Chapter 4
Varietal Improvement

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Abstract Considerable progress has been made in evolving high-yielding coconut cultivars and hybrids with desirable traits, despite critical constraints in breeding due to heterozygous, monotypic and perennial nature of the crop with a long gestation period and requiring extensive land area for experimentation. Comprehensive efforts in prospection and international cooperation have helped in the assemblage of 1837 valuable accessions maintained in the five international gene banks and various national gene banks. The significance of selection at mother palm level and seedling stage has been well established. The most significant stride came with the advent of hybrids especially between Dwarf and Tall varieties which led to concerted attention on production of high-quality hybrids. However, the area covered under hybrids is only 3% globally, mainly because of poor accessibility and availability of adequate quality assured planting material. Possibility of mitigating this limitation through seed gardens is indicated. Since no single method is infallible, a comprehensive breeding strategy based on the principles of reciprocal recurrent selection has been suggested, irrespective of the considerable time and resources required for such an initiative. Coconut breeding programmes in the major coconut-growing countries are described in the chapter. The main challenge today is in the development of biotic and abiotic tolerant materials to alleviate the negative impact of serious diseases and moisture stress conditions. Strides in biotechnology are the way ahead to complement future breeding strategies in coconut.

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4.1 Introduction

Availability of planting material, with high yield potential and other desirable traits, is a basic requirement for profitable coconut cultivation. Though the first record on coconut breeding became available about 275 years ago from the Indonesian publication *Herbarium Amboinense* (Harries 1991a), the palm has a very long history as stated by Foale (2005) 'Through a process of natural selection, over a period of perhaps a few million years, the coconut developed the means to disperse across vast expanses of ocean and take hold firmly on the perilous boundary between land and sea, adapting to fierce windstorms and periodic inundation, thriving unassisted by any other fauna and flora and delivering its fruit in turn to the ocean vehicle for further dispersal'.

Selection of palms based on field experience and raising their progenies for generations has been in vogue ever since the crop was in cultivation for some 2000–3000 years ago (Purseglove 1968; Anon 2016). There is evidence for exchange of coconut varieties between Papua New Guinea and Solomon Islands from very early times. German Government in Papua New Guinea introduced *Niu vai* and *Niu iu* from Samoa in 1911 (Dwyer 1938). Formal and scientific breeding started in 1916 in India (Nair et al. 1991). The special features like long gestation period, height, heterozygosity, large nut size, requirement of considerable space and other resources, poor multiplication ratio, lack of vegetative propagation and monotypic nature of the genus *Cocos* are all factors discouraging scientists to undertake coconut breeding work. In spite of all these odds, considerable strides have been made in evolving high-yielding coconut varieties, which is briefed in this chapter.

4.2 Genetic Diversity

Realising that wide genetic base is the basic requirement for breeding, prospection and collection of various coconut types were given the first priority. This is all the more important, because there are no known wild-/domesticated-related species, to be used as gene pool sources. The first attempt for coconut germplasm collection was made between 1901 and 1910 in Indonesia and Madagascar. But, unfortunately, the First World War put an end to these activities in both the countries (Ohler 1984). A Samoan tall planted in 1912 at Solomon Islands is the oldest accession registered in CGRD (Bourdeix et al. 2005). In India, collections were made right from 1920, mostly from domestic sources. Introductions of a few coconut types were also made from Malaysia and the Philippines. The progenies of these were planted at the Government Farms in Kerala, India. Added emphasis was given to exotic introductions from 1927, and accessions from Vietnam, Indonesia, Thailand, Malaysia, Sri Lanka, Fiji, Papua New Guinea and the Philippines were raised at the Coconut Research Station, Pilicode (now under the Kerala Agricultural University).

The first organised germplasm bank was established in 1940 at the erstwhile Central Coconut Research Station at Kasaragod, Kerala, India (presently ICAR-Central Plantation Crops Research Institute- ICAR-CPCRI) using open pollinated progenies of the introduced accessions maintained at Pilicode (Rao et al. 1993). The collections were conserved as separate accessions in a centralised germplasm bank. Similar work was later taken up in most of the other coconut-growing countries. For details, please refer Sect. 4.11 on global scenario of this chapter.

A prospection for coconut germplasm was conducted in the Pacific islands in 1981 by ICAR-CPCRI, with the financial assistance of International Bureau of Plant Genetic Resources Institute (now Bioversity International). While only a few nuts were collected in the earlier cases, 100 nuts per each accession were systematically collected which were planted in an offshore World Coconut Germplasm Centre in Andaman Islands (Rao and Koshy 1981). With the initiative under Coconut Genetic Resources Network (COGENT), international germplasm exchange was made possible between the member countries. ICAR-CPCRI now has the largest germplasm collection with 455 accessions (323 indigenous and 132 exotic) from 28 countries (ICAR-CPCRI 2016). The institute also hosts the International Coconut Genebank for South Asia (Nampoothiri 1999). The other ICGs are in Indonesia for Southeast and East Asia, Côt d'Ivoire for Africa and Indian Ocean islands, Papua New Guinea for South Pacific region and Brazil for Latin America and Caribbean Islands (Nampoothiri 2003). Table 4.1 gives a list of 1837 coconut accessions in 24 countries.

The strategies for collecting coconut genetic diversity are fairly well established (Guarino et al. 1998). Care has to be exercised to collect only distinct types since many of them seen in different locations and various countries may be only duplicates of the existing ones, with different local names. Adequate attention should be given to collect and keep permanent records of passport data of the collections (from the site of collection itself), seedling characters in the nursery, juvenile traits (till fifth year after planting) as well as yield, various yield attributes and nut analysis data of the adult palms. Cumulative yield of first eight annual harvests gives a fairly good indication of the yield potential of accessions. It has been found that girth at collar, number of days for germination and number of leaves of seedlings are important characters to discriminate coconut accessions. Based on nursery characters, an index has also been developed by Rao and Mathew (1981).

The movement of plants or plant parts between countries or continents entails the risk of introducing exotic plant pests or pathogens. Less-developed countries often lack adequate plant quarantine and diagnostic facilities and are especially vulnerable to the damaging effects of newly introduced diseases. It is extremely important that the risk is recognised and that a minimum risk transfer form of germplasm is chosen, such as in vitro plantlets instead of nuts (Batugal et al. 2005). In view of the importance in following strict quarantine regulations, COGENT has published a manual on the germplasm movement involving seed nuts, embryos and pollen (Ikin and Batugal 2004).

In a perennial crop like coconut, with no means of vegetative propagation, in situ conservation is of special significance. This refers to maintenance of coconut

Table 4.1 Global accessions in gene banks (as in 2012)

Countries and gene banks	Number of accessions
Benin – CRC Sémé Podji	4
Mexico – CICY Yucatan	20
Pakistan	32
Tonga – Ministry of Agriculture	7
China – Wenchang Coconut Research Institute	17
Western Samoa RS	9
Fiji – Taveuni Coconut Centre	11
Ghana – Oil Palm Research Institute	16
Bangladesh – BARI	40
Malaysia – Department of Agriculture, Sabah	45
Solomon Islands – Yandina Research Centre	21
Brazil – EMBRAPA, Brazilian Agricultural Research Corporation	29
Jamaica – Coconut Industry Board	60
Vietnam – Dong Go Experimental Centre	31
Malaysia – Malaysian Agriculture Research and Development Institute (MARDI)	44
Vanuatu – Saraoutou Research Centre	79
Papua New Guinea – Stewart Res. Centre and Cocoa and Coconut Research Institute	60
Thailand – Chumphon Horticultural Research Centre	52
Tanzania – National Coconut Development Programme	72
Cote d'Ivoire – CNRA Marc Delorme Research Station	149
Indonesia – Indonesian Palm Research Institute	203
Sri Lanka – Coconut Research Institute	157
Philippines – Philippines Coconut Authority	224
India – CPCRI (as in March, 2016)	455
Total	1837

Updated to 2012 from Nampoothiri (2003)

diversity in its natural habitat. In situ genetic diversity is lost due to many factors like land use changes, adoption of high-yielding varieties, urban area development, natural disasters and lethal diseases. Farmers conserve coconut varieties based on their own perceptions, disease resistance, quality of tender nut water, etc. Such conservation efforts are to be encouraged, and the palms are to be regularly monitored. Added importance is now given to promote 'conservation beyond gene banks' which includes in situ as well as on-farm conservation (Bourdeix et al. 2017). Duplicate germplasm banks are necessary to safeguard against any untoward catastrophe threatening the collections. In India, Agricultural Universities take the responsibility to collect and maintain local collections as well as duplicate samples of the central germplasm bank.

The coconut population in the Cocos (Keeling) Islands of the Indian Ocean displays fruit characters thought to be consistent with the wild-type form. This population remains unaffected by human intervention unlike that of the main atoll. The genetic uniqueness of the North Keeling population holds possible value for improvement of atoll populations elsewhere (Leach et al. 2003).

Cocos is a monotypic genus with only *nucifera* as the sole species. It is a diploid with a chromosome number of 32 (2n = 32). Coconuts are generally classified into two varieties, viz. tall (*typica*) and dwarfs (*nana*). Talls generally attain a height of 20–30 m, flower only by 5 or 6 years and are cross-pollinated and hence heterozygous. Dwarfs flower early (from 3 years), have a lower height increment (reaching 8–10 m height) and are homozygous because of their self-pollinating nature. There are also various intermediate types which do not show the typical characteristics of either tall or dwarf. Dwarfs are hypothesised to have originated from talls through continuous inbreeding and mutations (Swaminathan and Nambiar 1961; Nampoothiri 1974). According to Perera et al. (2016), SSR allele frequency differences between dwarf and tall accessions and ethnobotanical and geographic information indicate that dwarf coconut originated from a typical domestication event in Southeast Asia. The commercial cultivation of dwarf coconut is limited in the world, representing about 5% of global coconut population. However, dwarfs are now receiving added attention, especially for tender nut water and as a source of disease resistance. For details, please see Chap. 3.

Rao and Pillai (1982) attempted characterisation of coconut germplasm based on fruit component analysis. Descriptors are now available for 74 of the Indian accessions. COGENT also facilitated characterisation of collections and creation of a Coconut Germplasm Data base (CGRD). The catalogue of conserved coconut germplasm provides comprehensive information on 116 accessions (Bourdeix et al. 2010). The accessions which are found to be better performers are identified, their progenies raised and tested in multilocation trials. Based on the results, varieties are recommended for cultivation in a particular ecological region or at a national level. This type of simultaneous evaluation is necessary to reduce the time lag between germplasm collection and its direct use by coconut farmers. Through this process, 29 varieties have been released in India for cultivation (Niral et al. 2014). Details of a few important ones are given in Table 4.2. San Ramon, a Philippine variety introduced to Sri Lanka, was found to have the potential to yield 51% more copra nut^{-1} than the Sri Lankan Tall and 50% more copra than the improved CRIC 60. The mean copra yield for San Ramon (selfed), Sri Lankan Tall and CRIC 60 was 371 g, 240 g and 246 g, respectively. Based on these, Fernando (1998) recommended the use of San Ramon and its crosses for producing copra and oil in Sri Lanka.

