

Chapter 5

Varietal Resistance in Coconut



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Abstract Host plant resistance offers long-term and sustainable solution in biotic stress management in coconut. Among the diseases affecting coconut, phytoplasmal diseases reported from various countries are a major concern. Furthermore, bud rot, basal stem rot and stem bleeding are also very serious diseases limiting coconut production. Replanting with resistant varieties will go a long way in mitigating the adverse effects of these biotic factors, especially in cases where effective control measures are not available. The best and viable option in the future will be the management of coconut diseases mostly relying on integrated management practices centred on the exploitation of sources of disease resistance. Anticipating a rapid advancement in density and damage by sucking pests in the present era of climate change, efforts should be oriented to develop coconut varieties that can resist/tolerate coreid bug, eriophyid mite and emerging invasive pests as well. Besides, the focus to breed coconut varieties with resistance to red palm weevil, the most dreaded pest of coconut, should continue. It would be appropriate if the breeding programme in each coconut-growing country is fine-tuned to develop resistant varieties to combat pests/diseases of regional importance fully utilising the vast genetic resources available in those countries.

5.1 Introduction

Diseases and pests of various types are all the time a major production constraint in coconut. Cultivation of resistant varieties is considered as the most ideal and stable method for combating diseases and pests. Resistance or susceptibility is relative

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which is used in parlance only when it is transmitted from parents to offspring. Host plant resistance may be defined as the relative amount of heritable qualities possessed by the plants which influence the ultimate degree of damage caused by the pathogen or the insect pest (Painter 1951). Definitions of the common terms used in resistance breeding are given below to give a clear idea about the terminologies used.

5.2 Terminologies Used in Resistance Breeding

Resistance: Resistance is a state of less disease with immunity (no disease) representing the extreme (Simmonds 1983). All varieties that fall in between the extremes of the resistance scale, that is, immunity and extreme susceptibility, are partially resistant and partially susceptible (Kulkarni and Chopra 1989).

Immunity: 'Exempt from infection'. Immunity can be defined as absolute resistance to a pathogen (Robinson 1969).

Susceptibility: It is the sum total of qualities which make a plant a 'fit host' for a pathogen. Susceptibility is the opposite of resistance and is also inversely proportional to it (Robinson 1969).

Tolerance: A cultivar will be termed tolerant if it has the same yield and quality as another cultivar but supports more of the pathogen (Politowski and Browning 1978).

5.3 Disease Resistance

Breeding of disease-resistant varieties is one of the focus areas of coconut research. The major thrust of resistance breeding programme in coconut across the world has been to develop varieties with resistance/tolerance to phytoplasmal diseases. However, efforts have also been made for developing varieties with resistance to major fungal diseases as well. Among the phytoplasmal diseases affecting coconut, the major ones are root (wilt) disease and lethal yellowing disease. Of these, root (wilt) disease is restricted within India, whereas lethal yellowing is a global disaster especially in Caribbean and African regions.

5.3.1 *Phytoplasmal Diseases*

5.3.1.1 **Root (Wilt) Disease**

Root (wilt) is a serious, non-lethal, debilitating malady of coconut palm which was first reported from Kottayam District, India, as early as in 1882 (Butler 1908). Systematic investigations on the etiology have ruled out the role of any physiological

and nutritional disorders and also the role of biotic agents such as fungi, bacteria, viruses and nematodes (Nair et al. 1996). Investigations carried out at the Central Plantation Crops Research Institute under the Indian Council of Agricultural Research (ICAR-CPCRI), Regional Station, Kayamkulam, India, on the etiology of the disease have suggested the association of phytoplasma (Solomon et al. 1983a) transmitted through *Stephanitis typica* (lace bug) (Mathen et al. 1987) and *Proutista moesta* (plant hopper) (Anon 1991). Srinivasan (1991) reported that leaf rot disease gets superimposed on 65% of root (wilt) affected palms. For details, please refer to Chap. 11 on Phytoplasmal Diseases.

Donors for Resistance: In the absence of any effective control measure, planting of disease-resistant/disease-tolerant varieties is the only option to combat this disease. The search for resistance to coconut root (wilt) disease started with Butler (1908) who suggested that there could be resistance to coconut root (wilt) disease in the local cultivars grown in the diseased tract. Varghese (1934) initiated the studies to identify coconut palms resistant/tolerant to root (wilt) disease and surveyed about 10 km² in and around Kayamkulam, but in vain. Davis (1953) reported occurrence of high yielding palms among the heavily diseased palms.

Studies at ICAR-CPCRI (the erstwhile Central Coconut Research Station) Kayamkulam, India, showed that progenies of palms from disease-free areas also develop the disease when planted in the disease-affected areas during the course of 15 years (Anon 1966). Davis (1970) suggested that Malayan Dwarf could be a probable answer to root (wilt) disease of coconut, a surmise based on the performance of Malayan Dwarf in Jamaica where it replaced Jamaican Tall, which is susceptible to Lethal Yellowing Disease.

Rawther and Pillai (1972) studied the average yield in both healthy and diseased coconut palms and also disease incidence in Dwarf × Tall (natural cross), Tall × Dwarf, Dwarf Orange, Dwarf Green and West Coast Tall (WCT) as well. They found that Dwarf × Tall (natural cross) gave higher yield in both healthy and diseased palms compared to other varieties. Dwarf × Tall (natural cross) had the lowest percentage of disease incidence (4.6), and WCT had the lowest yield and also the highest disease incidence (48.5%). All the other varieties and hybrids studied were superior to WCT with regard to disease resistance and yield. Considering the higher level of resistance and yield, Dwarf × Tall (natural cross) was suggested for large-scale propagation in the root (wilt) diseased tract. However, this could not be put into practice since the specific male parents of these hybrids were not known and the quantity of natural cross progenies realisable from open-pollinated Chowghat Orange Dwarf (COD) was limited.

Ninan (1978) reported from a survey involving different varieties like WCT, Chowghat Green Dwarf (CGD), COD and their hybrids that CGD palms were the most resistant to root (wilt) disease with 92.2% palms being free from the disease. He also advocated further detailed study of hybrids of CGD with WCT for yield and disease resistance. Iyer et al. (1979) identified nine elite WCT palms in the disease-affected tract and monitored them for yield and reaction to root (wilt) disease. Among the nine elite palms under observation, three palms were subsequently

affected by root (wilt) disease but still gave nut yields ranging from 200 to 471 nuts palm⁻¹ year⁻¹ (Anon 1988). However, all the open-pollinated (OP) progenies of these elite palms planted at ICAR-CPCRI, Regional Station, Kayamkulam, India, during 1980 have contracted the disease with a disease incidence ranging from 40 to 100%.

All the field trials on disease resistance were conducted in the disease hot spots of Kerala, where the disease incidence was the highest with an average incidence of 45–50%. As leaf rot was found to be closely associated with root (wilt) disease, resistance to this disease was also simultaneously screened in most of the trials. Mathai (1978), from the Kerala Agricultural University, reported that out of 75 hybrids and 14 varieties tested for susceptibility to root (wilt) disease, Laccadive Dwarf and its hybrid progenies showed some tolerance. Mathai (1980) also studied the resistance to root (wilt) disease on 7-year-old palms belonging to Tall × Dwarf, Tall × Gangabondam, Tall × Yellow Dwarf, Tall × Nyiorgading, Tall × Strait Settlement, Tall × Laccadive Dwarf, Tall × Andaman Dwarf, Tall × Tall and WCT. All the hybrids contracted root (wilt) disease with varying intensity. WCT was the most susceptible followed by Tall × Nyiorgading. Tall × Laccadive Dwarf was the most resistant. Similarly for leaf rot, Tall × Dwarf was the most susceptible followed by Tall × Laccadive Dwarf. Tall × Nyiorgading was the most resistant.

Attempts to screen the available germplasm from ICAR-CPCRI, Kasaragod (a disease-free area), were made as early as in 1961 at CPCRI, Regional Station, Kayamkulam. The cultivars tested were Andaman Ordinary, Andaman Giant, Cochin China, Ceylon Tall, Laccadive Dwarf, Laccadive Ordinary, New Guinea, the Philippines, Strait Settlement Apricot, Strait Settlement Green, St. Vincent and Spicata. All these cultivars evaluated in the field developed typical symptoms of root (wilt) disease (Menon et al. 1981).

Mathai et al. (1985 and 1991) reported the reaction of 15 coconut cultivars and Dwarf × Tall (NCD) hybrid to root (wilt) and leaf rot disease of coconut evaluated in two field trials. All the tested varieties showed varying degrees of intensity to root (wilt) disease. The intensity of the disease was significantly lower in Andaman Ordinary, San Ramon and Guam cultivars. Java and WCT were found to be highly susceptible to the disease with a higher disease index. The results also showed that leaf rot disease was the highest in WCT, whilst Saint Vincent, San Ramon, Cochin China and Andaman Ordinary had the lowest incidence of leaf rot. The result on Andaman Ordinary should be taken with caution since the number of palms screened under this cultivar was limited.

Large-scale field experiments were undertaken during 1972 at ICAR-CPCRI, Kayamkulam, as well as in cultivators' gardens in different soil types in 63 villages of Alappuzha, Kollam and Kottayam districts of Kerala State. All the open-pollinated progenies of 36 cultivars and 43 hybrid combinations planted, in gardens that had 40–70% incidence of root (wilt) disease, contracted the disease. It was also observed that the percentage of disease incidence was comparatively high in alluvial and reclaimed soil types (Jacob and Rawther 1991).

