of 1.1–1.4:1.0 in *P. arecae* (Coleman 1910; Ribeiro 1978; Stamps et al. 1990; Waterhouse 1974). Sporangiophores in *P. meadii* are irregular with sparse branching and characterized by way of swelling at the nodes or somewhere else. The sporangia are round or ellipsoidal, distorted or lobed and every so often with more than one apex. They are laterally inserted with round base and hemispherical papilla. Sporangial diameter ranged from 25–75 × 15.0–40 µm with an L:B ration of 1.3:1.0 (Sastry and Hegde 1987) or 45–75 (Stamps et al. 1990) or 40–55 × 22.5–37.5 to 45–52.5 × 22.5–35.5 µm with an L:B ratio of 1.3–1.6 or 1.4–1.7 µm in solid media and in water respectively (Saraswathy 1994) or 41.09–50.85 × 27.84–33.30 µm with an L:B ratio of 1.43–1.74 (Chowdappa et al. 2003a, b).

Morphological characterization of *P. meadii* isolates revealed a significant variation in phenotypic characters with stellate to rosaceous pattern of mycelium, caducous, ovoid to ellipsoidal sporangia with conspicuous papilla and indicated the predominance of A2 mating type in arecanut *Phytophthora* population (Anonymous 2014, 2015, 2016). Sporangial size varied from 34.1 to 41.6 µm in length and 20.3–28.7 µm in breadth (Prathibha et al. 2020). Chlamydospores are not produced by all isolates of the same species. But the frequent occurrence of these spores was recorded in *P. arecae* and *P. meadii* (Stamps

et al. 1990; Tucker 1931; Waterhouse 1974). Chlamydospores are absent or seen in older cultures of certain isolates (Saraswathy 1994).

Sexual phase

Pathogen reproduces sexually through the formation of oospores produced by the fusion of compatible male gamete (Antheridium) and female gamete (Oogonium). The *Phytophthora meadii infecting* arecanut is mostly heterothallic and the occurrence of both A1 and A2 mating types has been reported. However, the formation of sex organs in single cultures and naturally infected nuts (homothallic) are observed both in *P. arecae* and in *P. meadii* (Coleman 1910; Desai 1950; Narasimhan 1922; Ramakrishnan and Seethalakshmi 1956; Saraswathy 1994). Sundararaman and Ramakrishnan (1928) could not observe oospores in nature and this character was attributed to the presence of '+' and '−' strains in nature (Uppal and Desai 1939). Desai (1950) observed the oospore production on fresh bean agar. Marudarajan (2000) reported the existence of A1 and A2 mating types within *P. meadii.* Chowdappa et al. (2002) recorded the occurrence of homothallic strain of *P. heveae* on fruit rot affected arecanut in addition to *P. meadii*.

Venkatarayan (1932) compared the isolation of *P. arecae* with the usual strain and found no difference in their behavior in paired cultures. He also found *P. arecae* forming oospores with a *Phytophthora* species resembling *P. palmivora.* Oogonial diameter of *P. arecae* varied from < 30 or 30–40 µm and in *P. meadii* < 30 or 30–40 or 40–50 µm. Oospores nearly fill the oogonium and wall thickness varied from 2 to 4 µm and was related to diameter. Oospore measurements recorded was 20–30 µm or 30–40 µm in *P. arecae* and < 20 or 20–30 or 30–40 µm in *P. meadii* (Sastry and Hegde 1987; Stamps et al. 1990). Antheridia are always amphygynous and are usually broader than its length. The measurements recorded ranged around 14 × 15 µm; or 12 × 13 µm (Sastry and Hegde 1987; Waterhouse 1963).

Studies on oospore formation involving different combinations of six *Phytophthora* species indicated that, three of the isolates belong to *P. palmivora* and others to *P. faberi, P. meadii* and *P. arecae,* respectively. *P. arecae* was found to produce oospores with *P. meadii, P. palmivora* and *P. faberi. P. arecae* therefore falls into "rubber" group and *P. meadii* into the "cocoa" group. The formation of oospores in combinations of *P. arecae* with *P. meadii* or any one of the members of the "cocoa" group lends additional support for merging all these isolates as strains of *Phytophthora palmivora* (Marudarajan 1941).