It could be seen that these varieties are released not only for yield but also for some of the desirable traits like better tender nut water, stress tolerance, etc. The south Pacific region contains a large genetic resource for the genetic improvement of coconut palms. Considerable diversity for fruit morphology was found that ranged from populations exhibiting wild-type characters in the central pacific to populations displaying domesticated characters in Rennell Island, Papua New Guinea, the Sikaiana and Marquesas Islands. Many populations exhibited continuous variation in fruit morphology between these two extremes which are presumed to have arisen from introgressive hybridisation between wild and domesticated

Table 4.2 Performance of certain varieties released in India

Variety	Germplasm	Important traits	Nut yield (number ha^{-1} year^{-1})	Copra yield (mt ha^{-1} year^{-1})	States for which recommended
Chandra Kalpa	LCT	Drought tolerant, high oil content – 72%	17,700	3.12	Kerala, Tamil Nadu, Karnataka, Andhra Pradesh, Maharashtra
Pratap	Banawali Green Round Tall	High yield	20,826	3.60	Maharashtra
Kamarupa	Assam Green Tall	High yield, cold tolerant	17,877	2.90	Assam
ALR(CN)1	Aliyar Nagar Tall	High yield	21,240	2.89	Tamil Nadu
Kera Keralam	WCT	High yield	26,019	3.53	Kerala, Tamil Nadu, West Bengal
Kalparaksha	MGD	Semi-tall, high copra yield, RWD resistant	13,260	2.85	Root(wilt)disease prevalent areas of Kerala
CARI-C2 (Surya)	Hari Papua Orange Dwarf	Ornamental, orange nuts	24,072	1.77	Andaman and Nicobar islands
Kalyani coconut	Jamaica Tall	High yield	14,240	3.90	West Bengal
Chowghat Orange Dwarf	COD	Dwarf, tender nut, ornamental	19,824	2.78	All regions

Source: Regi J. Thomas et al. (2016)

populations (Duhamel 1993). The wild and domesticated populations were found in disjunctive pockets throughout the area which did not form a part of the clines. This suggests the worthiness of further exploration to find potentially useful populations in the region, before this variability is completely lost (Ashburner et al. 1997).

Some rare types of coconuts also happen to be collected, which are worthy to be preserved. The case of palms, known as ‘sweet husk’ or SWH reported by Batugal et al. (2009) and reproduced here, is a typical example. ‘The husk of unripe fruits, which is usually tough and astringent, is tender, edible and sweet. A sufficiently ripe fruit can be husked by hand, which is impossible in the case of an ordinary coconut. The only place these rare types are found in any appreciable quantities is the islet of Onoiki in the Ha’apai group of Tonga. The islet is so small that it does not figure in most of the maps. Coconuts having a circumference of more than 60 cms have been found in another islet of Niu-foi in Tonga (Henry Teuira 1928). This islet has even taken the name of the newly located coconut variety, as its name -“Niu-foi” meaning “new coconut”. Planting in islets seems to have played some role in varietal creation and conservation. The geographical remoteness of the islets has been a reproductive barrier which has enabled new coconut varieties to become fixed’.

Standardisation of zygotic embryo culture technique has helped to increase the scope of collection, especially those from other countries, circumventing the disadvantage of nut size and ensuring better safety from a quarantine point of view. Koshy and Kumaran (1997) collected 15 accessions from the Indian Ocean islands of Mauritius, Madagascar and Seychelles. Parthasarathy (2001) used this technique to collect four accessions from Sri Lanka. Protocols developed for coconut embryo culture in the Philippines, India and France are very promising with 31–80% of inoculated embryos developing into plantlets in vivo. COGENT has published a manual on germplasm health management indicating the operational management of germplasm movement involving seed nuts, embryos and pollen (Ikin and Batugal 2004).

For long-term conservation of the coconut germplasm in vitro, a working protocol for efficient cryopreservation of embryo (i.e. storage at ultra-low temperature, − 196 °C, in liquid nitrogen) is necessary to be developed. Refinement and standardisation of the current technique, using various genotypes on a large scale, are essential (Engelmann 1999). Molecular tools when perfected would be helpful in further refining the characterisation of accessions.

4.3 Selection

Coconut is, by and large, a cross-pollinated crop and hence heterozygous, throwing out lot of segregants among its progenies. These inter- and intrapopulation variability gives ample scope for selecting the best ones for planting. In fact this was the first option available to growers, much before scientific breeding was started. Most of the populations available at present are the result of informal mass selection process. Selection can be practised at mother palm, seed nut and seedling stages.

4.3.1 Mother Palm Selection

The method, adopted for long, is mass selection wherein open pollinated seed nuts from high-yielding palms are pooled and used as planting material. The advantage of the method is its simplicity. The possibility of such a method is immense since palms yielding as much as 471 nuts palm^{-1} year^{-1}, under rain-fed condition, have been identified as in India (Iyer et al. 1979). Quite a few studies have been made in the earlier years to ascertain the efficacy of mother palm selection. There were always controversies about the efficiency of mass selection, because varied results were obtained, partially because of the cross-pollinating nature of tall variety. Liyanage (1967) observed that in a two hectare block in Sri Lanka, the yield of nuts varied from 15 to 148 nuts palm^{-1} year^{-1}. Tammes (1955) estimated that the best palms in a plantation yield about twice as much as the average. Adansi (1970) could identify only a meagre five palms qualifying as mother palms from a group of 4620 palms in Ghana. Ohler (1984) found that by selecting the best three palms from a population with an average yield of 40 nuts palm^{-1} year^{-1}, a yield of 160–175 nuts could be obtained. Some contradictory results were reported from Sri Lanka where a trial was conducted to compare the performance of progenies of high-yielding palms and low-yielding palms and from a heap of bulked nuts. The difference in yielding capacity between the three groups was very small and insignificant (Harland 1957; Liyanage 1958). However, these findings were criticised by Sakai (1960) for the reason that the parent palms for the trial belonged to different populations.

Certain criteria are generally to be adopted for mother palm selection. The palm should have attained stabilised yield. The yield should not be less than 80 nuts palm^{-1} year^{-1} (based on at least 4 years' yield data), and copra yield has to be at least 20 kg palm^{-1} year^{-1}. Apart from yield, higher number of female flowers, number of functional leaves on the crown, leaf production and time taken for flowering are important selection criteria. Disease affected or pest prone palms as well as those which show tendency of alternate bearing, barren nut production and bunch buckling are to be totally avoided (Menon and Pandalai 1960).

In such a selection procedure, there are two disadvantages. One is that the yield observed phenotypically is due to both genetic and environmental factors. It is therefore necessary to avoid the non-genetical effect to the extent possible. One way to overcome this is to avoid palms in an obviously site-specific favourable environment. The general practice is to select the best palms in a coconut garden raised in a more or less uniform environment so that the difference in yield can be presumed to be due to genetic factors. Charles (1961) observed that selection of 5% best palms from a group of 128 palms yielded 70% more nuts than the average. Liyanage (1967) reported that progenies of the best 5% palms yielded 14.4% more yield than the parents. Experiments conducted in Côte d'Ivoire have shown that by selecting 7–8% of the best families, a genetic gain ranging between 15% and 30% is achieved (Bourdeix et al. 1989).

The second short fall, in selection of mother palms based on phenotypic yield, is that weightage is given only for the potential of mother palms, the progenies being randomly mated ones, with no idea about the male parent. This defect is minimised if there are a high proportions of desirable palms in the concerned garden. It is therefore evident that, on a long-term basis, if mother palms are selected based on progeny testing, the efficiency of selection can be increased. However, the possibility of pure line breeding is questionable in view of the inbreeding depression reported from many experiments. Dwyer (1938), therefore, recommended 'plant-to-row method' in which seedlings of individual selected palms are grown in separate lines enabling rejection of rows with inferior seedlings. Vigorous seedlings from the selected rows are then planted side by side so that the potential of the mother palms can be assessed based on the performance of their progenies from the beginning. Liyanage (1967) who analysed open pollinated progenies of 104 Sri Lankan Talls found 32% higher yield could be obtained than the average when six best families were selected among them. It is generally accepted that the best 10% of the palms in a population are eligible to be selected for seed nut production, exercising caution to avoid environmental effects. In Sri Lanka, planting materials were produced through open pollination of a pool of about 50,000 selected palms and used in the national replanting programme in operation for four decades (Peries 1998). In Vanuatu, four mass selection cycles by open pollination/intercrossing were conducted from 1962 to 2002, using two Vanuatu Tall populations (Labouisse et al. 2004). There was no increase in the number of nuts palm^{-1} because the selection was mainly based on copra content nut^{-1} which is strongly and negatively correlated with the number of nuts.

The efficiency of mother palm selection can be increased by considering the heritability of characters and correlations between them. Results available across the coconut-growing countries show the significance of selection method in coconut improvement. This is not surprising since studies show comparatively high heritability for many characters of economic importance. The heritability for yield varies from 0.48 to 0.63, whereas the same for yield attributes like number of spathes, female flower production, setting percentage, etc. are higher, indicating the advantage of selection based on these characters (Nair et al. 1991). The high heritability value of 0.67 and 0.95 for nut weight and copra reported by Liyanage and Sakai (1960) meant that these characters could be reliable selection criteria. In West Coast Tall (WCT), (Fig.4.1) studies on the relationship between yield of nuts, copra content per nut, total yield of palm and yield of oil indicated the importance of exercising selection pressure for copra per nut and oil percentage in addition to number of nuts (Bavappa and Sukumaran 1976). For details, please see Sect. 4.8 on genetic studies in this chapter.

Selection is further refined by using the concept of prepotency (Harland 1957) which is defined as a phenomenon wherein the gene combination responsible for high yield potential, in certain mother palms, tends to be transmitted en bloc to progenies even under random mating. This means the high yield potential of such

Fig. 4.1 West Coast Tall. (Photo: MA Nair)

mother palms is transmitted to the progenies, irrespective of the pollen parent. Satyabalan and Mathew (1984) argued that prepotents are palms with good general combining ability. Based on progeny studies, five prepotent palms which gave 35–40% more copra than the population mean were identified in Sri Lanka (Peries 1993a). In India, Iyer et al. (1981) studied seedling progenies of 18 elite palms (bearing above 200 nuts palm^{-1} year^{-1}) and found that some progenies gave a close resemblance to those of prepotent palms. In India, eight prepotent palms could be identified through progeny studies of 30 West Coast Tall palms (Nampoothiri 1991). However, the number of prepotent palms which could be identified from a population is very few, that too after a laborious and time-consuming process of progeny testing. The selection at mother palm stage can be further refined through inter se mating of selected palms. This appears to be more effective, as it allows for a strict selection of pollen parents while retaining the potential for large seed nut production. However, experimental results are not available to assess the yield progress that could be realised from this method.