Data collected for 10 years from 21 cultivars and 15 hybrids (Tables 5.1 and 5.2), along with WCT as control, planted during 1972 revealed that none of the cultivars

and hybrids were resistant to root (wilt) disease. The percentage of disease incidence ranged from 33.3 to 100. Andaman Ordinary and FMS recorded the lowest percentage of disease incidence (33.3), yielding 18.4 and 18.7 nuts palm⁻¹ year⁻¹, whereas WCT recorded 61% disease incidence with 29 nuts palm⁻¹ year⁻¹. Laccadive Ordinary yielded 40 nuts with 58.3% disease incidence in the 16th year of planting. The average annual yield was the maximum in WCT × COD hybrids with 52.5 nuts palm⁻¹ year⁻¹ though the disease incidence was as high as 91.6% (Jacob and Rawther 1991). Another field experiment, laid out in 1972, in cultivator's garden, indicated that hybrid combination COD × WCT gave an average yield of 80 nuts palm⁻¹ year⁻¹ with 50% disease incidence followed by its reciprocal hybrid yielding 70.3 nuts with 94% disease incidence. WCT × GB (Gangabondam) yielded 52.5 nuts showing 87.5% disease incidence compared to 70 nuts and 37.5% disease incidence in WCT (Jacob and Rawther 1991). Trials involving 27 cultivars, 10 hybrids, F₂ (OP) of Dwarf × Tall and Tall × Dwarf progeny, progenies of elite palms of high-yielding WCT palms and prepotent WCT were laid out in cultivator's gardens

Table 5.1 Reaction of coconut cultivars to root (wilt) disease

Sl. No.	Cultivars	Percentage of disease incidence	Annual yield (nuts palm ⁻¹)
1.	Andaman Giant	100.0	4.5
2.	Andaman Ordinary	33.3	18.4
3.	B.S.I.	100.0	9.7
4.	Car Nicobar	92.0	22.1
5.	Chowghat Orange Dwarf	66.6	30.7
6.	Cochin China	50.0	14.4
7.	F.M.S.	33.3	18.7
8.	Gangabondam	92.0	13.3
9.	Java Giant	92.0	25.4
10.	Jamaica	66.6	24.1
11.	Kulasekharam Green Dwarf	66.6	22.0
12.	Kulasekharam Orange Dwarf	66.6	24.1
13.	Laccadive Micro	75.0	36.7
14.	Laccadive Ordinary	58.3	40.0
15.	M ₂ irradiated	100.0	28.2
16.	Malayan Green Dwarf	83.0	31.4
17.	Malayan Orange Dwarf	66.6	15.4
18.	Malayan Yellow Dwarf	100.0	29.2
19.	Philippines Ordinary	41.6	21.9
20.	S.S. Apricot	92.0	19.9
21.	S.S. Green	83.3	14.1
22.	West Coast Tall	61.0	29.0

Note: No. of palms – 12 in all except West Coast Tall, which had 36 palms

Source: Jacob and Rawther (1991)

Age at observation: 10 years

Year of planting: 1972

Table 5.2 Reaction of coconut hybrids to root (wilt) disease

Sl. No.	Hybrids	Percentage of disease incidence	Annual yield (nuts palm ⁻¹)
1.	COD × WCT	100.0	32.8
2.	Fiji × Gangabondam	66.6	16.4
3.	Fiji × SS Green	75.0	31.1
4.	Jamaica × Gangabondam	75.0	12.2
5.	Java Giant × KGD	83.3	43.0
6.	Java Giant × KOD	83.3	29.5
7.	Java Giant × KYD	33.3	38.2
8.	KGD × Java Giant	50.0	35.0
9.	KOD × Java Giant	75.0	37.0
10.	KYD × Java Giant	83.3	35.5
11.	Laccadive Ordinary × San Ramon	66.6	11.7
12.	San Ramon × Gangabondam	66.6	13.1
13.	WCT × COD	91.6	52.5
14.	WCT × Gangabondam	91.6	24.4
15.	WCT × MYD	66.6	13.1

Source: Jacob and Rawther (1991)

Age of observation: 10 years

Year of planting: 1972

No. of palms: 12

during 1982. Among the 27 cultivars tested, all except Kenthali took up the disease, and the disease incidence ranged from 7.1% to 55.6%. The disease also affected other hybrid combinations with disease incidence ranging from 12.5% to 66.7% in the fifth year of planting itself (Jacob and Rawther 1991).

Breeding Programme: A comprehensive breeding programme for evolving resistant/tolerant variety to root (wilt) disease is in progress at ICAR-CPCRI, Kayamkulam, since 1987 (Nair et al. 1996). In an intensive survey in a large number of farmers' plots in the hot spot districts of Kerala involving 200 Chowghat Green Dwarf (CGD) palms revealed that 75% of the observed palms were disease-free indicating that CGD had a higher level of resistance to root (wilt) disease compared to other varieties. Besides, a screening trial involving ten varieties initiated in 1988 revealed that CGD had the highest level of resistance (75%) 6 years after planting followed by Philippines Lono (70.8%), Zanzibar (70.8%) and FMS (66.7%). Please refer Table 5.3. WCT had intermediate level of resistance (62.5%). King Coconut (8.3%) and Kappadam (33.7%) were the most susceptible (Nair et al. 2004). Since the studies involving field survey as well as screening trials confirmed the higher level of resistance of CGD to root (wilt) disease, it was identified as a source of resistance for the breeding programme.

Breeding for resistance to root (wilt) disease was initiated based on the following observations: (i) CGD possesses higher level of resistance compared to other varieties. (ii) High-yielding disease-free WCT palms can be found in the disease-endemic

Table 5.3 Resistance of coconut varietal progenies to root (wilt) disease

Sl. No.	Variety	Disease incidence (per cent)		
		Self	Inter se	Average
1.	Karkar	50.0 (6.97)	66.7 (8.17)	58.3 (7.57)
2.	SS Apricot	58.3 (7.62)	58.3 (7.45)	58.3 (7.53)
3.	Kappadam	58.3 (7.45)	75.0 (8.65)	66.7 (8.05)
4.	CGD	25.0 (4.93)	25.0 (4.93)	25.0 (4.93)
5.	FMS	25.0 (4.93)	41.7 (6.42)	33.3 (5.68)
6.	Zanzibar	33.3 (5.58)	25.0 (4.93)	29.2 (5.25)
7.	Philippines Lono	25.0 (4.93)	33.3 (5.58)	29.2 (5.25)
8.	Fiji Rotuma	58.3 (7.62)	41.7 (6.42)	50.0 (7.02)
9.	King Coconut	100.0 (10)	83.3 (9.08)	91.7 (9.54)
10.	WCT	41.7 (6.42)	33.3 (5.77)	37.5 (6.10)
	General mean			6.69

Source: Nair et al. (2004)

Palms per treatment: 12

Year of planting: 1988

Year of observation: 1994

areas, in the midst of heavily disease-affected palms. Such palms were identified as the base material for the breeding programme. (iii) In the disease-endemic areas, a number of disease-free and high-yielding Chowghat Orange Dwarf (COD) palms were also found. These were also included in the programme to exploit the reported occurrence of high yield and tolerance to the disease in COD \times WCT hybrids.

Artificial pollination of mother palms was carried out in farmers' plots for producing progenies which can be used either for developing a root (wilt) resistant/tolerant variety or for the production of parental materials for establishing seed gardens (Nair et al. 2000). The mother palms were serologically tested to ascertain their freedom from disease (Solomon et al. 1983b). WCT (inter se), WCT (self), WCT \times CGD, CGD (self/inter se), CGD \times WCT and COD (self/inter se) cross combinations were produced for field planting.

In the absence of an artificial screening technique for systematic evaluation of resistance, the seedlings produced were tested for field resistance under natural conditions. For evaluation of resistance, 2725 seedlings of the above cross combinations were underplanted since 1991 with a spacing of 7.5 m \times 7.5 m inside the experimental farm. Care was taken to see that the old diseased palms were retained at least for 6–7 years after underplanting of the seedlings to provide sufficient inoculum for natural infection under field conditions. Heavy incidence of root (wilt) disease was observed in all the underplanted seedlings. Observations on root (wilt) disease recorded 12 years after planting from various progenies of WCT (WCT inter se/self/mixed pollen) revealed that the disease incidence varied from 55.0 to 58.7%, indicating that there was no significant variation in the susceptibility to the disease among the WCT progenies (Nair et al. 2003). However, in the case of the open-pollinated progenies of WCT, there was 80% disease incidence, showing the

superiority of artificially pollinated seedlings (full sibs) over the open-pollinated seedlings (half sibs) with regard to their resistance to the disease.

Observations on 31 CGD × WCT hybrids during 1991 revealed that hybrids came to flowering in 30–40 months after planting. 67.5% of these palms took up the disease 14 years after planting (Nair et al. 2006). Though both the parents involved were deficient in some of the desirable characters like disease resistance, palm height, average yield of nuts, early bearing, nut size and shape, the hybrids were better in the overall performance. Even though majority of CGD × WCT hybrids were diseased, they gave a 10-year cumulative average yield of 84 nuts palm⁻¹ year⁻¹ indicating that this hybrid is tolerant to root (wilt) disease. This yield is quite attractive compared to the average productivity of Kerala State (35 nuts palm⁻¹ year⁻¹). Considering the performance of CGD × WCT in the root (wilt) disease prevalent tract, it was released under the name ‘Kalpa Sankara’ (Table 5.4).