Cultural variation of *Phytophthora meadii*

The growth habit of *Phytophthora* differs according to the culture media supplemented and the cultural characters of *P. meadii*. The pathogen did not show any cultural pattern or growth was profuse in solid media with white fluffy mycelium having radial growth or fluffy with uniform growth in carrot agar and potato dextrose agar, respectively (Santhakumari 1987; Waterhouse 1974). Some researchers found that, aerial mycelium of *P. arecae* was luxuriant, scanty or sometimes absent and in submerged cultures, the hyphae are smooth, enlarged, even or uneven and on carrot agar medium the Oomycete put forth fairly copious growth with slightly radiate pattern (Ramakrishnan and Seethalakshmi 1956; Thomas et al. 1947; Waterhouse 1974).

Saraswathy (1994) studied the cultural variation of *P. meadii* on different synthetic and organic media and reported that the growth pattern varied from fairly striate or stellate or radial with fluffy mycelium either near the inoculum or the entire surface of the medium and colour of the colony varied from white to off white depending on the medium. Chowdappa et al. (2000a) described the colony characters as petalloid to radiate pattern with cotton wool like aerial mycelium on carrot agar medium.

Nutritional requirement of pathogen

Information on the nutritional requirements of *Phytophthora* affecting arecanut is scanty. In general, the different species of *Phytophthora* vary greatly in their nutritional requirement and different isolates within the species vary in their response to nutrient or environmental factors (Zentmyer et al. 1976). *P. meadii*, the incitant of fruit and bud rot in arecanut put forth good growth in sucrose and fructose as sources of carbon: sodium and potassium nitrates as nitrogen and riboflavin as vitamin source (Saraswathy 1994).

Molecular variability and pathogen diversity

Pathogen populations with excessive tiers of genetic versions are likely to conform more unexpectedly to various environments. However, the reports lack a combinatorial method of studying molecular characterization which offers treasured statistics on pathogen biology. A unique examination of molecular variation inside and amongst *P. meadii* isolates throughout growing seasons should lead to

higher changes in its epidemiology, host–pathogen interactions, and pathogen control from year to year.

Earlier *Phytophthora meadii* had classified under group II (Stamps et al. 1990; Waterhouse 1974). Recently, Kroon et al. (2012) analysed genus wide phylogeny with mitochondrial and nuclear genes and classified *P. meadii* into clade II with other species viz., *P. colocasiae*, *P. capsici, P. citrophthora*. The pathogen identity was also confirmed by Chowdappa et al. (2003a, b) based on ITS-RFLP of rDNA and AFLP patterns and found that isolates of *P. meadii* from arecanut, cardamom and rubber were synonymous and also pathogenic to plantation crops.

Later, Sharadraj et al. (2015) developed specific and sensitive PCR assays for the detection of six *Phytophthora* sp. infecting coconut, cocoa and arecanut and observed that *P. palmivora* (325 bp), *P. nicotianae* (300 bp) and *P. capsici* (400 bp) had distinct amplicon size; however *P. meadii, P. citrophthora and P. colocasiae* exhibited same band length (362 bp). Thereafter, a real-time PCR protocol was standardized for species identification of *P. meadii* using five pairs of primers. The primer pair PM1F and PM1R specifically amplified *P. meadii* and was able to distinguish from other *Phytophthora* species which did not give amplification with the same pair of primers. However, the primer pairs also amplified the intently associated species in the clade II (Anonymous 2015). Later, Prathibha et al. (2019) performed a high-resolution melting curve (HRM) analysis using primers designed based on single nucleotide differences in A/T and C/A alleles to differentiate closely related species i.e. *P. meadii, P. citrophthora and P. colocasiae.* HRM curve evaluation proved to be a quick and correct technique for differentiation of intently associated species of *Phytophthora.* Diversity analysis of *Phytophthora* species infecting arecanut using RAPD markers grouped 30 *P. meadii* isolates in two clusters. But no correlation was found with geographical origin, aggressiveness or morphological variations (Prathibha et al. 2020).