4.3.2 Seed Nut Selection

Having selected the mother palm, the next stage at which variation can be expected is among the seed nuts, since the nuts harvested from the same palm show variable nut characters for nut size, nut shape, colour, copra content, oil percentage, etc. Selection practised at the seed nut stage is to ensure that seedlings are raised from good and healthy nuts, by discarding all small, malformed and abnormal nuts. There is a preferential selection towards medium-sized nuts preferred by farmers as market price in most of the cases is based on the number of nuts. There are not many studies to prove or disprove the need/efficacy of seed nut selection. Seed nut selection is, however, practised more from an agronomic consideration.

4.3.3 Seedling Selection

Due to the heterozygous nature of the palms, high variability is observed for various characters – right from the germination in the nursery which gives scope for rejection of ‘undesirables’. Nursery selection is based on characters which are correlated with high yield of adult palms, such as early sprouting, faster growth rate, early splitting of the unexpanded leaf into leaflets, seedling vigour in terms of girth at the collar, height, number of leaves and colour of petioles.

Correlations between seedling characters and adult palm performance have been reported by many workers (Charles 1959; Nampoothiri et al. 1975). Satyabalan and Mathew (1983) reported high and positive correlation of growth characters like collar girth and leaf production of the seedlings from the fifth month with those of the later months. This finding enabled them to identify palms of superior genetic value based on the growth characters of the progeny even from the fifth month. From studies conducted on seedlings of West Coast Tall variety of coconut in India, it was found that the most important criteria to be used are speed of germination, vigour, girth at collar, number of leaves and splitting of leaves (Thomas and Gopimony 1991a and b). Selection for leaf number and leaf production rate at early stages proved to be a rapid method for genetic improvement (Prabhakaran et al. 1991). In Nigeria, Akpan (1994) found that selection for seedling height and girth resulted in earlier inflorescence initiation in the local Badagry Tall. However, selection pressure is, by and large, arbitrary. Liyanage (1953) found that the advantage of seedling selection is 12% and advocated selection of 50% of the seedlings. In general, 35% rejection is considered satisfactory from a farmers' point of view. Coconut management all over the world adopt culling of weak seedlings from the nursery. Needless to emphasise that very strict selection criteria are to be used when the material is used for further breeding. The selection criteria and selection pressure are left to the discretion of the breeder, the results being better when there is stringent selection for as many characters as possible. Rajesh et al. (2013) suggested use of molecular markers in identifying the good progenies.

4.4 Hybridisation

Ever since the report of coconut hybrids in 1932 by Patel in India (Patel 1937), the attention was completely turned to hybridisation between the two major coconut varieties, the talls and dwarfs. Though the first hybrid was produced by Marechal in 1928, by crossing Niu Leka and Malayan Dwarf in Fiji, the work was discontinued due to financial crisis (Marechal 1928; Ohler 1984), and Patel was the first to report hybrid vigour in tall × dwarf hybrids (Menon and Pandalai 1960). This was followed some 15 years later by Sri Lanka and in the early 1990s by IRHO and its partners. Tall × Dwarf (T × D) as well as its reciprocal (D × T) have been found to be early bearing intermediate in height and expressing hybrid vigour resulting in higher yield (Fig.4.2).

The major problem faced was the highly variable performance between hybrids involving different parental palms (Harries 1991b). This was minimised to a certain extent by identifying parents on the basis of combining ability tests (Line × Tester, diallel) for selection of parents. This was well evidenced in the production of MAWA hybrids (Malayan Dwarf × West African Tall) in Côte d'Ivoire. Bourdeix et al. (2016) estimated a 20–30% genetic gain when seven to 8% of parents are selected. Dwarf × Tall crosses are many a times preferred because of the advantage of using comparatively homozygous dwarfs as mother palms. The feasibility of identifying genetically pure mother palms through the use of molecular markers like SSRs has also been indicated (Regi et al. 2015). In India, diallel analysis involving 16 parental lines indicated Gangabondam Green Dwarf (GBGD) and Laccadive Ordinary Tall (LCT) to be good general combiners, and LCT × GBGD was identified as the combination with the best specific combining ability for copra and nut yield (Nair et al.

Fig. 4.2 D × T coconut hybrid. (Photo: KUK Nampoothiri)

2016). A number of hybrids have been produced by crossing different dwarf and tall cultivars originating from various geographical regions. In India, West Coast Tall × Chowghat Orange Dwarf (COD) and Chowghat Green Dwarf (CGD) and their reciprocals also showed their superiority in precocity and yield. Although both T × D and D × T hybrids are high yielding, D × T has certain advantages such as short stature of mother palms facilitating easier emasculation and pollination as well as easiness in identifying hybrid seedlings, especially if COD is used as the mother palm.

It may, however, be pointed out that farmers often express some concern about these hybrids in terms of bunch buckling, high input requirement, as well as vulnerability to moisture stress and pests and diseases (Batugal et al. 2009). Since the performance of hybrids vary with the environment, they are usually tested in various locations within the country using local cultivars as control before their release for cultivation. COGENT facilitated hybrid multilocation trials involving three African countries and three Latin American and Caribbean countries resulting in the identification of 19 early bearing and high-yielding coconut hybrids (Batugal et al. 2009). Hybridisation involves selection of parent palms, emasculation of mother palms, pollen collection from male parent, pollination and bunch-wise harvest. For details, please see Menon and Pandalai (1960) and Ohler (1984).

In India, 19 hybrids with a potential for high yield and possessing other desirable characters have been released. The best among them yield as much as 167 nuts palm^{-1} year $^{-1}$equivalent to 6.28 mt copra ha^{-1} year^{-1} as compared to 80 nuts palm^{-1}year $^{-1}$ and 1.5 t copra ha^{-1} year^{-1} realised from the local WCT. Details of certain hybrids released in India are given in Table 4.3.

Apprehension is often raised on the longevity of the hybrids. It is now known that yield of hybrids does not decline even after 80 years as is evidenced from the performance of hybrids planted as early as in 1935 in India. The hybrids can be further improved using information on the individual combining ability and by exploiting within population variability (Gascon and Nuce de Lamothe 1976). It was possible to improve the yield of PB121 hybrid from 15% to 25% in just one generation of half-sib mating (Batugal et al. 2009).

Table 4.3 Performance of released hybrids in India

Hybrid	Parents	Important traits	Nut yield (number ha^{-1} $year^{-1}$)	Copra yield (mt ha^{-1} $year^{-1}$)	States for which recommended
Chandra Sankara	COD × WCT	High yield	20,532	4.27	Kerala, Karnataka, Tamil Nadu
Kera Sankara	WCT × COD	High yield, drought tolerant	19,116	3.78	Kerala, Karnataka, Maharashtra, Andhra Pradesh
Chandra Laksha	LCT × COD	High yield, drought tolerant	19,293	3.76	Kerala, Karnataka
Kalpa Sreshta	MYD × TPT	Dual purpose variety, High yield	29,227	6.28	Kerala, Karnataka
Kalpa Sankara	CGD × WCT	Tolerant to root (wilt) disease, high yield	14,868	3.2	Root (wilt) disease prevalent tracts of Kerala
VHC-4	LCT × CCNT	High yield	28,497	4.27	Tamil Nadu
Vasista Ganga	GBGD × PHOT	High yield	22,125	3.88	Andhra Pradesh, Karnataka
Ananta Ganga	GBGD × LCT	High yield	22,656	3.84	Andhra Pradesh, Karnataka
Konkan Bhatye coconut hybrid 1	GBGD × ECT	High yield	20,532	3.47	Maharashtra

Source: Regi J Thomas et al. (2016)

Though most commercial hybrids are D × Ts, and T × Ds, certain T × T hybrids have a comparable potential. They are more suitable as a main crop for intercropping and offer better prospects for long-term genetic progress. So far, Thailand is the only country where T × T hybrids have been released to farmers (Anupap et al. 1992). D × D crosses are not very popular among coconut breeders, but more than 40 crosses are being evaluated in Côte d'Ivoire and Malaysia since 1993. An important feature of D × D hybrids is their high genetic homogeneity, since the two dwarf parents are close to being pure lines (Batugal et al. 2009). Hybrids have been recovered even from open pollinated progenies. Komadan, a variety identified and perpetuated by a farmer family in Kerala, India, is a typical example. These are rare recombinants (10–15%) arising due to the natural crossing of Chowghat Orange Dwarfs with the neighbouring talls and hence called NCDs (natural cross dwarfs), identified at the seedling stage itself, primarily by their typical bronze colour of the petiole and high vigour. Studies have shown that Komadan has maintained its genetic identity over generations with respect to economically important characters like copra and oil content which reflects its prepotent nature (Satyabalan 1956; Ninan and Satyabalan 1964).

The PB series of hybrids were produced in Côt d'Ivoire. Comparisons made between plantations consisting of PB121, PB111 and 141 with local West African Tall (WAT) showed that the hybrids were superior for precocity, number of nuts and copra content (80% higher) than WAT (de Taffin et al. 1991). In Sri Lanka CRIC 60 (Tall × Tall) and CRIC 65 (Yellow Dwarf × Tall), yielding higher number of nuts with higher copra content, have been recommended for cultivation. A large number of hybrid combinations have been field tested in India, the Philippines, Indonesia, Sri Lanka, Côt d'Ivoire and Jamaica using local talls and dwarfs. More than 400 hybrids were developed till 1993, worldwide under established coconut improvement programmes using various breeding strategies (Batugal et al. 2009). The technology gap between average yield in farmers' fields and that of research stations in 15 coconut-growing countries, in terms of nuts or copra yield, was estimated to be 33–84% (Batugal 2005). However, these results have to be viewed in the light of the environmental influence on yield of coconut. Recent developments in biotechnological tools have resulted in considerable advancements in the identification of parental lines and hybridity testing (Preethi et al. 2016).

4.4.1 Seed Gardens

As hybrids became popular among the farmers, the demand for planting material increased phenomenally, and it was not possible to meet even a portion of the demand, which leaves the farmer with no other alternative than to plant materials of uncertain quality from various sources. In India, for example, the annual production of quality planting material from authentic institutions is only 4.2 million as against a demand of around 14 million coconut seedlings (Jayasekhar et al. 2016). The reasons for limited hybrid seed production are many, such as inadequacy of mother palms, cumbersome procedure for hand pollination of individual palms and low multiplication rate. This is one of the primary reasons for the poor coverage of area (0.1–14%) under hybrids. It is estimated that on an average, the hybrids represent only <3% of the 10 to 20 million coconut palms planted yearly worldwide. Establishment of accredited nurseries involving registration of mother palms as well as certification of seedlings is one of the ways to improve the situation. This should be read with the fact that the estimated coconut technology gap in terms of nut and copra yield ranges from 33% to 84% (Batugal and Bourdeiux 2005).