Root (wilt) disease incidence and intensity of selected CGD was further evaluated and compared with WCT in the disease prevalent tracts of Kerala. The studies confirmed the high yield and low incidence of root (wilt) disease in CGD in hot spots of root (wilt) disease. Considering the high yield and low incidence of root (wilt) disease, selection made from Chowghat Green Dwarf was released under the name ‘Kalpasree’ for cultivation in homesteads of the root (wilt) prevalent tracts.

Studies carried out during 2004 involving five dwarf varieties of coconut, viz. Malayan Green Dwarf (MGD), Malayan Yellow Dwarf (MYD), Malayan Orange Dwarf (MOD), Chowghat Green Dwarf (CGD) and Chowghat Orange Dwarf (COD), resulted in identification of another promising variety, viz. Malayan Green Dwarf (MGD) (Fig. 5.1), as resistant to root (wilt) disease (Nair et al. 2007).

West Coast Tall (WCT), in an adjacent plot, showed 84% disease incidence indicating the availability of sufficient inoculum for evaluation of resistance of the dwarf varieties. CGD showed maximum resistance with disease incidence of 19.9% followed by MGD with a disease incidence of 22.4%. MGD gave the highest nut yield (88.8 palm⁻¹ year⁻¹) followed by WCT (48.7 palm⁻¹ year⁻¹). Considering the high yield and resistance to root (wilt) disease, this MGD selection was released under the name ‘Kalparaksha’ for cultivation in the root (wilt) disease prevalent tracts of India.

Table 5.4 Root (wilt) disease incidence and yield of ‘Kalpa Sankara’ in comparison to its parents

Sl. No.	Variety	Disease incidence (per cent)	Average nut yield (palm ⁻¹ year ⁻¹)	Copra content (g nut ⁻¹)	Copra (kg palm ⁻¹)
1.	Kalpa Sankara (CGD × WCT)	67.7	82.5	170	14.00
2.	CGD	25.0	90.0	104	9.36
3.	WCT	80.0	48.7	177	8.62

Source: Nair et al. (2006)

*Period of observation: 1999–2004

Year of planting: 1991

Fig. 5.1 Malayan Green Dwarf (MGD). (Photo: V. Krishnakumar)



Crossing programme for the development of an improved WCT variety, by inter se mating/selfing of selected disease-free WCT palms from the hotspots, was initiated during 1990–1991. The selected disease-free palms were selfed and inter se mated to produce two sets of first-generation progenies (viz. 100 self and 450 inter se mated progenies). Observations recorded on these progenies after 18–19 years of planting revealed that the disease incidence in inter se mated progenies was only 47% compared to 63% in selfed progenies. The inter se mated progenies recorded 35–40% higher nut yield compared to selfed progenies and were also superior with regard to nut characters. A total of 40 high-yielding and disease-free palms belonging to the first generation were selected during 2009–2010 to produce the second-generation material. The inter se mated progenies were superior to selfed progenies with respect to nut yield and resistance to the disease (Thomas et al. 2016). Analysis of population structure of the mother palms and first-generation progenies using SSR markers indicated higher values for inbreeding coefficient and homozygosity in subsequent generations.

In order to meet the acute shortage of quality planting materials, five seed gardens were established in the root (wilt) prevalent tract, by planting selfed or inter se progenies of selected WCT, CGD and COD mother palms, spread over nearly 40 ha (Nair et al. 2001). These seed gardens are expected to produce nearly 2,50,000 seedlings annually.

Molecular Markers: Considering the long life cycle of coconut, selection of resistant varieties through conventional methods will be time consuming and laborious. Molecular markers offer numerous advantages over markers traditionally used in plant mapping and selective breeding. Rajesh et al. (2002) identified AFLP primer pairs detecting variations between resistant and susceptible palms.

Devakumar et al. (2011) studied the population structures among the root (wilt) disease-resistant and susceptible coconut palms from 12 locations in the 3 disease-endemic districts of Southern Kerala using 9 microsatellite markers. Two major populations and a subpopulation cluster were identified among the resistant palms. The analysis of genetic relatedness between the resistant mother palms showed that most of the palms located in a single locality shared sib relationship among them.

Rajesh et al. (2015) used RNA-Seq to generate the transcriptome of leaf samples of coconut root (wilt) disease-resistant cultivar CGD. Analysis using bioinformatic tools identified 243 resistance gene analog (RGA) sequences, comprising 6 classes of RGAs. Domain and conserved motif predictions of clusters were performed to analyse the architectural diversity. Phylogenetic analysis of deduced amino acid sequences revealed that coconut NBS-LRR-type RGAs were classified into distinct groups based on the presence of TIR or CC motifs in the N-terminal regions. Furthermore, qRT-PCR analysis validated the expression of randomly selected NBS-LRR-type RGAs. The results of this study provide a sequence resource for the development of RGA-tagged markers in coconut, which would aid mapping of disease-resistant candidate genes.

Rachana et al. (2016) subsequently used a comparative genomics approach to amplify putative RGAs from the coconut root (wilt) disease-resistant cultivar, Chowghat Green Dwarf (CGD), by using primers designed based on conserved motifs of the NBS-LRR domain of the date palm. The amplified sequences were cloned, sequenced and characterised. The coconut RGAs had high identity to monocot NBS-LRRs. Real-time quantitative polymerase chain reaction analysis indicated that the isolated coconut NBS-LRR class RGAs were expressed more in root (wilt) disease-resistant genotypes than in susceptible ones.

5.3.1.2 Lethal Yellowing Disease (LYD)

Lethal yellowing was first reported nearly 100 years ago from Jamaica. Subsequently, it was reported both from East and West Africa including Kenya, Tanzania, Nigeria, Ghana and Mozambique, the Caribbean, the Natuna Islands of Indonesia and most recently from Madang on the north coast of Papua New Guinea. The disease is caused by phytoplasma which is transmitted by adult plant hopper (*Myndus crudus*). Because of its ability to spread rapidly and destroy coconut populations, lethal yellowing disease (LYD) is considered as one of the most serious threats to coconut cultivation globally (Harries 1978). In Jamaica, five million Jamaican Tall palms were destroyed in 20 years following the spread of this disease (Romney 1983). Please see Chap. 11 on Phytoplasmal Diseases for details.

Sources of Resistance: Most of the exotic coconut varieties introduced and tested in Jamaica were susceptible to LYD (Whitehead 1968; Harries 1973). However, resistance of Malayan Dwarf variety (red, yellow and green colour forms) to LYD in Jamaica was first recognised in the midst of the 1950s (Nutman and Robert 1955). Harries (1974a) also reported that all the three colour forms of the Malayan Dwarfs

have good resistance to LYD in Jamaica, and they also outyielded Talls when grown under suitable conditions. Large-scale planting of Malayan Dwarf in Jamaica led to the control of the disease. Subsequently F_1 hybrids were introduced in large scale, combining the high resistance of the Malayan Dwarf with more attractive agronomic characteristics of the more susceptible Tall parents such as Jamaican Tall, Rennel Tall and Panama Tall. Each parent was deficient in at least one of the characteristics considered such as productivity, leaf and bunch production, disease resistance, number and weight of nuts and crop production. The nature of resistance to LYD has not been determined. In an effort to locate additional sources of resistance, some evidence has been obtained about resistance in certain cultivars. Most of the hybrids have intermediate degree of resistance between that of parents. The degree of resistance of Panama Tall (PNT) nearly approaches the resistance of Malayan Dwarf (Harries 1974b). However, Malayan Dwarf \times Panama Tall (Maypan hybrids) was found to be the most promising, and it was widely planted in Jamaica during the 1970s (Harries and Romney 1974).

Malayan Dwarf and Maypan, as well as crosses involving Cameroon Dwarf, showed high resistance to lethal yellowing disease in Jamaica. However, observations in Ghana suggested that Malayan Dwarf and Cameroon Dwarf are more susceptible to LYD in that country than in Jamaica (Anon 1976). The Malayan Dwarf variety was highly resistant to LYD in West Africa, Caribbean Islands and Florida (USA), and the only means of prevention in affected areas was to plant resistant varieties. However, studies conducted during 1982–2001 showed a 70% crop loss in over 19 years for Malayan Dwarf coconuts and 83% for Maypan coconuts. Results indicate that these cultivars cannot be considered resistant to lethal yellowing caused by phytoplasmas, as claimed in other studies (Broschat et al. 2002). The PNT is the pollen parent of the Maypan hybrid, which used to be planted in Jamaica to control lethal yellowing. The main source of contamination was the susceptible Jamaica Tall, thus increasing the susceptibility in the resulting Maypan progeny. The incidence of genetic contamination seems to be insufficient to be the only cause of the latest outbreak of the disease in the country. Hence, Maypan and its parents cannot be classified as resistant in the present context of Jamaica (Baudouin et al. 2008).