Epidemiology

Phytophthora diseases are major threats to arecanut growers, since pathogen could perpetuates and overwinters during off-season through resting chlamydospore and dormant mycelium. The humidity and microclimate within the arecanut plantations favour the survival of the pathogen throughout the year (Anandaraj 1980).

Role of climatic factors in disease development

Temperature plays an important role in the growth and sporangial formation of *Phytophthora meadii*. The minimum, optimum and maximum temperatures favored the growth and sporulation of *P. arecae* is 10–12, 27–30 and 35 °C; and > 5, 25–30 and > 30 °C for *P. meadii* (Ribeiro 1978; Sastry and Hegde 1987). Saraswathy (1994) observed good growth and sporangial formation of *P. meadii* at 24–30 °C and 27–30 °C, respectively.

Similarly, south-west monsoon plays a key role in the occurrence; persistence and spread of fruit rot disease. Continuous heavy rainfall with intermittent bright sunshine hours, low temperature (20–23 °C) and high relative humidity i.e. more than 90% are the factors congenial for disease development (Coleman 1910; Kamath 1956; Narasimhan 1922). The disease intensity is high in gardens with high relative humidity (Kamath 1953). Koti Reddy and Anandaraj (1980) attempted to correlate the intensity and spread of the disease in relation to the rainfall and temperature for a period of nine years (1970–1978) and reported maximum crop loss in 1978 when the rainfall was as high as 5088.6 mm. The fungus requires bright sunlight for a short while for the formation of sporangia and the liberation of zoospores (Anandaraj 1985). Rarely a wide gap of 40–50 days had also been recorded between first monsoon rain and initial incidence of fruit rot in the season wherein the rainy days were scattered and discontinuous (Anandaraj and Saraswathy 1985; Marudarajan 1950b; Saraswathy 1994).

Earlier findings indicated that the occurrence of the disease is mainly depended on the onset and pattern of rain. The spread of the disease is favored by heavy wind and to a certain extent by small insects and rain splashes. Under favorable conditions the zoospores released from the sporangia germinate in the films of water and penetrate the nut surface through the stomata (Anandaraj 1985; Anandaraj and Saraswathy 1985; Coleman 1910; Kamath 1956; Narasimhan 1922; Saraswathy 1994). Anandaraj et al. (1992) studied the weather parameters viz., maximum-minimum and ambient temperature, the quantity of rainfall, relative humidity and sunshine hours with regards to disease occurrence and labored out a linear version to expect the disease in four days advance. In 2013, a study conducted in arecanut gardens at Kidu and Dharmasthala of Karnataka to correlate the climatic factors with disease incidence indicated that, maximum disease incidence was recorded during the first week of July coinciding with the highest rainfall, high relative humidity and low temperature. In Dharmasthala, disease incidence was noticed from 2nd week of July and maximum disease severity was observed during the first week of August (Anonymous 2013).

Though the reports revealed the existence of bud rot disease since early 1900's, the epidemiology of this disease has not been studied systematically. The bud rot disease mainly appears in the months of October and November. Fresh infection initiating in the fag end of monsoon slowly develops from October onwards and become severe in subsequent cooler months. This may be due to lower temperature, the

occasional rains and cool nights with dew formation prevailing during these months helps the pathogen to remain active during the off season.

Survival of pathogen

Reports from earlier findings indicated that, the pathogen survives in the form of dormant mycelium in the tree top either on the infected dried bunches or bud rot affected dead palms or upper layers of soil or in the form of oospores on fruit rot affected nuts under natural condition (Coleman 1910; Kamath 1956; Saraswathy 1994; Sastry and Hegde 1985a; Uppal and Desai 1939). Anandaraj (1985) attempted to collect sporangia of the pathogen using bidirectional and multidirectional traps kept at a height of 7.5 m at the crown level. Further, he could observe sporangia at a height of 7.5 m traps and concluded that pathogen movement could be observed up to 10 m of height. Sastry and Hegde (1987) recovered *P. meadii* isolates from arecanut, cardamom, cocoa and rubber. Bud and crown rots appeared frequently due to manifestation of fruit rot and further, survived in tree tops, nuts and bunch which favoured through excessive rainfall and relative humidity.