Establishment of seed gardens was suggested to circumvent the issue of inadequacy of hybrid planting material. The first isolated seed garden in the world was established in Sri Lanka at Ambakalle in 1955, for producing seed nuts of local talls. Seed gardens using inter se mated progenies of selected talls and pure dwarfs were later established in that country during 1959 (Peries 1993b). In Côt d'Ivoire, seed gardens were established with West African Tall and Malayan Yellow Dwarf in a 1:5 ratio, talls being considered only as a pollen source. But it did not have scope for any flexibility, restricting production of only D × T hybrids. Therefore, it was replaced by a more flexible system. Seed gardens came to be planted with only mother palms, isolated to avoid pollen contamination. Pollen from the desired male parents is dusted on to the inflorescences of the mother palms, which has already been emasculated. Several combinations with dwarfs as female parent can be produced in this system. In India, seed gardens were established in different states, including the isolated one in a forest where selected progenies of West Coast Tall and Laccadive Ordinary were planted in two separate blocks. Chowghat Orange Dwarf and Gangabondam were planted in adjoining rows of the talls in such a way that the two rows of talls and dwarfs form a double hedge with every dwarf coming in the centre of the talls. It is possible to produce D × T, T × D or T × T hybrids by adjusting the emasculation of mother palms as per the requirement (Bavappa 1973). Absence of male sterile lines in coconut is a handicap in this effort.

Following the success of crossing inbred lines to evolve high-yielding hybrids in annual crops, efforts were made in coconut also to produce inbreds with very little success due to inbreeding depression. Four generations required to create 95% homozygous structures will need 25–60 years. Studies on first- and second-generation inbreds of 18 WCT palms showed that the selfed progenies were inferior to their grandparents and sibs, indicating depression from S_2 generation (Sukumaran Nair and Balakrishnan 1991). Results from inbreeding populations in Mapanget Tall for three generations in Indonesia showed that inbreeding depression was evident in all vegetative characters except plant height and number of leaflets (Novarianto and Miftahorachman 1991). Same was the experience with Markham valley Tall by Sugimera et al. (1994). Thus, the possibility of producing homozygous lines through inbreeding was dismissed.

4.5 Breeding Strategy

As none of the above-mentioned methods are foolproof, it is worthwhile to incorporate all the possible methods in evolving a hybrid. A general scheme, following the reciprocal recurrent selection (RRS) method, is indicated in Fig. 4.3 (Bavappa and Nampoothiri 1974; Nampoothiri 2016).

Here a procedure is described for the improvement of the D × T hybrids, as an example. Dwarf and tall coconut varieties (the base populations) show complementarities and good reciprocal combining ability. Hence, the tall population is improved in respect to the dwarf population, and this improvement is reciprocal for both. At each stage, mother palms in both the populations are selected carefully, and their progenies are produced (preferably by inter se mating). The best seedlings in the nursery are then selected to raise the parental palms for the next stage. For stage 2, parental palms are selected not only based on physical attributes but also based on the combining ability assessed on the basis of the performance of hybrid progenies. Inter se mated progenies of these selected parents are raised from which the best seedlings are taken forward to raise progenies. At each stage D × T hybrids can be distributed to farmers, in view of the time lag of 10–15 years for each stage. These steps are continued stage after stage so that the potential of the hybrids distributed

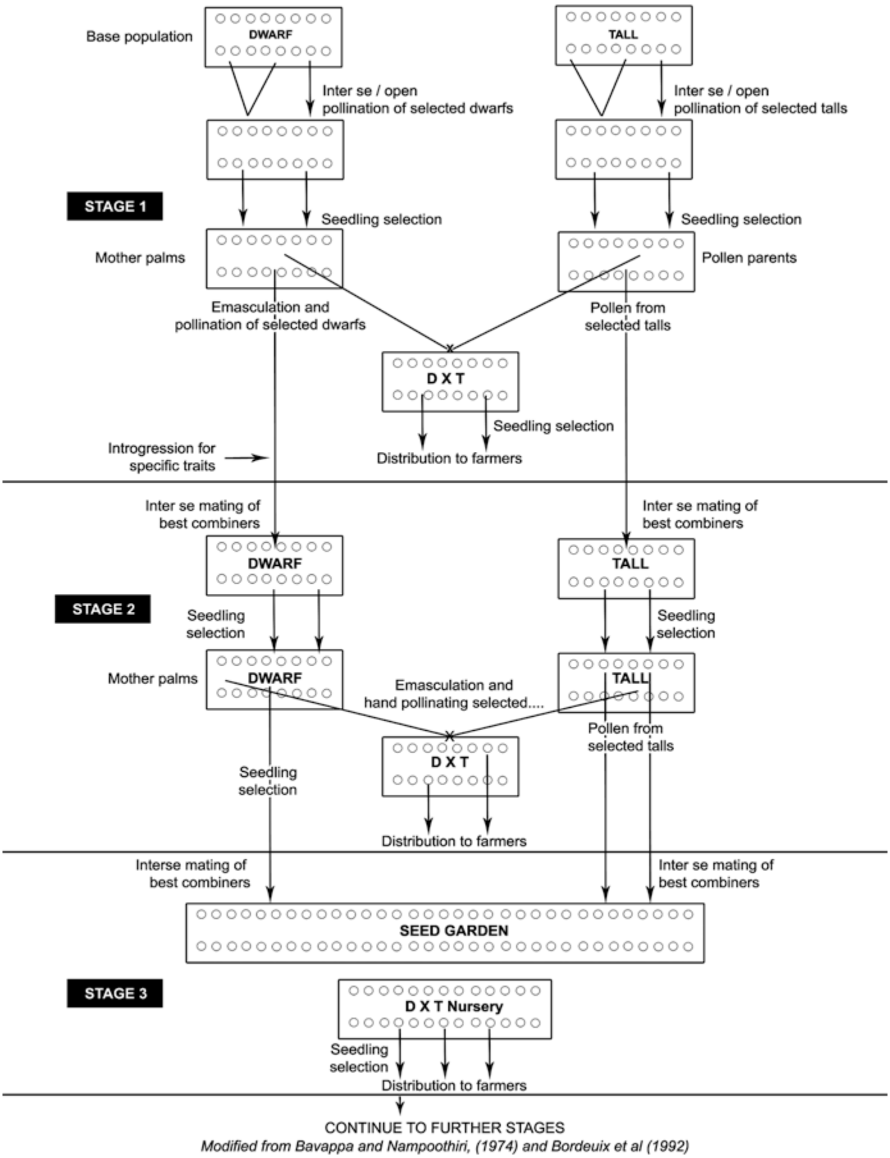

Fig. 4.3 Breeding strategy for D × T coconut hybrid production

gets higher and higher as the process continues due to the additional homozygosity as well as the improved genetic base of both the parents. To meet the increased demand of these improved hybrids, proper seed gardens have to be raised at stage 3. It is an open-ended system providing scope for introgression from desired sources identified during the programme. This only indicates a general scheme which can suitably be modified based on the local situations, additional information becoming available and the nature of populations available. Similar method can be adopted for other hybrid combinations, the major difference being in the selection of concerned base populations. Bourdeix et al. (1993) followed a comprehensive breeding scheme in Côt d'Ivoire for improving T × T and D × T hybrids. To be fully efficient, the RRS method requires the evaluation of at least 100 half-sib families per year. Including the hybridisation test, the selfing and the intercrossing of the parent palms, this would require planting of at least 100 ha each year for field experiments. This level of activity was reached in Côte d'Ivoire in the 1980s and in the Philippines in the 1990s. Currently, there is no research programme allocating such levels of resources to coconut breeding, which is a matter of concern (Batugal et al. 2009).

4.6 Complex Hybrid

A coconut hybrid with another hybrid or a variety is called a complex hybrid. While F_1 hybrids have helped in varietal improvement to a great extent, the method limits a complete exploitation of polygenic recombinations of crosses. Therefore, efforts were made for testing multiple crosses to develop varieties with desirable multiple characters. Harries (1991a) suggested the production of three-way hybrids using D × D, D × T or T × T crosses. Some plantations with composite characters could be exploited for nuts or for hybrid seed nut production depending on the demand. A three-way cross MYD × (WAT × RAT) planted in Côte d'Ivoire in 1976, under average management, yielded only 77% more than the WAT. In the 1990s, three-way hybrids (D × T) × T and (T × T) × D were produced in Thailand, which is not known to have reached a logical conclusion (Petchpiroon and Thirakul 1994). The first experiment testing of complex hybrids was established in Côte d'Ivoire in 1976 (Bourdeix et al. 1993), essentially searching for exceptional coconut palms that could be propagated rapidly, when a method of vegetative propagation would become operational. However, successful coconut in vitro propagation technique has not been developed hampering the aim of this experiment (Batugal and Bourdeiux 2005).

Complex hybrids between dwarf varieties were produced in Côte d'Ivoire in the lethal yellowing disease-resistant programme (Batugal et al. 2009). However, no breeding programme went further than the second-generation (D × T) × (D × T) or (D × D) × (D × D) since the 1990s, except in the Philippines which aimed to develop Makapuno Dwarf autogamous varieties involving Makapuno Tall and normal dwarf varieties (Nunez and de Paz 2004). One could hope to have hybrids with genes from many accessions in the future.

4.7 Synthetic Variety

Synthetic variety is an open pollinated variety purposely created to be more adaptable and stable over many generations due to its wide genetic base. Breeding for a synthetic or a composite coconut variety (CCV) has been first proposed in India and Sri Lanka. Subsequently, more attention was given to the development of CCV by Santos (1990) and Santos and Rivera (1994) in the Philippines. Philippine Coconut Authority (PCA) started work on synthetic variety in 1979. A base population of palms having a high degree of balanced heterozygosity was produced, and a breeding scheme was developed that would allow individual palms to mate at random and maintain high heterozygosity from generation to generation. Single crosses of six tall coconut cultivars and varieties, four local and two exotic ones, which had good combining ability were used. The intercrossed or open pollinated nuts from the first-generation constituted the second-generation synthetics, with no considerable loss in yield (Anon 2006). This hybrid as well as its open pollinated progenies was distributed to farmers as Complex Coconut Varieties (CCV).

San Ramon Orgullo Tall is a synthetic variety developed from a combination of 15 different coconut hybrids in the Philippines. (Please see Sect. 4.11 Global scenario in this chapter.) In spite of its simplicity, this method has some disadvantages. Though synthetic varieties are expected to have more stability and wider adaptability due to the involvement of several selected parents, compared to single cross hybrids, one major constraint in developing synthetic varieties in coconut is that the poly genes controlling the many desirable characters may attain an equilibrium only after many cycles of inter mating since inbreeding to purify parental lines is not possible to be resorted to (Batugal 2005). They are likely to be less productive than the best F_1 hybrid that could be made from the parental varieties. Though planting material can be reproduced by open pollination by the farmers themselves, the progenies will progressively become less productive because of pollination from the many coconut varieties planted in the garden, as is the usual practice of most of the farmers. Currently, there are very few countries evaluating multiple crosses to develop varieties with desirable multiple traits. Induction of mutation and polyploidy has also been experimented in India, though on a very limited scale, without any worthwhile result.