Fiji Dwarf (also known as Niu Leka) has shown variable resistance to LYD in Florida (USA). Flores (2008) reported that not even a single Fiji Dwarf died of the disease at Subtropical Horticultural Research Station (SHRS), Miami, USA, during the period 2000–2008. However, further confirmatory work was not carried out at SHRS. It was noted that recovery from lethal yellowing has been observed only in Malayan Dwarf, in crosses of Malayan Dwarf and in one unspecified cross not involving Malayan Dwarfs. Some Tall varieties also showed variable resistance (Sherman and Maramorosch 1977). Maypan hybrid was also found to be resistant to LYD in Florida (USA), Belize and other countries (Eden-Green 1997). In pure stands, LY resistance was estimated at 90% for Maypan (Table 5.5) compared to 96% for Malayan Dwarf (Been 1981). Resistance was also recognised in certain populations of Panama Tall and a progeny population of Malayan Dwarf \times Fiji

Table 5.5 Incidence of lethal yellowing disease (percentage of incidence)

Variety/hybrid	Average	Fair prospect	Kildare	Caenwood	Rodney Hall	Plantain Garden
Jamaica Tall (JAT)	90	90	88	83	98	97
Malayan Dwarf (MAD)	4	1	10	11	3	4
Panama Tall (PNT)	44	–	38	–	–	67
Fiji-Malayan × JAT	5	4	5	–	–	–
Fiji-Malayan × self	8	8	–	–	–	–
JAT × Cambodia Tall (CBT)	53	53	–	–	–	–
JAT × Cameroon Red Dwarf (CRD)	14	8	20	–	–	–
JAT × Cuban Dwarf	40	–	40	–	–	–
JAT × MAD	36	49	9	–	–	–
JAT × Mozambique Tall (MZT)	53	53	–	–	–	–
JAT × PNT	46	54	29	–	–	–
JAT × Rennel Tall (RLT)	95	92	–	–	–	97
JAT × Solomon Tall (SNT)	52	–	–	–	–	–
JAT × Tahiti Tall (TAT)	79	79	–	–	–	–
Malayan Dwarf × CBT	11	0	–	50	–	–
Malayan Dwarf × CRD	15	15	–	–	–	–
Malayan Dwarf × JAT	23	24	15	34	5	20
Malayan Dwarf × MZT	30	17	–	50	–	–
Malayan Dwarf × PAT (Maypan)	10	13	4	21	13	7
Malayan Dwarf × RLT	26	29	30	44	23	25
Malayan Dwarf × SNT	20	14	–	24	–	–
Malayan Dwarf × TAT	38	0	–	100	–	–
PNT × CRD	28	28	–	–	–	–
PNT × JAT	38	58	17	–	–	–
PNT × MAD	11	–	11	–	–	–
PNT × RLT	50	54	–	–	–	42
PNT × SNT	17	17	–	–	–	–

+ Fair Prospect, Kildare, Caenwood, Rodney Hall and Plantain Garden are the experimental locations

Source: Been (1981)

*Year of planting: 1962–1970

– Data not available

Year of observation: 1979

Dwarf (F_1 hybrid). Promising source of resistance was also identified in Sri Lankan Dwarf, Indian Dwarf and King Coconut (Table 5.6) and intermediate resistance in a few of the tall varieties (Been 1981).

An assessment made in 1977 suggested that coconut genetic resources in Africa were vulnerable to loss from disease and replacement by improved varieties was considered necessary. Since then, losses due to diseases in Tanzania, particularly

Table 5.6 Incidence of lethal yellowing disease (percentage of incidence)

Variety	Average	Fair prospect	Plantain Garden	Kildare	Caenwood	Orange River
Indian Dwarf	0.0	0.0	–	–	–	–
King Coconut	0.0	0.0	–	–	–	–
Malayan Dwarf	1.1	1.1	–	–	0.0	–
Sri Lanka Dwarf	3.2	–	–	–	–	–
Malayan Dwarf (Local)	6.0	1.0	6.7	16.7	13.8	0.0
Rotuma Tall	26.3	60.0	14.0	–	–	–
Bougainville Tall	31.0	35.0	28.0	–	–	–
Cambodia Tall	35.4	35.4	–	–	–	–
Thailand Tall	36.0	31.9	–	–	57.1	21.8
Malayan Tall (Solomon Is)	39.5	54.3	26.5	28.6	–	–
Malayan Tall	39.8	44.1	–	–	52.1	31.0
Yap Tall	45.7	76.5	26.2	4.9	61.5	–
Markham Valley Tall	48.0	58.0	44.0	–	–	–
Peru Tall	48.7	48.7	–	–	–	–
Karkar Tall	50.0	19.5	44.0	–	–	–
Panama Tall	50.6	–	70.5	44.7	–	–
Niu Leka Dwarf	53.9	31.6	62.1	100.0	–	–
Sarawak Tall	55.8	56.0	–	58.0	–	52.8
Fiji Tall	66.7	60.7	–	73.4	–	–
Rennel Tall	67.7	72.9	67.3	–	–	–
Solomon Tall	70.2	80.0	58.9	–	–	–
Rangiroa Tall	71.8	76.1	100.0	40.3	–	–
Seychelles Tall	72.5	78.9	88.8	27.7	79.7	–
Samoa Tall	74.7	74.7	–	–	–	–
Tahiti Tall	77.4	83.7	71.1	73.1	–	–
Tonga Tall	86.6	83.0	79.0	100.0	–	–
Rangiroa Dwarf	93.5	100.0	86.5	–	–	–
Vanuatu Tall	94.0	94.0	–	–	–	–
Sri Lanka Tall	95.8	100.0	95.0	100.0	100.0	–
India Tall	96.9	100.0	–	–	96.0	–
Jamaica Tall	100.0	100.0	100.0	100.0	100.0	100.0

+ Fair Prospect, Plantain Garden, Kildare, Caenwood and Orange River are the experimental locations

Source: Been (1981)

–Data not available

Year of planting: 1962–1970

Year of observation: 1979

those caused by phytoplasma, have proved higher than anticipated as several introduced varieties with resistance in their countries of origin were not resistant under African conditions. Also, with reference to Tanzania, foreign introductions were not as numerous as anticipated because of the disease problems encountered and also

because many potential introductions had very similar counterparts among the native varieties. However, the need to conserve coconut genetic resources was emphasised. Though germplasm collections existed in Côte d'Ivoire and Tanzania, it was recommended that every African country should have its own collection of native and standard varieties (Harries 1991).

The results of studies conducted by Sangare et al. (1992) during 1981–1992 on the occurrence of LYD in West, Central and East Africa revealed resistance in both Dwarf and Tall varieties, although West African Tall and its hybrids with both a Dwarf and a Tall were highly susceptible. Losses of 81% were reported in imported cultivars at Kifumangao, the tall cultivars being the most severely affected (Mpunami et al. 1992). Local palms were also susceptible, with the exception of East African Tall from Tanga. Some resistance to lethal disease was found in a hybrid between East African Tall and Pemba Red Dwarf.

Lethal disease of coconut in Tanzania is very similar to lethal yellow disease in the Caribbean Islands and West Africa. Schuiling et al. (1992) reported that varieties that show resistance to lethal yellowing in Jamaica are highly susceptible to lethal disease in Tanzania. The dwarf varieties are only marginally less susceptible than the Talls though hybrids are equally susceptible as their corresponding Tall parents. However, all the ecotypes appear to be more susceptible to disease in Tanzania. Promising resistance to lethal disease in Tanzania was observed only in two sub-populations of the local East African Tall. Resistance to lethal yellowing in different regions may be influenced by factors such as temperature, vector preference or sub-optimal growing conditions (Harries 1998), or it could be due to different strains of phytoplasma (Eden-Green 1997). No permanent cure has yet been found for LY, and to date, the use of resistance is the only effective means of coping with it to some extent (Been 1998).

Mariau et al. (1996) observed that very few cultivars are absolutely resistant/tolerant, necessitating testing of several most promising hybrids on a larger scale. A successful coconut rehabilitation scheme, developed in Jamaica in the 1960s–1980s, replaced the lethal yellowing-susceptible Jamaica Tall variety, first with the resistant Malayan Dwarf and then with its Maypan hybrid. The hybrid, which is still being produced and planted, is the product of a breeding programme that showed very promising performance in field exposure trials. Yet a rehabilitation programme, using introduced hybrids against lethal disease in Tanzania in the 1980s–1990s, did not succeed, and field exposure trial results were disappointing. Similar trials laid out with introduced material in the early 1980s in Mexico also did not give any encouraging result (Harries 1998). An alternate strategy for field exposure trials, based on the Jamaican experience and formulated in 1975, was partially implemented in Tanzania and Mexico after 1990, and positive results were reported. It was argued that the coconut palm-phytoplasma disease relationship calls for a pragmatic strategy in which simple, block plantings generate both the test material for field exposure trials and the seed nuts and pollen of resistant selections for direct use in the rehabilitation programmes. The more complicated strategy of small, replicated trial plots does not screen resistance realistically and cannot provide source material directly to rehabilitation programmes. The limitations of the replication

method have been overlooked though, superficially, it appears to be more scientific. It was concluded that disease screening must be done under conditions that match the farming systems that will apply to the rehabilitation programme (Harries 1998).