Sastry and Hegde (1989) collected samples of nuts, bunches and tree tops from arecanut plants at monthly intervals from January to June in Uttara Kannada district of Karnataka during 1980. The results suggested that *P. meadii* survives in infected tree tops and arecanut bunches which acts as primary inoculum and affirms the importance of removing infected plant material as a first step during the dry season (January–June) and also the nuts fallen on soil. The pathogen survives in various modes (dormant mycelium, chlamydospores) during off-season and during wet season snails were the main limiting factor in arecanut gardens. Though the population of snails in arecanut garden is ignored but their impact in the dissemination of pathogens leading to further spread of the disease was more vibrant. Dutta and Hegde (1987) studied and established the role of snails in dispersal of fruit rot inoculums in areca gardens by detecting the presence of *P. meadii* in the excreta of snails collected from arecanut gardens and by proving its pathogenicity on arecanut. They also observed that dispersal and germination of the pathogen were induced by passing through the gut of the snail *Cryptozona semirugata.*

Alternate hosts as a reservoir

Alternate hosts enable this pathogen to survive and provide inoculum to initiate disease which leads to the development of disease epidemics in many instances. Understanding of alternate host is a key component in the formulation of disease management stratums. Thus, an attempt was made by Hegde et al. (2016) to establish the role of self-grown colocasia and colocasia planted as a mono-crop in arecanut garden to act as an alternate host for *P. meadii*. Further, they confirmed that self-grown colocasia in arecanut garden could serve as an alternate host for *P. meadii.* Isolates were collected from both systems, based on sequencing of ITS region rDNA of majority of *Phytophthora* isolates collected from arecanut gardens cropped with colocasia had 100% homology with *P. meadii.* The role of alternative host plants such as sandalwood and *Jatropha* had already been reported earlier (Venkatarayan 1944).

Integrated disease management

Diseases caused by *Phytophthora meadii* are regarded as the most destructive and the major constraint in arecanut production for the last several decades. Though different disease management practices have been developed over the years, substantial yield losses due to fruit rot are common. Researchers across the country have put their efforts over the years to identify effective of chemicals, biological control agents etc., in order to develop effective management strategies.

Host plant resistance

Host-plant resistance is considered as a eco-friendly, cost-effective and sustainable choice to mitigate *Phytophthora* diseases. Identification of stable resistance sources to fruit rot disease is a prerequisite for the development of resistant variety but in the present scenario, all the cultivated varieties and germplasms of arecanut (*A. catechu*) are susceptible to fruit rot disease. In an attempt to identify any resistance source in closely related species of *Areca,* Muralikrishna et al. (2018) reported that *Areca triandra* and *A. concinna* could be possible candidates to develop disease-resistant inter-specific hybrids. Prathibha et al. (2015) screened seven arecanut varieties, a dwarf mutant and wild types against *Phytophthora meadii* under In vitro condition by detached arecanut method and found all varieties and a dwarf mutant susceptible to *P. meadii*, whereas, wild types *Areca triandra* and *Areca concinna* showed resistance reaction. In earlier study also, Sarma et al. (2002) did not find any resistant and tolerant sources out of 49 genotypes and associated species. However, Saraswathy (1994) found that *Areca normabyu, A. concinna and Actinorytis calapparia* remained free from fruit rot under disease-endemic field conditions for many years and these wild species could be the source of resistance to *P. meadii*.