4.8 Genetic Studies

Genetic studies, which are very helpful in designing breeding strategies, have been few in coconut, for inherent reasons already explained.

4.8.1 Genetic Variability

Genetic variability among individuals of a variety or population of a species results from the many genetic differences between individuals and may manifest in differences in DNA sequence, in biochemical characteristics (e.g. in protein structure or isoenzyme properties) or in physiological properties (Ramanatha Rao and Hodgkin 2001). Nut yield, copra weight, copra yield, whole nut weight and husked nut weight have shown high heritability and genetic advance (Ganesamurthy et al. 2002; Thomas and Gopimony 1991b; N'Cho et al. 1993). Generally, economic characters showed higher genotypic coefficients of variation (16–22%) compared to vegetative and reproductive characters. Among the many characters, heritability was the highest for petiole length (52%), followed by 45% for both oil content and nut yield (Sindhumole and Ibrahim 2000a). Since such characters may be controlled by additive genes, pure line selection could improve them. On the other hand, characters like oil content, diameter of husked nut (polar as well as equatorial) and thickness of meat had high heritability coupled with low to moderate genetic advance as percentage over mean. This indicates nonadditive gene action which could be exploited by resorting to heterosis breeding. Discriminant function analysis showed husk: nut ratio, followed by thickness of meat and oil content to have more positive weight. The relative efficiency of selection based on discriminant function analysis was more rewarding compared to direct selection. Repeatability coefficients obtained by the variance analysis and structural analysis (correlation) showed the smallest values for fruit and solid albumen production. Considering the repeatability estimates by the main components method (covariance), five and three evaluations could be recommended for fruit and solid albumen production, respectively (Farias Neto et al. 2003). Prabhakaran et al. (1991) reported that selection for number of leaves and leaf production rate at early stages would quicken genetic improvement. They indicated that selection for nut yield can be effectively done, as early as in sixth year after planting, on the basis of number of functioning leaves. Varagas and Blanco (2000) in Costa Rica, evaluated tall coconut cultivars from Pacific coast of Costa Rica and the Philippines (San Ramon, Tagnanan and Laguna) for fruit characteristics. He found that most of the introduced cultivars showed high heterogeneity. A cluster analysis, using the Ward method, classified the palms into four groups with high internal homogeneity. Some of the palms from the Costa Rican Pacific area had nut characters similar to the San Ramon and Tagnanan groups but not with Laguna group. At the association level used (semi-partial $R^2 = 0.10$), another group was constituted which included the remaining palms sampled from the area. Jayalekshmy and Rangasamy (2002) did cluster analysis and grouped 30 genotypes into six clusters, based on 20 morphological traits, including vegetative, inflorescence and fruit characters. All the dwarf cultivars were grouped into one cluster. Talls fell into three clusters. T × D hybrids came along with the Tall cultivars, and the D × T hybrids were clustered with dwarf cultivars. Laccadive Micro formed a separate cluster, where the intercluster distance was the highest. Andaman Giant and San Ramon which show distinguishable nut characters constituted a separate cluster. The nut characters were efficient in assessing genetic divergence. Their analysis indicated the possibility of obtaining promising progenies from the parents belonging to divergent clusters.

4.8.2 Correlations

From coefficient of correlations calculated involving 19 floral, vegetative and yield traits, Kalathiya and Sen (1991) suggested that the number of spadices and duration of female phase, which are correlated significantly with nut yield, could be used as selection criteria for nut yield improvement. A number of leaves and length of spadix were significantly correlated with number of spadices. The number of female flowers per spadix was also correlated with spadix length. The copra yield in coconut is reported to be strongly and positively correlated with nut yield, copra weight, kernel weight, whole nut weight and dehusked nut weight. The direct effects of dehusked nut weight, percentage of husk to whole nut weight, percentage of kernel to whole nut weight, copra weight and nut yield on copra yield were positive and high. These characters are to be given emphasis while selecting for copra yield improvement (Ganesamurthy et al. 2002). In a study of yield and its morphological and chemical components in low-, medium- and high-yielding types, Narayanan Kutty and Gopalakrishnan (1991) found that yield was correlated with total number of leaves on the palm (r = 0.69), leaf length (r = 0.68), N and K content of leaves (r = 0.42 and 0.61, respectively), total chlorophyll content (r = 0.63) and sugar content (r = 0.37). The correlation between yield and total phenolic constituents of the leaves was negative (r = −0.55). There was a marked direct effect of leaf length, K content and chlorophyll content on yield and a yield prediction model based on these traits showed 74% efficiency. The morphology of the palms in relation to nut yield has also been reported. In a study on WCT palms, the number of leaves in mother palms showed positive correlation with number of bunches, whereas number of nuts per bunch showed negative correlation with most of the nut and seedling characters (Thomas and Gopimony 1991a). High nut yield was associated with high stem circumference, many closely spaced short leaves with short petioles and a few broad leaflets as in the case of Pratap, a high-yielding variety released for cultivation in Maharashtra.

A total of 43 coconut germplasm accessions were characterised for nut yield and fruit component traits by Geethanjali et al. (2014). Fruit length, fruit breadth, fruit weight, nut weight, kernel weight and copra weight nut^{-1} were found to be positively correlated with each other but showed significant negative correlation with the number of nuts produced palm^{-1} year^{-1}; shell thickness and husk thickness were not correlated with any of the fruit components. Nut yield and copra content nut $^{-1}$ had positive direct effect on the total copra yield palm^{-1}. They argued that equal consideration should be given for both nut yield and copra content nut^{-1} while selecting elite genotypes.

Nampoothiri et al. (1975) reported phenotypic and genotypic correlations of nine characters with yield. Girth at collar of seedlings, time taken for flowering, spathe production and number of female flowers were found to be correlated with nut yield. There was significant genetic correlation between yield and number of leaves at seedlings stage. In a study on dwarf coconuts, Aragao (2000) worked out correlations between 15 pairs of phenotypic, genotypic and environmental characters. Fruit weight (FW), fibre weight (FiW), nut weight (NW), copra weight (CW), solid albumen weight (SAW) and liquid albumen weight (LAW) were the characters evaluated. Phenotypic and genotypic correlations, in general, were significant and positive (at one per cent level) between FW and FiW (0.97 and 0.98), FW and NW (0.74 and 0.76), FW and SAW (0.74 and 0.83), FW and LAW (0.53 and 0.52), FiW and NW (0.55 and 0.60), FiW and CW (0.42 and 0.38), FiW and SAW (0.60 and 0.75), FiW and LAW (0.36 and 0.37), NW and SAW (0.87 and 0.82), NW and LAW (0.77 and 0.0.79), CW and SAW (0.55 and 0.36) and SAW and LAW (0.41 and 0.31). The correlations were negative between CW and LAW (−0.47** and − 0.88**) and NW and CW (−0.14**and − 0.30). The results showed a strong association between these pairs of characters due to genetic effects. The strong and positive association noted between majority of these pairs of characters in the dwarf coconut should favour selection for these characters. Association between FW and CW (0.67**) and NW and CW (0.76**) was due to environmental effects. If selection is performed with the aim of increasing fruit and nut weight, the outcome is uncertain with regard to copra weight.

Path analysis has been used by some workers to understand the pattern of relationship between characters. Relationship of 12 traits with oil yield palm^{-1} was evaluated. A number of nuts palm^{-1}, fruit weight, kernel weight, copra weight, fruit quality value and oil content had marked effects on oil yield. A number of nuts palm^{-1}, fruit weight and kernel weight had considerable direct effects. Oil yield could be increased by direct selection for these three traits or by simultaneous progeny selection for nut palm^{-1} and fruit weight or oil content. In another study in India by Sindhumole and Ibrahim (2000b), it was revealed that reproductive characters exerted less influence on nut yield compared to vegetative characters. The effect of trunk height was the most prominent but was highly modified due to indirect effects through trunk girth and female flowers. Among the reproductive characters, female flowers spadix^{-1} had the highest direct effect, whereas, the direct effect of spadix production on nut yield was the lowest.

4.8.3 Stability

Coconut, being a perennial crop, should perform stably to get regular yield and hence the importance of studies on stability. Balakrishnan et al. (1991) studied stability in 32 cultivars grown at Pilicode, India, by non-parametric procedures using

20 year's yield data. The two non-parametric measures of stability used were mean of the absolute rank differences of the cultivar over the environments and variance among the ranks over the environments. Significant differences were found in the stability of cultivars. West Coast Tall, Java, Fiji, Laccadive Ordinary, Philippine Ordinary, Andaman Ordinary and Godavari were stable. Cochin China, S. S. Green and Laccadive Small were among the highly unstable cultivars, mainly as a result of their biennial (alternate) bearing tendency. When cumulative yield for 2 years was considered, varieties like Cochin China, S. S. Green, Andaman Giant, Kappadam and Basanda were found stable although they were not stable in annual yield owing to irregular bearing. In another study in the Konkan region of India, the mean square due to environment + (genotype × environment) was found to be highly significant contributed by the sib components, environment (linear) and genotype × environment (linear). The population studied by them was free from the unpredictable component of interaction. On the magnitude of stability parameters, variety Pratap was the best genotype for general cultivation, whereas T × D (orange) and Benawali Yellow Round were better adapted for cultivation under fluctuating environmental conditions. Morpho-physiological variation and phenotypic plasticity in Mexican populations of coconut was reported by Daniel-Zizumbo and Colunga-GarciaMarin (2001). They studied the pattern of variation in 19 morphological and physiological characteristics of leaves and their phenotypic plasticity in 18 Mexican coconut populations experimentally grown under similar conditions and in the presence of lethal yellowing disease. They found five ecotypes, viz. Atlantic Tall; Pacific Tall 1, 2 and 3; and Malayan Yellow Dwarf, were differentiated by means and plasticity for these characteristics. The traits that best differentiate these ecotypes were the leaf length, number of leaves per unit time and percentage of proximal rachis in leaf. The ecotypes corresponded to the population groups previously observed in a study of morphological characterisation of fruit in situ. Diallel analysis in India with 36 crosses involving nine coconut cultivars of diverse origin showed that girth, height, total leaf production and leaf production during the year were significantly different among the characters studied. Laccadive Ordinary × amaica and Fiji × Jamaica exhibited, high specific combining ability (sca) effects for total leaf production and leaf production during the year. Laccadive, Jamaica, Java, Fiji and San Ramon cultivars proved as useful tall parents (Sukumaran 1982). Different values and relationships are reported by different workers, which leave the breeder with no other option than exercising selection for as many characters as possible which have shown positive correlation with yield in one study or the other.