Zizumbo-Villarreal and Arellano-Morín (1998) studied 20 coconut populations and suggested a correlation between precocity and resistance. The general perception is that cultivars from Malaysia and South East Asia are resistant to lethal yellowing disease. However, Caribbean and Atlantic Coast coconut cultivars are susceptible to LY, but hybrids of parents which originated in South East Asia have maintained excellent levels of resistance (Harries 2001). Sporadic outbreaks of non-epidemic phytoplasma disease in South East Asia may be linked to the introduction of susceptible cultivars from the Caribbean and West Africa (Maramorosch and Harries 1998).

Considerable efforts have been devoted throughout the world to screen varieties often involving international cooperation, which though was a lengthy and difficult task. Baudouin et al. (2009) opined that although no variety so far has been proven fully and permanently resistant, treating resistance level as a threshold trait makes it possible to demonstrate significant differences among varieties, which can be exploited effectively to make genetic improvement a component of an integrated control strategy. They have also made a few suggestions to increase the diversity of resistance sources and increase the level and the sustainability of resistance to LY in coconut.

The most viable alternative for control of lethal yellowing in Mexico and the Caribbean was to develop hybrids of crosses of dwarf coconut palms with tall landraces, combining disease resistance, earliness and production of large number of nuts per cluster of dwarf palm, with the hardiness and greater fruit size of the tall palms of the Pacific. The Donají hybrid, which is resistant to lethal yellowing, was produced at the experimental field of Oaxaca Coast of INIFAP, by crossing the Malayo Enano Amarillo cv. Acapulco as the female parent and the Landrace Alto Pacífico cv. Escondido as the male parent. This dual-purpose hybrid is recommended for all coconut-growing regions of Mexico, as it is high yielding and pre-cautious (Serrano et al. 2011).

In the 1990s, bunch and nut yield dominated the coconut breeding programmes in Nigeria. With the outbreak of Awka wilt, focus was shifted to resistance breeding for LYD due to decline in yield and the high susceptibility of West African Tall (WAT). Odewale et al. (2013) evaluated the performance of different coconut varieties surviving under natural field conditions in an LYD endemic area of Nigeria. Five coconut varieties (viz. Malayan Green Dwarf (MGD), Malayan Yellow Dwarf (MYD), Malayan Orange Dwarf (MOD), West African Tall (WAT) and a hybrid derived from WAT and Malayan Dwarf) were evaluated for bunch and nut production for a period of 7 years. The results indicate that the surviving palms in the respective varieties are vigorous with the dwarf varieties showing more resistance to LYD compared to WAT. However, WAT recorded the highest yield for bunch (8.1) and nut production (63.7 nuts palm⁻¹ year⁻¹). Evidence of biennial rhythm was revealed among the palms across the years. Despite the relatively poor performance of the varieties, the high yielding palms could be used in crossing programme for

the production of nucleus planting material for further testing whilst serving as a germplasm base for resistance breeding.

Arroyo-Serralta et al. (2012) isolated a number of metabolites from coconut leaf cuticular waxes and explained the role of the wax layer in host plant-vector and host plant-pathogen interactions. Chromatographic analysis of the leaf cuticular wax from five coconut ecotypes showed that three main components (I, II and III) can be used as chemotaxonomical markers for classification of varieties either as resistant or susceptible. However, the results obtained from the antifeedant assay did not conform to the positive correlation found between the metabolites in the wax obtained from the various ecotypes and their resistance or susceptibility to the lethal yellowing disease. However, their study indicates that the full composition of the cuticular wax may have some role in host plant-insect vector interaction.

Molecular Markers: Breeding coconuts for any desirable trait is hindered by the long life span, low multiplication rate and ineffective clonal propagation. Additionally, the lack of adequate genotypes for identifying markers linked with LY resistance demands alternative approaches. Cardeña et al. (2003) identified three coconut populations which could be used for this purpose comprising of the susceptible West African Tall (WAT), the resistant Malayan Yellow Dwarf (MYD) and a resistant population of Atlantic Tall (AT) palms. AT was closely related to WAT, and both of them were distantly related to MYD. The objective of this work was to use those populations for identifying RAPDs associated with LY resistance. A total of 82 RAPDs could differentiate the DNA pools from MYD and WAT, and 12 of them appeared at frequencies ≥ 0.85 in MYD and ≤ 0.15 in WAT.

Zizumbo-Villarreal et al. (2006) reported that the Mexican genetic pool had high genetic diversity ($pl = 94$; $H_T = 0.34 \pm 0.02$) similar to that of the populations imported from the world's main gene pools ($pl = 94$; $H_T = 0.36 \pm 0.01$). Both molecular variance and Wright's index of differentiation indicated strong differentiation among Mexican ecotypes ($F_{ST} = 0.32$) despite significant gene flow ($Nm = 1.4$ to 5.6). UPGMA analysis and exact tests of differentiation suggested that the Indo-African gene pool is found along the Caribbean and Gulf of Mexico coasts, whilst the Asia-Pacific pool is found on the Pacific coast. High positive correlations were found between genetic distance and LY mortality percentages under severe incidence conditions during 9 and 14 years ($r^2 = 0.80$; $P = 0.02$; $r^2 = 0.78$; $P = 0.04$), suggesting that genetic distance may be useful for the estimation of the potential LY mortality in regions as yet unaffected as well as identification of potential parents for LY resistance breeding.

Konan et al. (2007) evaluated the genetic differences between the tolerant genotypes and the susceptible ones using 12 microsatellite markers. This work aimed to use identified materials as reference to select suitable parents for gene mapping studies. A total of 58 alleles were detected at the 12 microsatellite loci. The number of alleles varied from three to seven, with an average of 4.83 alleles. The F_{st} index revealed that 59.7% of the total allele variability explained differences between the three accessions. Genotypes of West African Tall, susceptible to the lethal yellowing disease, were less genetically clustered with the genotypes of the two resistant/tolerant

accessions. This differentiation was based on specific alleles and frequency variation of shared alleles in the three accessions. This molecular typology was useful as reference for large molecular screening of coconut genetic resources and the identification of suitable parents for the development of mapping populations for tagging the lethal yellowing resistance genes.

There are several possible causes for the devastation of the Maypan hybrid due to an epidemic outbreak of LYD in Jamaica. Studies revealed that the LY affected planting material in Jamaica is genetically the same as the material shown to be resistant. Lebrun et al. (2008) compared the deoxyribonucleic acid (DNA) of MYD sampled from four locations in Jamaica with a reference DNA of the same cultivar collected in five different countries. The results of analyses showed more variation at 34 simple sequence repeat loci in Jamaica than in the rest of the world providing clear evidence for the presence of about 16% of alleles that do not match with the typical MYD genotype. These alleles appear to have already been present in the introduced germplasm. The observed heterogeneity might have caused some loss of resistance though insufficient to explain a massive outbreak of the disease.

Puch-Hau et al. (2015) used degenerate primers to amplify nucleotide-binding site (NBS)-type sequences from coconut ecotypes which were either resistant or susceptible to lethal yellowing. Genomic DNA fragments of approximately 500–700 bp were obtained and sequenced. Phylogenetic analysis of these fragments revealed that they clustered in seven different clades. All CnRGC sequences were grouped within the non-TIR-NBS-LRR subclass of NBS-LRR genes. The expression analysis revealed changes in expression profiles in response to salicylic acid (SA) and a constitutive expression profile in plants untreated with SA. This is the first large-scale analysis of NBS-type sequences in coconut palm.

5.3.1.3 Cape St. Paul Wilt

The Ghanaian form of LYD of coconut is known as the Cape Saint Paul Wilt Disease (CSPWD). The disease is caused by phytoplasmas and has been active in the country since 1932.

Varietal Screening: Danyo and Dery (2011) conducted studies to update the disease situation among Malayan Yellow Dwarf × Vanuatu Tall (MYD × VTT) hybrids in the Western and Central Regions of Ghana. Studies also compared the level of LYD susceptibility in the local West African Tall (WAT) variety and the MYD × VTT hybrid recommended for replanting. Losses were higher in the Central Region than in the Western Region. Overall, only 4.8% of total area under MYD × VTT coconut plantings had been affected by the disease as in 2009. LYD incidence was significantly higher in the WAT variety than the MYD × VTT hybrids. There was variation in disease incidence and severity in MYD × VTT hybrids between the different coconut growing areas. The susceptibility of the MYD × VTT hybrids under intense disease pressure calls for screening of more coconut varieties, to identify truly resistant types to the lethal yellowing disease.

Quaicoe et al. (2009) reported the results of screening trials on CSPWD carried out on 38 varieties since 1956. Two varieties, viz. Sri Lanka Green Dwarf (SGD) and Vanuatu Tall (VTT), have shown high resistance to the disease, and their hybrid (SGD \times VTT) is under observation to determine its performance. A programme to rehabilitate the CSPWD-devastated areas was started in 1999. Emerging results indicate that the MYD \times VTT hybrid used for the programme succumbs to the disease under intense disease pressure.

Johnson and Harries (1976) after a visit to Ghana and Togo in 1975 reported that there are great similarities between Cape St. Paul Wilt in Ghana, maladie de kaincope in Togo and Dahomey, Kribi disease in Cameroon and lethal yellowing in the Caribbean. The situation is more serious because both Malayan Dwarf, which was planted as a resistant variety in the Caribbean and the Cameroon Dwarf, which withstands the disease in Cameroon, succumbed to the disease in Ghana. Information on the susceptibility of various Dwarf and Tall varieties includes evidence which questions the resistance of Malayan Dwarf and Cameroon Dwarf, which have shown resistance to lethal yellowing in the Caribbean area and to Kribi disease in Cameroon, respectively, but have succumbed to Cape St. Paul Wilt in Ghana.