Mechanical method

Though the fungicides are effective in combating the disease, the repeated climbing and spraying during the rainy season poses difficulties in carrying out the operations. Traditionally during early 1950s arecanut farmers used to follow the practice of covering the arecanut bunches before the onset of monsoon with areca leaf sheath (called as "kotte") or with dry grass (called as "Karada") to protect it from fruit rot disease. Later, covering of bunches with polythene (125–200 gauge 24 × 30 in.) was found effective to prevent the fruit rot. Studies on this aspects revealed that cent per cent control of fruit rot could be achieved by covering of bunches prior to monsoon rains (Chowdappa et al. 2002; Saraswathy 1994; Sastry and Hedge 1985a) and environmental pollution and health hazards due to fungicide spraying could be avoided. However, these methods have not become popular among farmers because of the difficulty in climbing and the requirement of skilled labourers for the proper tying of polythene sheets.

Biological method

To counteract the ill effects of fungicides, efforts were made to identify effective bio-agents and plant extracts against *P. meadii*. The laboratory study indicated that *Trichoderma viride, T. harzianum, Aspergillus terreus, Pseudomonas fluorescence* etc. are potential bioagents against *P. meadii* (Saraswathy 2000b). Similarly study conducted at CPCRI, Kasaragod, indicated the compatibility of bacterial isolates antagonistic against *P. meadii* with Potassium phosphonate and Ovis 20 fungicides (Anonymous 2003). While screening, three native *Trichoderma* species against a highly virulent isolate of *Phytophthora meadii*, *T. virens* exhibited the highest mycelia growth inhibition (62.5%) of *P. meadii* both in simultaneous inoculation and inoculation of *Trichoderm*a, 48 h after inoculation of *P. meadii* (Prathibha et al. 2016). Hence it was suggested that these effective fungicides and *T. virens* could be evaluated in field conditions to develop effective integrated management practices for *Phytophthora* diseases. Result of multilocational evaluation of microbial consortia of *Trichoderma harzianum*, *Pseudomonas fluoroscens* and *Bacillus megatarium* revealed a significant reduction in disease severity and development of new roots, increase in number of leaves and yield of palms (Gangadhara Naik et al. 2019).

Plant extracts

Among the various plants extracts tested, 10% aqueous extract of leaves of Mehendi (*Lawsonia inermis*) and sacred basil (*Ocimum sanctum*) were effective in checking the growth of *P. meadii* under In vitro condition (Saraswathy 2002). Antifungal activity of 13 plant extracts tasted In-vitro, garlic bulbs and rhizome of haldi (Turmeric) were highly inhibitory to *P. arecae* and was followed by leaf extracts of Mehendi (*Lawsonia inermis*), Neem, Tulsi, and Tridax (Ningdale et al. 2018). Under pot culture study, areca seedlings were artificially infected with *P. meadii* and were sprayed with individual plant extracts and results revealed that the extracts of *Andrographis paniculata* followed by *Eucalyptus globules* were effective in checking *P. meadii* infection on areca seedlings (Anonymous 2004). The above studies indicated that the source plant of extracts could be used for soil suppression of *Phytophthora* population to below the level of infection especially in areca plantations where black pepper and cocoa are grown as mixed crops.

Chemical method

As the disease is a constant threat to arecanut growers of southern states of India, various researchers attempted to find out an effective chemical to manage the disease. Among them, Venkatarayan (1943) recommended spraying of Bordeaux mixture (1%) with spreader before the onset of monsoon followed by 30–45 days after the first spray. Further, tenacity of Bordeaux mixture was studied and it was observed that spray deposit was retained on the nut surface up to 40–45 days and was supported by drenching the crown with mercuric compounds like cerason 0.2% or leytosol or Bordeaux mixture 1% (Lingaraj 1969; Naidu 1960; Nambiar 1956).

Further studies on control of fruit rot were continued with new contact and systemic fungicides during 1985–90. Though the contact fungicides viz., copper oxychloride (Blitox), Captafol (Difolatan), Mancozeb (Dithane M45) and Ovis-20 (natural citronellal) were effective against the pathogen in the laboratory studies (Saraswathy 1999), but, these fungicides were not found effective in control of fruit rot under field condition due to poor retention capacity especially during the monsoon season. Among the systemic fungicides tested, metalaxyl at 0.5% or fosetyl-Al (Aliette) at 0.15% gave good control of fruit rot (Anandaraj and Saraswathy 1986; Sastry and Hegde 1985a).