4.8.4 Field Experiments

Timely collection of data and safe keeping of records for a long period are primary requirements for deriving meaningful results from coconut breeding experiments. The data once missed is lost forever. In the case of germplasm collection, passport data have to be recorded at the time of collection itself. Problems faced in coconut breeding trials are different from those of annual crops because of the long gestation period, height, perennial nature, larger area required, lack of uniformity in the experimental material, time lag between treatments and manifestation of effects, differences in pre-bearing age as well as yield realisation from harvests throughout the year. Measurements are usually taken right from the time of planting. The characters recorded on seedlings are the height, girth at collar region, leaf splitting, number of leaves and leaf area. Thereafter annual measurements are made on juvenile characters, and the date of emergence of the first inflorescence is noted when the palms come to bearing. Performance of palms is measured based on number of bunches, number of nuts, size of nut, copra content, copra weight, other nut characters and oil percentage (based on laboratory estimates). The annual yield increases progressively as the palms grow and therefore the actual assessment is possible only when the yield stabilises, i.e. in 8–10 years. Coconut palms are generally harvested 8 to 12 times a year, the number of nuts obtained being different in different harvests. Therefore the cumulative figure from all the harvests in a year is considered as nut yield. While it is possible to monitor each of the harvests and get data of annual yield in research stations and well-maintained farms, it is not feasible when palms are to be evaluated in cultivators' gardens or when an assessment has to be made in an unknown population (for germplasm collection, etc.). In such cases a reliable estimate can be made by using the regression eq. $Y = -0.527 + 0.914\ x$ where y is the estimated annual yield and x is the count at the time of observation. One another problem is that many populations show annual/biennial bearing habit, giving high and low nut yields in the successive years. Analysis of mean yield for two consecutive years is recommended to reduce this error. Keen observations are also to be made on resistance to biotic and abiotic stress as well as special characters like nut water quality, etc., depending on the experimental objectives. In view of the seasonal differences in nut characters, a sample of two nuts is to be analysed six times a year for 4 years on 30 palms to get a reliable estimate of nut characters.

The most common design followed for breeding trials is randomised block design. All over the world, the number of palms used has fluctuated from <10 to over >140, depending on various local factors (Batugal et al. 2009). Marshall and Brown (1973) have estimated that 60–100 palms could represent a natural population of allogamous plants. The STANTECH manual recommends a minimum number of 96 palms for hybrid evaluation (Santos et al. 1996), which calls for resources unaffordable by many research organisations. Small plots with more number of replications are now preferred. Jacob Mathew (1991) found that a plot size of six to eight palms as adequate, though larger plots understandably, increase the accuracy. The number of replications is generally decided based on available experimental area, residual degrees of freedom required and the efficacy required for estimates. In addition to standard statistical considerations, effects of competition between palms in the adjacent plots should also be considered, which is overcome by providing at least one nonexperimental guard row.

4.9 Breeding for Special Characters

Although coconut is known for its multifarious uses, its potential has not been fully exploited except for yield of nuts, copra and oil. An expanded product range will help the crop in moving away from the vegetable oil sector, especially in view of the growing competition from other vegetable oils. There are varieties which possess special attributes. Their identification and use in breeding programme deserve breeder's attention. Selection of the trait will depend on the market demand and availability of the local variability.

4.9.1 Tender Coconut

Tender coconut water is recognised as a health drink for a very long time, and it is becoming more popular with the present increased awareness on health. It is possible to use 20–25% of the fresh nuts to satisfy the domestic demand, the tender nuts often receiving a better price than mature nuts (Nampoothiri 2017). This is apart from the scope for exports, Sri Lanka, Malaysia, Thailand and the Philippines taking a lead in this. Suitable varieties will be those with better volume (say 350 ml nut^{-1}), sweetness (7 g 100 ml^{-1} of water) and good flavour of water as well as taste and consistency of kernel and mineral content, at the 7–8 months stage of the nut. Chowghat Orange Dwarf was released in India for large-scale cultivation as a tender nut variety (ICAR-CPCRI 2014). Galas Green Dwarf (Philippines), Nam Wan and Nam Hom-aromatic coconut (Thailand), Green Dwarf-BGD (Brazil) and Malayan Dwarfs and King Coconut (Sri Lanka) are some of the examples (Thampan and Gopalakrishnan 2010). Such varieties and even exceptional individual palms could be multiplied, and gardens could be established to produce inter se material for establishing further improved generations. In view of the increased demand for tender nut, certain private nurseries now concentrate their efforts in producing hybrids which are suitable for tender nut purposes, mainly using selected Malayan Dwarfs as mother palms. 'Pandan' an Aromatic Green Dwarf, in Malaysia, is preferred for fresh beverage, due to its special aromatic flavour. Brazil Green Dwarf (BGD) is also renowned for its very sweet tender nut water. Under proper management, BGD produces around 150 nuts palm^{-1} ha^{-1}, and about 59,000 ha of this cultivar are planted in Brazil annually. Both Aromatic and Brazil Green Dwarf are currently being improved in their respective countries (Batugal et al. 2009).

4.9.2 Toddy and Sugar

There are cultivars which yield 1.5–2.0 l of toddy palm^{-1}daily with a sugar recovery of 15%. Neera is the unfermented inflorescence sap, with good market scope. In Sri Lanka, the hybrids give 792 l of toddy year^{-1}. Thailand varieties such as Tha-le-Ba, Suricha, Sai Bua, Theung Bong, Kathi and Khi Kai yield up to 4 litres of toddy. These cultivars, if used for toddy tapping and sugar production, can give 7 to 10 times more income than from nut production. The employment opportunities are also increased due to this activity. Malayan Dwarfs yield up to 3.4 l of toddy daily. The toddy is reported to be sweeter than the one from talls. Dwarf varieties are at an advantage because of the easiness in tapping due to the small stature and the possibility of high density planting. It is also possible to use the same palm for tapping and nut yield. This can be done by using alternate spathes for tapping or tapping only the top portion of the spathe, leaving the lower portion for nut production (Thampan and Gopalakrishnan 2010). The low glycaemic index (35) of coconut sugar is an added advantage for health conscious consumers. Considering these facts, breeding varieties for toddy and sugar production and studies on economic feasibility of establishing gardens, especially with dwarf varieties, solely for this purpose deserve attention.

4.9.3 Husk

Production and marketing of coir and its products help to derive additional income and thus enable better stability to the coconut industry. In some of the countries like India and Sri Lanka, where coir industry has recorded substantial progress, production of husk attains special significance. There are varieties and hybrids which produce nuts with a higher proportion of up to 54% husk (Malayan Yellow Dwarf × Jamaica Tall). But unfortunately there is a proportionate reduction in the kernel component, to say 24%, in these cases. There has not been any concerted effort to evolve 'high husk varieties'. This has to be read with the fact that the available husk is not being fully utilised especially because of the predominance of scattered small holdings. It appears more logical to advocate breeding for varieties which produce nuts with a comparatively high husk (40%) as well as kernel components (30%).

4.9.4 Dwarfness

Dwarf coconut types have the advantage of reduced harvest cost and feasibility for high density planting. Developing compact dwarfs is another possibility in coconut breeding for which, apart from the identified dwarf cultivars, every dwarf mutants from natural populations can be used. Bourdeix et al. (2017) reported the presence of compact dwarfs in French Polynesia and the Cook Islands. One mutant identified in India from Lakshadweep coconut populations has shown extreme dwarfism compared to the dwarf cultivars available in the germplasm (Nair et al. 2016). Compact dwarf hybrids of MYD × NLAD have been developed in India (CPCRI 2013). The use of such dwarf progenies would help in changing the plant type enabling high density planting of coconut.

4.9.5 Makapuno Palms

Some palms exhibit unique features, though with limited distribution. Makapuno type (gelatinous mutant coconut) of the Philippines is a typical example. In this, a few tall palms produce characteristic nuts with soft- and jelly-like endosperm filling the entire cavity. While these are not good as mature nuts, they are considered as delicacies and have high demand in ice cream industry. This character is governed by a single recessive factor, and the palm which occasionally bears Makapuno nuts is heterozygous for the character. Two issues in their propagation are that only few nuts in a bunch show this special trait and that the nuts do not germinate. Its propagation is now possible through embryo culture. As they are found only in the Laguna Tall variety which are late bearers and highly cross-pollinated, embryo-cultured homozygous Makapuno palms are developed from these heterozygous Makapuno-bearing sources. At the National Coconut Research Centre in the Visayas, 4 Dwarf × Makapuno crosses have been developed. Homozygous Makapuno palms of the second and third filial generations have been derived from those hybrids. The homozygous palms were precocious (flowering in 26 months) and self-pollinated and gave high percentage of Makapuno nuts (Nunez and de Pas 2004). Although comparable varieties are known in many other countries, such as Sri Lanka, India, Cambodia, Thailand and Vanuatu, the Philippines' Makapuno is the most popular and economically important among the soft-endosperm coconuts. Kopyor coconut of Indonesia is a similar type, occurring to the extent of 24–38% of the harvested nuts. In India also tall coconuts with similar features, called 'Thairu Thengai' (curd coconut), have been identified since the 1930s.

4.9.6 Unique Forms

Sweet husked coconut palms (SWH) of Sri Lanka produce a special type of husk which is tender, edible and sweet. A fairly mature nut can be de husked with bare hands. Various surveys have shown that while most islanders are familiar with these SWH coconut palms, the palms are becoming increasingly scarce. It is currently very difficult to obtain any of their seed nuts, as immature fruits of these palms are eaten by children. Such types are seen in many Pacific islands also. Another interesting Thailand variety called Maphrao or fiddle sound box produces very thick nuts with three lobes. The shell of nuts from this variety is very thick and dense with three lobes making it suitable to be used to make sound boxes of the local fiddles. The fruits are sold at exorbitant prices. Unfortunately only a very few palms of this type are now in existence (Thampan and Gopalakrishnan 2010). The other types of importance are Kaithathali (soft, fleshy husk) and ornamental coconuts (Maphrapo Pradap of Thailand).

Some of these types possessing special characters may not be of immediate economic importance. But these varieties should be conserved, propagated and improved. It is the breeders' prime responsibility to see that these bio resources are preserved in nature foreseeing their economic importance in the future.

4.9.7 Disease Resistance

Unfortunately coconut production is seriously impaired in most of the major coconut-producing countries due to very serious diseases, whether it is root (wilt) disease in India, LYD in Central America and Africa, Cadang Cadang in the Philippines or Weligama Coconut Leaf Wilt Disease (WCLWD) in Sri Lanka. In the absence of any chemical cure, the only option left is evolving and planting resistant/ tolerant varieties.

The most popular variety-West Coast Tall (WCT) grown in India is highly susceptible to root (wilt) disease. A comprehensive screening of 84 cultivars and 68 hybrids during 1961–1988 did not yield any source for resistance (Regi et al. 2010). However, individual disease-free palms with high yield have been located in the midst of heavily disease-affected palms. Selected palms among these were inter se mated to generate more homogeneous tall parents. Very strict criteria such as freedom from root (wilt) disease, yield of 80 nuts palm^{-1} and absence of phytoplasma in the sieve tubes, among others, were considered for selection.