Molecular Markers: Swarbrick et al. (2013) isolated eight putative receptor-like kinase (RLK) genes from coconut using oligonucleotides designed against kinase subdomains of RLKs of other plant species, and the intron sequence of one of these was further analysed. Three single nucleotide polymorphisms (SNPs) were identified within this intron that could be used as a traceable marker to differentiate two distinct genotypes which could be differentiated using high resolution melt curve analysis. Analysis of different varieties of coconut used in the breeding programme included promising hybrids such as Sri Lankan Green Dwarf \times Vanuatu Tall. F_1 crosses between these palms were self-pollinated to generate F_2 populations. Genotyping of palms at the RLK marker suggested that some F_2 progenies of parent F_1 palms might have been sired via cross-pollination from neighbouring palms, a possibility that would bear significance for such breeding programmes.

5.3.2 Fungal Diseases

5.3.2.1 Bud Rot

Bud rot is a fatal disease of coconut. The disease is characterised by rotting of the terminal bud and surrounding tissues with a foul smell and can even lead to mortality of the palm. Franqueville et al. (1989) observed the existence of *Phytophthora* resistance characters in a wide range of coconut varieties and hybrids in Côte d'Ivoire and suggested that coconut performance with respect to *Phytophthora* can be improved. The West African Tall proved sensitive to bud rot, but resistant to nut fall, whereas the Malayan Yellow Dwarf \times West African Tall hybrid reacted vice versa. Some hybrids are sensitive to both forms of diseases, whilst others presented good tolerance. Within the Malayan Yellow Dwarf \times West African Tall hybrid (PB

121), there is considerable variability, and some crosses are sensitive, whereas others are highly resistant. These studies reveal that a compromise can be found, both between the different hybrids and within the same hybrid to accommodate lower resistance to *Phytophthora* whilst retaining high yields.

With a view to improving PB 121 hybrid, two combining ability trials of WAT parents with a MYD tester were undertaken in 1978 and 1982 (Bourdeix et al. 1992). Results of the first trial showed that three progenies were significantly superior to PB 121. In terms of copra palm⁻¹, the difference amounted to 19% in young palms (4–8 years old) and 15% in adult palms, during which these progenies exceeded 4.8 mt ha⁻¹ of copra, whereas PB 121 levelled off at 4.2 mt. Two out of three progenies had an excellent level of tolerance to nut-fall caused by *Phytophthora katsurae*, whilst the third was too productive for disease to adversely affect it.

Brahmana et al. (1993) conducted a study on the resistance of eight varieties to bud rot (*Phytophthora palmivora*), using the extent of disease attack on the nuts and the content of phenolic compounds in the husk as indicators of resistance. The varieties Nias Yellow Dwarf × Palu Tall and Bali Tall were more resistant, with high content of phenolic compounds and low disease attack. Whilst fungicide application is recommended for control, planting of resistant varieties is the most sustainable and practical method to combat this malady.

5.3.2.2 Basal Stem Rot

Basal stem rot (BSR) caused by *Ganoderma lucidum* is a major limiting factor in coconut production in Tamil Nadu, India. An experiment was laid out during 1989 in disease-endemic area to evaluate the performance of East Coast Tall (ECT) crossed with BSR-resistant ECT in comparison with nine other coconut cultivars, i.e. San Ramon, Lakshadweep Ordinary, British Solomon Islands, Java Giant, Straight Settlement Green, WCT × COD, COD × WCT, VHC-1 and ECT. Observations recorded after 15 years of planting revealed that ECT × BSR-resistant ECT recorded higher survival percentage, better growth characters, higher nut yield and lower disease index compared to the other cultivars (Karthikeyan et al. 2005).

5.3.2.3 Stem Bleeding

Stem bleeding disease starts with bleeding from the stem and later causes wilting and drying of leaves. Radhakrishnan and Balakrishnan (1991) conducted a trial with six coconut hybrids involving Gangabondam (GB) for resistance to stem bleeding caused by *Ceratocystis paradoxa*, and the correlation between disease index and mean yield during 1975–1984 was also worked out. There was a negative correlation between the disease index and yield. The lowest percentage of infection (29%) was found in Cochin China × Gangabondam (GB). Ramanujam et al. (1998) studied the reaction of 26 coconut cultivars involving 16 Talls, 6 Dwarfs and 4 hybrids against stem bleeding disease using a detached petiole inoculation method. All

cultivars tested were susceptible to *C. paradoxa* to different degrees. The maximum lesion size was recorded in Malayan Green Dwarf, and the minimum was recorded in Banawali Green Round.

5.3.2.4 Leaf Spot and Leaf Blight

Leaf spot and leaf blight are minor diseases of coconut. During 2000–2002, more than 14,000 coconut palms were destroyed in Brazil by leaf spot caused by *Bipolaris incurvata*. Experiments were carried out in 2003 at Sococo plantations located in Para (Brazil) on 1.5-year-old juvenile coconut palms using three coconut hybrids, viz. PB 121, PB 123 and PB 132. Less number of leaf spot was observed in PB 121, whilst the hybrids PB 123 and PB 132 were more susceptible to the foliar spots (Gomes et al. 2009).

Ray and Kaiser (1990) reported that an acceptable level of resistance to leaf blight (*Pestalotia palmarum*) was found in 11 cultivars (Andaman Ordinary, Local Tall, Laccadive Micro, Laccadive Ordinary, Strait Settlement Green, Philippines Ordinary, West Coast Tall, Dwarf, Tall × Dwarf, Dwarf × Tall and Malayan Dwarf × West Coast Tall) out of 13 tested. In these, resistance was found to be dominant over susceptibility. Govindan et al. (1991) reported that none of the 8 varieties and 12 hybrids evaluated in Kerala proved resistant to leaf blight, but Malayan Yellow Dwarf showed low disease incidence, based on percentage of leaves and leaflets affected, as reflected with a lower disease index of 4.44. This was followed by CGD (6.66). In both these varieties, the area of infection was low.

Performance of eight coconut cultivars, viz. Tiptur Tall, Malayan Orange Dwarf, Malayan Yellow Dwarf, Sakhigopal Tall, Chowghat Orange Dwarf, Chowghat Green Dwarf, West Coast Tall and East Coast Tall, was evaluated against grey leaf spot in coastal Odisha, India. Tiptur Tall was found to be the most tolerant among the eight cultivars with 26% mean annual disease incidence, and Chowghat Orange Dwarf was the most susceptible with 35.4% disease incidence. The disease occurrence was probably influenced by high rainfall and drop in temperature (Ghose et al. 2006).

Studies on reaction of 28 different coconut hybrids/varieties against grey leaf spot or leaf blight caused by *Pestalotiopsis palmarum* revealed that no hybrid/variety was resistant to the disease (Suriachandraselvam et al. 2000). The intensity of leaf spot ranged from 23.7 (Malayan Yellow Dwarf) to 57% (Philippines × San Blas). The hybrids were more susceptible showing an intensity range of 42–57% compared to varieties which recorded an intensity range of 24–44%. This study proved that coconut hybrids are more susceptible to grey blight than varieties.

Five coconut hybrids, viz. PB 121, 141, 111, 231 and 132, introduced to Brazil were evaluated for resistance to *Botryodiplodia theobromae*. Ten plants were selected at random from each hybrid, and data were collected monthly for 34 months on the number of healthy leaves, number of infected leaves, lesion size and number of new lesions. The PB 141 hybrid was more leaf blight tolerant than Brazilian Tall and PB 231 hybrid (Warwick et al. 1991).

Helminthosporium halodes causes serious damage to introduced coconut varieties in Côte d'Ivoire. Inoculation techniques were used in the nursery to investigate entry site, susceptibility and progression of damage. Coconut varieties were classified as resistant, susceptible or intermediate (Quillec and Renard 1975). The red and yellow forms of Malayan Dwarf tended to be more susceptible to *Helminthosporium incurvatum* than the green form (Anon 1976).

5.3.2.5 Small and Big Verrucosis

Small and big verrucosis are important diseases affecting Brazilian coconut palms. It produces necrotic lesions on the palm leaflets. Five coconut hybrids introduced from Côte d'Ivoire were evaluated for their susceptibility to small verrucosis and big verrucosis in Sergipe (Brazil). The hybrid PB-141 showed low susceptibility to both the verrucoses. PB 132 and PB 121 were less susceptible to the small verrucoses and PB 111 to the big verrucoses. The climatic factors had no effect on the occurrence of the diseases. Higher disease incidence was observed from May to June and from November to January (Leal et al. 1996).

The dwarf coconut germplasm accessions planted in Brazil were evaluated in relation to the incidence of small verrucosis (*Phyllachora torrendiella*) and big verrucosis (*Sphaerodothis acrocomiae*). The incidence of verrucosis disease was observed in a 5-year-old dwarf coconut plantation. Of the six varieties assessed, the lowest incidence of small verrucosis was detected in Malaysian Yellow Dwarf, Gramame Yellow Dwarf and Cameroon Red Dwarf. The varieties Malayan Red Dwarf, Gramame Red Dwarf and Jiqui Green Dwarf were susceptible to big verrucosis disease. However, since the yellow dwarfs have a greater foliar emission, they might be able to tolerate the disease better (Leal et al. 1997).