Result of multilocational trial on the management of fruit rot revealed that Bordeaux mixture 1% spray still holds good in controlling fruit rot as disease incidence was 3.8% and 8.6% in Bordeaux mixture and 0.3% akomin sprayed palms, respectively (Chowdappa et al. 2000b). Application of either conventional or stabilized Bordeaux mixture (1%) as foliar spray along with the removal of fallen nuts found effective in reducing fruit rot disease (Narayanaswamy et al. 2017). Among several chemicals that were screened against disease, Ramachandran et al. (1988) estimated ED_{50} values of metalaxyl that exhibited more sensitivity against *Phytophthora*

isolates. In combinational application of Metalaxyl + Mancozeb 72 WP at 0.2% twice to the bunches of arecanut was found significantly superior over copper fungicides (Lokesh et al. 2014).

In search of an efficient fungicide against *Phytophthora* diseases, Hegde (2015) found that, two sprays at monthly intervals with potassium phosphonate @ 6 ml/L were significantly effective in reducing fruit rot of arecanut. Hegde et al. (2019) reported efficacy of mandipropamid 23.3% SC fungicide was found as effective as spraying of 1% Bordeaux mixture in controlling fruit rot of arecanut. Furthermore, Ravikumar et al. (2019) standardized the concentration of Bordeaux mixture to mitigate fruit rot disease of arecanut. The results revealed that Bordeaux mixture @ 1.0% concentration was found to be most effective compared concentration tested.

Recently, Patil et al. (2018) tested various groups of fungicides against *P. meadii* among them, coumarine compounds could act as a potential fungicides which acts against pathogen and also more efficient in management. It is evident from the on-going discussion that prophylactic spraying with 1% Bordeaux mixture to the bunches just before the onset of monsoon (last week of May or first week of June) and two more sprays at 45 days interval was ideal for control of *Phytophthora* diseases in arecanut.

Soil application of fungicides loaded briquettes

Looking into the difficulties faced by the farmer for spraying of Bordeaux mixture during the rainy season, few researchers in recent years have evaluated soil application of systemic fungicides amended in fertilizers for management of *Phytophthora* diseases in arecanut with partial success which needs further large scale evaluation. In this context, Pande et al. (2016) reported that, soil application of fertilizer amended fosetyl-AL briquettes (100 g/palm at 30–45 days interval) reduced the disease and showed less fruit drop of arecanut over the control. Information related to management of other *Phytophthora* diseases such as bud and crown rot using briquettes have to be carried out.

Conclusion and future prospects

Phytophthora diseases are the major limiting factors in arecanut production especially in the high rainfall areas. The century-old disease is still a major challenge for researchers and farmers. Prophylactic spraying of 1% Bordeaux mixture recommended more than five decades ago is still being practiced by farmers to manage fruit rot disease. Lack of *Phytophthora* resistant varieties has made farmers to incur more expenses in spraying of fungicides. Unlike *Phytophthora* diseases of other annual crops, the major issue in the management of *Phytophthora* diseases in arecanut is difficulty in climbing the tree during the rainy season for timely spraying. Hence, efforts are required for the development of suitable spray machinery for spray from the ground or unmanned aerial vehicle (UAV) for the target application of fungicides. Most of the remedial strategies have provided short term solutions for managing the *Phytophthora* diseases in arecanut. A systematic study is required to understand the complete epidemiology of the disease and to develop prediction or forecasting models. Exploration of powerful endophytes against *Phytophthora* and the development of management techniques for *Phytophthora* diseases with biocontrol agents and eco-friendly chemical compounds are also vital. Elucidation of the resistance mechanism of wild *Areca* species to *Phytophthora* and identifying the genes governing resistance, and exploring the possibility of the use of resistance genes in the development of *Phytophthora* resistant arecanut varieties are also essential to reduce the loss due to this serious malady.

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