Later, comparatively higher level of resistance was observed in the Chowghat Green Dwarf (CGD). Field testing of CGD × WCT hybrids was therefore undertaken. The criteria used for selecting the CGD mother palms, identified from heavily disease-affected gardens (with at least 80% disease affected palms), were good yield (>100 nuts palm^{-1} year^{-1}), freedom from the disease and age (more than 15 years). Individual inflorescences were artificially pollinated using pollen from selected disease-free WCT palms. These hybrids were found to be early bearing and semi-tall in nature giving a 10-year cumulative average yield of 84 nuts palm $^{-1}$ year^{-1} equivalent to 2.5 mt of copra ha^{-1}. Though after 18 years of planting, 67.7% of the palms showed root (wilt) disease symptoms, the disease-free hybrids gave an average yield of 107 nuts palm^{-1} year^{-1} compared to 72 nuts from disease-affected hybrid palms. Considering the high yield and resistance/tolerance to root (wilt) disease, three coconut varieties, viz. Kalparaksha (MGD), Kalpasree (CGD) and Kalpa Sankara (CGD × WCT), were released for cultivation in root (wilt) affected areas. Genomics approach to amplify putative RGAs from the coconut root (wilt) disease-resistant cultivar, Chowghat Green Dwarf, by Rachana et al. (2016) indicates the scope of using biotechnological tools in resistance breeding (Nair et al. 2016).

Warwick et al. (1993) found none of the eight varieties tested to be resistant to Lixas and leaf blight in Brazil, though Polynesian Tall, Rotuma Tall and Tonga Tall performed better. Lethal yellowing disease is a very serious disease devastating large areas of plantations in many countries, and identification of possible resistance at field level was started from early years (Whitehead 1968). Maypan hybrid (Malayan Dwarf × Panama Tall) claimed to possess resistance to LYD later broke down. A hybrid between Vanuatu Tall and Sri Lankan Green Dwarf is reported to be resistant to LYD in Ghana (Wikipedia 2016). One recently selected cultivar in the Philippines – the 'Maypan' – is identified as resistant to lethal yellowing disease. Brazil Green Dwarf × Panama Tall (Brapan hybrid) and Malayan Yellow Dwarf (Maybraz hybrid) as well as hybrids between Malayan Dwarf Yellow with many local varieties are being field tested against LYD in Jamaica (Coconut Industry Board 2016). 1500 lethal yellowing-resistant coconut plantlets from Mexico are reported to have been added to Grenada's 'coconut stock' under the coconut rejuvenation programme (Harries 2016). In all the countries the dwarfs, especially the Dwarf Green, have been found to be the source of resistance and the need for in depth investigations on this variety with respect to disease resistance needs no over emphasis.

4.9.8 Pest Resistance

Among the many pests attacking **c**oconut, only a very few such as rhinoceros beetle, leaf-eating caterpillar, eriophyid mite and red palm weevil cause major economic losses. No pest-resistant variety or hybrid has so far been developed, maybe because there are satisfactory control measures available. However differences in the severity of pest attack have been reported in a few varieties. Preliminary screening of cultivars and hybrids against leaf-eating caterpillar (*Opisina arenosella*) and rhinoceros beetle (*Oryctes rhinoceros*) indicated variations in susceptibility among cultivars, though no resistant cultivar could be observed (Kapadia 1981; Sumangala Nambiar 1991). Greater tightness between the nuts and the petals seen in round rather than elongated and angled nuts offers better resistance to the eriophyid mite, *Aceria guerreronis* (Moore and Alexander 1987). In India, Chowghat Orange Dwarf and Kulasekharam Green Tall (derived from Malayan Green Dwarfs), were found to be less prone to mite infestation, whereas WCT and Laccadive Micro were highly infested (Nair 2000). Molecular studies have shown positive indications on the possibility of selecting varieties resistant to *Aceria* mite infestation.

All the coconut cultivars are prone to damage by rhinoceros beetle, the hybrids with Chowghat Orange Dwarf as pollen parent being more susceptible (Nambiar 1988). Sosamma et al. (1988) reported Java Tall, Klapawangi Tall, Kenthali and Andaman Giant Tall as more tolerant to burrowing nematodes. For details, please see Chap. 5 on varietal resistance.

4.9.9 Drought Tolerance

With coconut being, by and large, a rain-fed crop, long dry spells adversely affect the yield to the extent of 50%. Under this circumstance, developing drought-tolerant varieties/hybrids are of great importance to increase coconut production. Screening coconut germplasm and its evaluation in drought-prone areas would take a very long time. A better option would be to use phenotypic and the physiological parameters for selection, as has been demonstrated by Naresh Kumar et al. (2006). A cultivar with more roots and a fine root density is less affected by drought (Cintra et al. 1993). Physiological traits such as leaf stomatal frequency, stomatal index, chlorophyll fluorescence, epicuticular wax content, lipase activity and proteases are reliable parameters for the identification of drought-tolerant coconut cultivars (Rajagopal et al. 1988; Repellin et al. 1994). Rajagopal et al. (2005) found that talls and hybrids (with talls as mother palms) had better drought tolerance than the dwarfs and the hybrids (with dwarfs as mother palms). Federated Malay States, Java Giant, Fiji, Laccadive Ordinary, Andaman Giant, Laccadive Ordinary Tall × Chowghat Orange Dwarf and Malayan Yellow Dwarf × West Coast Tall were identified as drought-tolerant varieties in India (Kasturi Bai et al. 2006; Rajagopal et al. 2005). For details, please see Chap. 9 on Physiology and Biochemistry.

4.9.10 Cold Tolerance

Coconut prefers a typical tropical climate. However it is planted even in regions like Assam in India where comparatively cold climates are experienced. Kamrupa, a selection from Assam Green Tall, is considered as a suitable variety for such regions. It is characterised by a yield of 16.34 kg copra palm^{-1} year^{-1}, 64.5% oil and tolerance to high rainfall (>2000 mm year^{-1} and cold weather – where temperatures goes below 8 °C in winter (Chaudhury et al. 2001). There are varieties which can thrive in cooler temperatures in the island of Hainan, China. However, work on cold tolerance aspect is very limited, obviously because of the smaller area under cultivation in this situation.

4.9.11 Ideotype

Idiotype refers to an ideal coconut palm possessing all the desirable characters apart from the yield and yield attributes, as a result of increased physiological efficiency. Palms should have a good architecture possessing an open crown with a horizontal orientation of leaves rather than the one with drooping or erect crown (Iyer et al. 1981). They are high regular yielding palms with good nut characters and possessing other favourable characters such as dwarfness, early bearing and tolerance to unfavourable conditions such as drought, diseases and pests. Moreover it should be able to perform in varied situations (universal/plastic variety) with steady production predictable with least fluctuation (Wikramaratne 1993). Such an ideal palm is a dream of every breeder. While the theoretical concept is appealing, it is easily said than done as there are no donor varieties available for developing such idiotypes and combining as many good characters as possible is the only alternative, no matter the large number of years which may be required for such an effort.

4.10 Biotechnology

There are five major areas of biotechnology which are directly useful for coconut breeding, viz. micropropagation through tissue culture, embryo culture, molecular markers, cryopreservation and genome sequencing. The primary goal of tissue culture is production of uniform elite palms. Plantlets have been regenerated using plumular explants and successfully established in the field (Raju et al. 1984; Karun et al. 2016). Eeuwens and Blake (1978) obtained initial success using inflorescence tissue for callus production. But a repeatable and commercial protocol using adult palm explants is yet to be developed, since coconut palm is highly recalcitrant to in vitro manipulations (Iyer and Parthasarathy 2000).

A simple protocol from field collection of embryos to field establishment was standardised at CPCRI (Karun et al. 2004). This has been used for germplasm collection from the Indian Ocean islands of Mauritius, Madagascar, Seychelles and Sri Lanka. Karunaratne et al. (1991) studied the feasibility of developing an in vitro technique for screening drought tolerance. PCR-based molecular markers are being used in screening parents for the Weligama Coconut Leaf Wilt Disease (WCLWD) resistance programme in Sri Lanka (Lalith Perera 2014). Molecular markers are useful in differentiating varieties and genuine hybrids. This would therefore help in characterisation of varieties and eliminate duplicates in germplasm collections (Rajesh et al. 2012, 2014). Genetic mapping will be of immense value in selection of coconut palms for conventional breeding (Rohde et al. 1999). In vitro conservation techniques such as cryopreservation of both coconut zygotic embryos and pollen have been standardised, and these would enable long-term storage of coconut germplasm at a lower cost and reduced space (Karun and Rajesh 2007; Sajini et al. 2006). Only a few research institutes worldwide such as ICAR-CPCRI, Kasaragod; CCRI, Sri Lanka; PCA, the Philippines; and CIRAD, France are still engaged in serious biotechnological research. The breeding programmes will get a boost if and when the whole genome sequencing of coconut becomes available (Jaccoud et al. 2001). Please see Chap. 6 for details on Coconut Biotechnology.

4.11 Global Scenario of Coconut Breeding

The coconut breeding work in India has been adequately detailed in the foregoing sections. The work in other major coconut-growing countries is briefed below, though they all follow more or less the same pattern.

4.11.1 Sri Lanka

As per legends coconut palms were introduced to Sri Lanka as early as in 137 B.C. Selection from tall coconut palm population right from 1930 resulted in the identification of elite palms producing 100 nuts palm^{-1} year^{-1} with 220 g copra nut^{-1}, under average conditions. The tall form of coconut, San Ramon, was introduced from the Philippines and was established in the north western province. Open pollinated seeds of this form the base material for the current genetic improvement of San Ramon. This cultivar has the potential to produce 51% more copra nut^{-1} than the local talls. Tall × Tall (CRIC 60) and Dwarf × Tall (CRIC 65) were released for planting during the 1960s. Seed gardens were established to produce larger number of hybrids (Liyanage 1996). Two more hybrids, viz. Sri Lankan Tall × San Ramon (CRISL 98) and Sri Lankan Green Dwarf × San Ramon (Kapruwana), were produced in 2004. A seed garden has been established to mass produce the former hybrid. A new variety of dwarf with brown nuts, petioles and inflorescence has been identified, named Sri Lanka brown dwarf, which is superior to other forms of dwarf in the country in terms of kernel weight and tolerance to moisture stress (Perera et al. 2002). Crosses between Brown Dwarf × Sri Lanka Tall, its reciprocal as well as Brown Dwarf × San Ramon were made in 2003. Their performance till the ninth year in multilocation trials indicates that they are promising (Gopalakrishnan 2012). Added emphasis is now given to produce varieties resistant to Weligama Coconut Leaf Wilt disease (WCLWD).

4.11.2 Bangladesh

BARI Narikel-1 and BARI Narikel-0.2 (selections from local talls), producing 65 to 70 nuts palm^{-1}, have been recommended for cultivation. Hybrids involving CRI 60 and Malayan Dwarf are being produced by BARI (Bangladesh Agricultural Research Institute) (Nazrul and Amzad Hussain 2000).