Field experiments were conducted in Brazil during 1989 to 1992, to determine the severity of these two diseases on eight tall coconut genotypes under field conditions. The cultivars studied were GPY (Polynesia Tall), GRL (Rennell Tall), GOA (West African Tall), GRT (Rotuma Tall), GTG (Tonga tall), GML (Malaysia Tall), GVT (Vanuatu Tall) and GBR-PF (Brazil-Praia do Forte Tall). A number of leaves and verrucosic stromata were counted from selected palms. GBR-PF, GML and GOA had the highest number of stromata. Cultivar GPY, although not significantly different in stromatal count from the others, was the one with the lowest average number of stromata for both diseases (Leal et al. 1998).

5.3.3 Protozoan Diseases

Protozoa of the genus *Phytomonas* (Trypanosomatidae) have been implicated as the causal agent of several lethal diseases of coconut palms in South America and islands of the southern Caribbean. Parthasarathy et al. (1976) recorded these flagellated organisms in the phloem of 'hartrot' diseased coconut palms in Surinam.

Infected coconut palms exhibit inflorescence necrosis, rapid dieback of foliage and extensive root loss. Alexander (1980) reported that Surinam Tall was the most resistant to hartrot.

5.4 Pest Resistance

The coconut palm is damaged by a number of pests. It includes the larvae of Lepidopteran pests like leaf eating caterpillar (*Opisina arenosella*), which feeds on the lower epidermis and mesophyll tissues of coconut leaves. The nut is damaged by eriophyid mite (*Aceria guerreronis*). This mite can reduce up to 90% of coconut production. In addition, borers like Rhinoceros beetle and Red Palm weevil also damage coconut. Please refer to Chap. 12 on Pest Dynamics and Suppression strategies for details.

Management strategies have been developed against major and minor pests of coconut. However, emerging and invasive pests always pose a threat to coconut cultivation. Chemical and biological control measures have, at times, proved ineffective and ecologically undesirable. Breeding for resistance/tolerance to pest is an alternative sustainable and effective method for controlling major pests. Among the many pests, eriophyid mite is a serious pest in almost all coconut growing countries. Hence, breeding for resistance/tolerance to eriophyid mite has received more attention in coconut breeding programmes.

5.4.1 Eriophyid Mite (*Aceria guerreronis*)

Eriophyid mite develops in the meristematic regions of the immature nuts, which is covered by perianth (tepals). Their feeding causes scarring and distortions of the nuts and may cause their premature drop. Based on laboratory observations, the tightness of the perianth to the nut was identified as a key factor in determining susceptibility or resistance to attack by *A. guerreronis*. Penetration tests showed that as the nuts grew, it became increasingly larger in proportion to the perianth. Tepal aestivation in female flowers, shape of the developing nut, growth rate and pattern of nut enlargement are some of the traits identified as contributing to a lesser mite attack. Biophysical traits of habitat of the mite in the plant provide selection indices for tolerance. However, a conclusive test to determine resistance is still elusive.

The entry of mites depends on the tightness of tepals to the fruits at the early stages of fruit development. Greater tightness is achieved in round rather than elongated and angled fruits (Moore 1986; Aratchige et al. 2007). Varadarajan and David (2002) measured the gap by estimating the ratio of length of nut to radius of tepal. A large gap could also allow the predatory mites and hence is not congenial for herbivorous mite. In Malayan Yellow Dwarf, the space developed between the coconut surface and the perianth was large enough to allow mite to penetrate to the

meristematic tissue (Howard and Rodriguez 1991). Differences for the gap in uninfested nuts are significantly different among the three varieties, Sri Lankan Green Dwarf, Sri Lankan Tall and their hybrids. Sri Lankan Green Dwarf palms are susceptible to mites as the nuts of this variety are small with an elongated shape. The gap in the nuts of this variety before infestation is large enough for the eriophyid mite to enter, but too small for the predatory mites. However, this perianth-fruit-rim gap in infested nuts does not differ significantly and hence accessible to predatory mites. Access of predatory mites long after the eriophyid mites reach a sufficient population is insufficient to keep the pest population below normal level. Hence, the gap between the nut and tepal is important and needs breeders' attention.

A good ideotype for resistance/tolerance to mite needs to consider the size, shape and perianth-fruit-rim gap of 2-month-old nuts before the mite could infest. Aestivation of tepals in coconut is of two types: *contortions* (with regular twisting or overlapping of tepals at one end) and *imbricate* (with irregular twisting or non-overlapping of inner tepals or one tepal overlapping at both ends). Aestivation also decides the tightness of the tepals (Moore 1986) and consequently the population of different herbivorous and predatory mites (Lawson-Balagbo et al. 2007). Tall varieties possess a higher percentage of contorting tepals than dwarf varieties, whereas Dwarf \times Tall hybrids are intermediate (Davis et al. 1990). Round and dark green fruits show better tolerance against the eriophyid mite than the elongated fruits and those of other colours (Moore and Alexander 1987). Drought is also a predisposing factor which makes coconut palms susceptible to mite attack, since the growth rate of nuts is slow because of the lack of available soil moisture (Mariau 1986).

Thirty one varieties in India were evaluated in 1999 for eriophyid mite damage using a one to five scale. Under conditions of natural infestation, Laccadive Ordinary, Cochin China, Andaman Ordinary and Gangabondam recorded minimum nut damage, whereas Seychelles, St. Vincent and Nigerian Tall were highly susceptible (Muthiah and Bhaskaran 1999). Screening of coconut varieties for tolerance to coconut mite resulted in identification of some accessions such as Kenthali (Ramaraju et al. 2000) and Chowghat Orange Dwarf (Nair 2000) with lower incidence of mite. Muthiah and Rajarathinam (2002) screened 33 coconut cultivars for eriophyid mite resistance for 3 years during 1999–2002. Chowghat Orange Dwarf, Siam, British Solomon Island (BSI), Ayiramkachi, Philippines Ordinary and Spicata were found to be moderately tolerant. The cultivars Seychelles and St. Vincent were found to be highly susceptible to mite attack. Among 34 coconut hybrids screened during 2001, 4 hybrids, viz. Java Giant \times East Coast Tall, Ayiramkachi \times West Coast Tall, Cochin China \times Philippines Ordinary and West Coast Tall \times Chowghat Orange Dwarf, were found to be moderately tolerant.

Levin and Mammooty (2003) reported that the Spicata mutant showed a fair level of tolerance to eriophyid mite. They also reported that the genotype BSI recorded the highest percentage of nut damage by mites followed by Philippines Lono (81.1%). Laksha Ganga (Laccadive Ordinary \times Gangabondam) recorded the minimum incidence (19.4%) compared to the maximum mite damage (30.0%) in Ananda Ganga. The cultivars Ayiramkachi (90.2%) and Andaman Dwarf (85.3%)

were the most susceptible to mite damage among the indigenous cultivars, whereas the genotypes Bombay (6.4%), Laccadive Micro (7.4%), Chowghat Orange Dwarf (8.8%) and Spicata (9.5%) were the least susceptible.

Muthiah and Natarajan (2004) conducted a field experiment in Tamil Nadu, India, during 1999–2001 to evaluate the resistance of 33 coconut cultivars and 34 hybrids to eriophyid mite. Four cultivars, viz. BSI, Chowghat Orange Dwarf, Philippines Ordinary and Spicata, and two hybrids, viz. Philippines Ordinary × San Blas and Cochin China × Philippines Ordinary, were moderately resistant, whereas all the other materials tested were moderately susceptible or highly susceptible to the pest.

The cross between Sri Lankan Yellow Dwarf × Sri Lankan Tall has been identified as tolerant to *Aceria* mite, in an evaluation of five commercially cultivated coconut cultivars in Sri Lanka in a severely mite-affected area (Perera 2005, 2006). Sri Lankan Yellow Dwarf and Gonthebili have also been identified as tolerant cultivars to coconut *Aceria* mite (Perera 2006).

Eleven coconut cultivars were screened against eriophyid mite in Andhra Pradesh (India) during September 2000 to January 2005 (Raju et al. 2006). None of the cultivars were resistant to *A. guerreronis*. However, Java Giant and Ceylon Green Tall were moderately resistant, and the rest were susceptible. The maximum percentage of infested nuts was recorded by Fiji (83.65), followed by Chowghat Orange Dwarf (80.13).

Girisha and Nandihalli (2009) screened ten coconut varieties, viz. West Coast Tall, Arsikere Tall, Laccadive Ordinary, Gangabondam, Philippines, ‘Green Dwarf’, Andaman Dwarf, Laccadive Dwarf, ‘Green Tall’ and Spicata, against eriophyid mite. Significantly less mite population was recorded in Gangabondam (28.96/28.28 mm² area of perianth) which was found significantly superior over other varieties followed by West Coast Tall, whereas varieties Laccadive, Green Dwarf, Arsikere Tall and Green Tall recorded more mite population. The superiority of Gangabondam might be due to the tight attachment of perianth to nut surface. Gangabondam also recorded least damage grade (1.40) and damaged nuts (16.00) with the highest number of healthy nuts (78 nuts palm⁻¹).

Sujatha et al. (2010) screened 8 tall coconut varieties (45 years old) and 17 hybrids (15 years old) for resistance against the mite for 4 years during 2004 to 2007 under natural conditions of coastal ecosystem of Andhra Pradesh, India. The lowest mite damage index was recorded in Laccadive Ordinary and the highest in Laccadive Micro. Among the 17 coconut hybrids screened, ECT × GB (Godavari Ganga) recorded the lowest mite damage, whereas LM × GB recorded the highest damage among various cross combinations. Badge et al. (2016) screened coconut genotypes for their level of susceptibility to coconut eriophyid mite in India. Based on mean damage score, none of them were found to be resistant to eriophyid mite. Among the 26 coconut cultivars screened, minimum infestation was observed in the genotypes, viz. Jamaica, BSI, Philippines Lono, Guam and Orange Dwarf.

Molecular markers: Molecular analysis of coconut accessions from different parts of South India was done using 32 simple sequence repeats (SSRs) and 7 RAPD primers. In single-marker analysis, nine SSR and four RAPD markers associated

with mite resistance were identified. In stepwise multiple regression analysis of SSRs, a combination of six markers showed 100% association with mite infestation. Stepwise multiple regression analysis for RAPD data revealed that a combination of three markers accounted for 83.9% of mite resistance in the selected materials. Combined stepwise multiple regression analysis of RAPD and SSR data showed that a combination of five markers explained 100% association with mite resistance in coconut (Shalini et al. 2007).

5.4.2 Rhinoceros Beetle (*Oryctes rhinoceros*)

Although all coconut cultivars are prone to damage by rhinoceros beetles, the hybrids developed with Chowghat Orange Dwarf as pollen parent was reported to be more susceptible (Nambiar 1988). Coconut varieties were screened in Tamil Nadu, India, for reaction to rhinoceros beetle. Average leaf damage over 3 years recorded from different hybrid combinations and varieties revealed that Laccadive Ordinary × Cochin China and Gangabondam × East Coast Tall had significantly minimum damage. Among the 12 varieties evaluated, West Coast Tall (WCT) and East Coast Tall (ECT) recorded less damage. The damage was more in hybrids involving dwarf genotypes (Muthiah and Bhaskaran 2000).

5.4.3 Red Palm Weevil (*Rhynchophorus ferrugineus*)

Red palm weevil (RPW) is known to cause serious damage to the crop and has attained key pest status. A preliminary survey on the damage of coconut cultivars in different districts of Tamil Nadu, India, showed that Andaman Giant, Java Giant, East Coast Tall, West Coast Tall, Federated Malay States × Laccadive Ordinary, East Coast Tall × Malayan Green Dwarf, West Coast Tall × Gangabondam, Java Giant × San Blas and Laccadive Ordinary × Cochin China were more susceptible to red palm weevil attack (Sadakathulla and Ramachandran 1993). Faleiro and Rangnekar (2001) studied the ovipositional preference of RPW to different coconut cultivars and reported that the highest cumulative egg lay was in CGD, COD and Benaulium, which recorded an average of 31.3, 30.9 and 27.4 eggs, respectively.

5.4.4 Red Spider Mite (*Oligonychus velascoi*)

Red spider mite feeds on coconut leaves. Large-scale attack causes yellowing and early dieback of the leaves of young palms and can retard growth severely. Five biological parameters were evaluated in populations of *O. velascoi* growing on three coconut varieties in the Philippines. All parameters indicated Baybay Tall as the most susceptible variety. On the basis of total developmental period, fecundity

and adult longevity, MAWA (Malayan Yellow Dwarf \times West African Tall) was the most resistant hybrid, followed by Malayan Orange Dwarf (MOD). However, mortality of immature mites was significantly higher in MOD than in the other varieties, suggesting the presence of an antibiotic component in its sap (Capuno and de Pedro 1982).

5.4.5 Nematodes

The most important nematode found in coconut root is burrowing nematode, *Radopholus similis*. General decline symptoms like stunting, yellowing, reduction in number and size of the leaves and leaflets, delay in flowering, button shedding and reduced yield are exhibited by burrowing nematode infested palms. Sosamma et al. (1980) reported that the cultivar Java had the least root lesion index and root population of burrowing nematode (*Radopholus similis*; 7 g⁻¹ of roots), whereas cultivar Jamaica Tall (259 g⁻¹ of roots) and Fiji Tall (137 g⁻¹ of roots) were most severely infested. Java Tall, Klapawangi, Kenthali and Andaman Giant showed fair level of tolerance to burrowing nematode (Sosamma et al. 1988). But Sudha (1998) reported that all 25 coconut cultivars screened against *R. similis* were susceptible to the nematode. Philippines Ordinary was the least susceptible with an average population of 48.4 nematodes 10 g⁻¹ root, whereas COD was highly susceptible recording 953.4 nematodes 10 g⁻¹ root.

5.4.6 Rodents

Rodents damage tender coconuts throughout the year, but with a higher intensity during July–October (Sadakathulla 1996). Evaluation of 28 cultivars and 9 hybrids for rodent (*Rattus rattus wroughtoni* and *Funambulus palmarum*) damage for 1 year in India indicated that Ayiramkachi, Laccadive Micro and East Coast Tall \times Ayiramkachi were highly susceptible, followed by Siam \times Ayiramkachi. The varieties Jamaica Tall, Andaman Giant, Andaman Ordinary and Federated Malay States were moderately resistant to rodents (Sadakathulla and Kareem 1994).

5.4.7 Ash Weevil

A study was carried out in Kerala, India, on 37 coconut cultivars and hybrids to record the infestation of ash weevil (*Myllocerus curvicornis*) and the relationship between infestation by this pest and incidence of root (wilt) disease. The highest infestation rate (69.7%) was observed on Malayan Green Dwarf and the lowest (7.29%) on Fiji \times S.S. Green. Weevil damage was related more to the high nitrogen content of diseased palms (Ponnamma et al. 1985).

5.5 Breeding Coconut with Their Microbiome

The current concept of ‘holobiont’ theory, where the plant is considered as a meta-organism (i.e. plant and its microbiome present in the rhizosphere and endophytic compartment), is giving a new dimension to the plant breeding programme (Zilber-Rosenberg and Rosenberg 2008; Theis et al. 2016; Gopal and Gupta 2016). The plant microbiome is known to govern many of the positive traits in plants (Vandenkoornhuys et al. 2015). In coconut, basic research on rhizosphere microbiota have shown differences in microbial community profile, particularly with relation to arbuscular mycorrhizae in drought-tolerant varieties (Thomas et al. 1993) and in palms located in the high-yielding tracts in Kerala, India (Rajeshkumar et al. 2015). A preliminary study of rhizosphere microbiota of coconut root (wilt) diseased and field resistant palms indicated differences in plant-beneficial bacterial communities (Gopal et al. 2005) that need further detailed investigation using genomic protocols. Thus, the use of arbuscular mycorrhizae and endophytic microbiota has already emerged as an innovative technology for phytoplasma disease management (Musetti et al. 2012; Bianco et al. 2013) that could possibly lead to tailored microbiome for plant disease management (Gopal et al. 2013).

5.6 Future Strategy

From the data so far available, it appears that MGD, CGD and CGD × WCT hybrids can be very important in the management of coconut root (wilt) disease. The development of an improved WCT variety, by inter se crossing or selfing of selected WCT palms, seems to be a promising line of research irrespective of the long time and resources required. Considering the long gestation period required for the large-scale production of planting materials, the approach of establishing nucleus seed gardens in different districts of root (wilt) prevalent tracts, concurrent with the varietal improvement programmes, is a pragmatic approach to reduce the acute shortage of quality planting materials in the diseased tract. Control of coconut root (wilt) disease, in the long run, will most likely rely on integrated management practices centred on the exploitation of source of disease resistance.

Collective effort for sharing coconut germplasm to breed varieties with resistance to phytoplasmal diseases should be accorded maximum priority. In addition, research on tagging disease-resistant genes should employ molecular markers which are stable and dependable, and such work should utilise next-generation sequencing technology so that the long-cherished objective of identification of resistant progenies in nursery stage itself materialises. Among other diseases affecting coconut, bud rot, basal stem rot and stem bleeding are the most devastating, and developing resistant varieties will go a long way to combat the diseases by taking up replanting programmes. Since, Talls have certain specific advantages over Dwarfs, recurrent selection to improve the level of disease resistance in tall populations

should be envisaged, involving sib (inter se) mating between highly divergent coconut populations so as to simultaneously increase the yield of the resultant progenies.

In the present era of climate change, a rapid increase in density and damage of sucking pests should be anticipated. Hence, efforts should be oriented to develop coconut varieties that can resist/tolerate sucking pests like coreid bug, eriophyid mite and – recently emerged – invasive spiralling whitefly. Besides, the focus to breed coconut varieties with resistance to red palm weevil, the most dreaded pest of coconut, should continue. It would be appropriate if the breeding programme in each coconut-growing country is fine-tuned to develop resistant varieties to combat pests/diseases. Since growing coconut as a monocrop is no more profitable, it is suggested to develop coconut varieties which can fit well into high-density multi-species cropping systems with the additional trait of resistance to major pests/diseases of specific coconut-growing tracts. In view of the regional specificity of the biotic factors, priority attention should be given for location-based breeding programmes with necessary international cooperation wherever appropriate.

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