4.11.3 China

In China, because of the cold weather, coconut palms can grow only in the country's southern parts, mainly in Hainan Province, parts of Yunnan Province and in Guangdong Province. A few coconut palms are sporadically distributed in Guangxi Province in the southwest and Fujian Province in the southeast. The only recommended hybrid is Malayan Yellow Dwarf (MYD) × Local Hainan Tall (HAT). This hybrid (WY78F1) is early flowering (3–4 years) and gives three- to fourfold increase in nut yield (80 palm $^{-1}$ year^{-1}) and copra (4 t ha^{-1} year^{-1}). The Wenchang Coconut Research Institute is the agency for taking up coconut research in the country (Tang and Ma 2005).

4.11.4 Philippines

Coconut breeding is undertaken at the Philippine Coconut Research Institute (PHILCORIN). Large quantity of planting materials becomes necessary when millions of palms are destroyed by typhoons like Haiyan. Important planting materials used are Genetically Multi-Ancestored Farmers' Composite Variety, Tacunan Green Dwarf (TAGD), Tutupaen Tall (TTPT), Tangnanan Tall (TAG), Bago Oshiro Tall (BAO, PCA 15-9), Tacunan Green Dwarf × Tagnanan Tall (TACD × TAGT) , PCA 15-4, Catigan Green Dwarf × Tagnanan Tall (CATD × TAGT) and Makapuno (embryo-cultured seedlings). Out of the nine hybrids recommended for cultivation by the Philippine Coconut Authority (PCA), MRD × TAGT (PCA 15–2) and MRD × BAYT (PCA15–3) have been outstanding, giving the highest number of nuts (144 to 155 palm^{-1}) and copra yield (6 mt ha^{-1}). The local tall BAYT was also comparatively good, producing 114 nuts palm^{-1} with a copra yield of 5 mt ha^{-1}. Galas Green Dwarf (GALD) is recommended for tender coconut purpose.

Dwarf × Tall F_1 coconut hybrids are popular because they bear fruits early, give high yield and recover quickly from stress. But due to various constraints, the hybrid did not become very popular, and therefore breeders have developed the Genetically Multi-Ancestored coconut farmers' variety (GMA farmers' composite variety) combining the agronomic qualities of four local tall varieties (Laguna, Bago Oshiro, Baybay and Tagnanan) and two foreign tall varieties (West African and Rennell). This composite variety combines high yield, precocity, vigour and genetic stability. It has a potential to yield two to four tonnes of copra ha^{-1} year^{-1}. Unlike the F_1 hybrids, coconut farmers can use this composite variety as a source of seeds for successive generations (PCA 2016). Seed gardens are maintained to support the long-term coconut planting/replanting programme. San Ramon is a tall variety (native to one of the islands known by the same name) characterised by very big nuts, giving up to 500 g copra nut^{-1}. San Ramon Orgullo Tall is a synthetic variety developed from a combination of 15 different coconut hybrids. It starts flowering in 3.5–5 years and produces 17 bunches in a year (Santos and Rivera 1994). One ha can yield 3.2 to 6.7 mt of copra, which is much more than that of local talls. Other aspects of work undertaken are embryo culture multiplication of Makapuno, establishment and management of coconut field gene bank, cryopreservation, biotechnology and tissue culture.

4.11.5 Indonesia

The first survey for coconut germplasm was conducted in the beginning of 1930. Unfortunately the activities were discontinued till 1973 due to financial constraints. From intensive surveys carried out later, 98 collections were made which are maintained at the Coconut Research Institute. Several dwarfs, talls and hybrids were also introduced from Côte d'Ivoire (Yohannes and Sumardjan 1993). Pati Dwarf Kopyor coconut originated from Pati (Central Java) is one of the local coconut populations in Indonesia. Three varieties, viz. Kopyor Green Dwarf, Kopyor Brown Dwarf and Kopyor Yellow Dwarf, have been released in 2010 as superior varieties. The estimated yield of nuts palm^{-1} year^{-1} is much higher than that of Kopyor Tall coconuts. Four improved intra-varietal hybrids (Kelapa Baru or KB1, KB2, KB3 and KB4) produced by crossing selected tall cultivars have been released. The hybrids started flowering in the sixth year, with 16 bunches year^{-1}, 96 to124 nuts palm^{-1} year^{-1}, 3.88

to 4.66 mt copra ha^{-1} and oil content of 67–71%. Three D × T hybrids evolved from the local material: Khina 1 (Nias Yellow Dwarf × Tenga Tall), Khina 2 (Nias Yellow Dwarf × Bali Tall) and Khina 3 (Nias Yellow Dwarf × Palu Tall) have been released. These hybrids have been found to be superior to the parental types with respect to precocity for bearing and high production of copra (Maskromo et al. 2013).

4.11.6 Thailand

The most common variety is the local tall although hybrids are being produced since 1982. The Chumphon Horticulture Research Centre (CHRC) of the Horticulture Research Institute of Thailand recommends Chumphon hybrid No.60 (Thai Tall × WAT) and Chumphon No.2 (MYD × Thai Tall) for cultivation since 1987 and 1995, respectively. These hybrids give nut and copra yields ranging from 80 to 126 nuts palm^{-1} and 3.4 and 4.2 mt copra ha^{-1}, respectively (Chulapan Petchpiroon 2000). Aromatic Green Dwarf is another popular special variety preferred for tender nuts having unique smell, sweet water and meat (Batugal 2005).

4.11.7 Malaysia

Studies from 1920s found that Malayan Green Dwarfs are robust and resistant to adverse conditions and produce 1.3 kg copra palm^{-1} year^{-1}, nearly as much as the average tall palm. MAWA hybrids (Malayan Yellow, Orange or Red Dwarf × West African Tall combinations) are less variable in terms of nuts palm^{-1}, fruit weight and copra weight and produce more copra than other hybrids. These MAWA hybrids have been used in the National Planting Programme since 1978. The Malayan Red and Yellow Dwarf × West African Tall have been found to be high yielding (25.82 and 24.98 kg copra palm^{-1}, respectively) and suitable for planting in the imperfectly drained but highly fertile coastal plains (Rethinam et al. 2005).

4.11.8 Vietnam

Ta is the most widely cultivated (79%) traditional tall variety, Dau and Giay are the other two tall varieties being commercially cultivated. Breeding work was initiated in 1984, with the introduction of 14 varieties and seven hybrids from Côte d'Ivoire, Sri Lanka, the Philippines and Fiji (Long 1993). The Vietnam Oil Plant Institute (OPI) is recommending seven introduced high-yielding hybrids, viz. PB111, PB121, PB 132, PB 141, JVA 1, JVA2 and CRIC 65 which have significantly outyielded the Ta local tall. Nut production was 48 to 69 palm^{-1} in 1996, as against 31–35 nuts by the Ta variety. Six local hybrids (Eo × Ta; Tam Quan × Ta; Tam Quan × BAOT; MYD × Rennel Tall; MYD × Palu Tall and MYD × Ta) are under field testing (Batugal et al. 2009). Among the local varieties, Ta, Dau and Giay have been identified as the best for copra making. A seed garden of 120 ha has also been established at Trang Bang, Tay Ninh Province for producing hybrids and seed material of local varieties.

4.11.9 Côte d'Ivoire

Coconut was introduced from Mozambique by Portuguese to West Africa in the early sixteenth century. Now it is cultivated in Côte d'Ivoire in about 50,000 hectares. Generally an average Ivorian coconut grove is composed of 48% hybrids and 52% West African Tall (WAT), which is the only local ecotype in the country (Konan et al. 2000). Coconut research was initiated in Port Bouet in 1950, by collection of accessions from republic of Benin. The outstanding hybrids identified are PB 213 (WAT × RIT), PB 214 (WAT × VTT), PB121 (MYD × WAT), PB 132 (MRD × TAT- Tahitian Tall), PB123 (MYD × RIT) and PB111 (CRD or Cameroon Red Dwarf × WAT). These hybrids flower very early (40–57 months after field planting) under Côte d'Ivoire conditions. They produce 100 to 132 nuts palm^{-1} year^{-1}which is 34–138% higher compared to WAT. Further, their copra yields ranged from 3.15 to 4.8 mt ha^{-1} or 86–135% more compared to WAT (Bourdeix et al. 2016). Two breeding schemes (Dwarf × Tall and Tall × Tall), using the recurrent reciprocal selection method, are adopted. The creation of complex hybrids and their clonal exploitation are expected to increase yield of copra considerably (De Taffin et al. 1991). The crop is under threat by Lethal Yellowing Disease especially since 2013. Therefore priority is now for production of hybrids involving tolerant varieties like Vanuatu Tall, Panama Tall, Sri Lanka Green Dwarf, MYD, MRD and Niu Leka Dwarf.

4.11.10 Benin

Most of the plantations in Benin are made up of 50- to 70-year-old West African Tall (WAT) variety. Breeding programme is handicapped due to poor genetic base available. PB 121 and PB 111 hybrids were found to outyield the local talls, though the yields are low, in general, due to poor environment. In 1989, promising varieties from Côte d'Ivoire were identified for collection and introduction, namely, Polynesian Tall (PYT), Rennell Tall (RT), Vanuatu Tall (VTT) and Malayan Red Dwarf (MRD) (Sanoussi 2016).

4.11.11 Nigeria

Since the vegetable oil demand is largely met from palm oil in the southern states (oil palm being native to the area) and ground nut oil in the northern states of the country, coconut had not been a popular crop in Nigeria, and obviously much attention has not been given to coconut research. A few introductions were made from India, Malaysia and Cameroon in 1966 and maintained in the germplasm. A comprehensive prospection was made in the southern states of the country which enriched the germplasm collection to 60 indigenous and 25 exotic accessions. Coconut research was intensified with the establishment of a substation at Badagry, Lagos state in 1976 (Nampoothiri 1982). Now hybrid seedlings are produced from Nigerian Tall and a mixture of Nigerian Dwarf, Cameroon Dwarf and Malaysian Dwarf. Evolving high-yielding varieties resistant to Awka wilt disease is a priority area in the breeding programme. The West African Tall (WAT) is the most extensively grown tall variety, giving up to 80 to 170 nuts palm^{-1} per year^{-1}. Two hybrid seed gardens have been established, one in Badagry and the other one near Benin city, to produce hybrid planting materials. Two rows of Malaysian, Cameroon and Nigerian Dwarf cultivars are planted to one row of tall palms in these gardens (Akpan 2016).

4.11.12 Ghana

All coconut cultivars in Ghana are considered to be at risk from the Cape St. Paul Wilt Disease (CSPWD), a lethal yellowing type of disease. Hence, the coconut breeding programme in the country is geared towards developing hybrids resistant or highly tolerant to CSPWD. There are 6 cultivars and 21 hybrids being tested in four locations. These varietal resistance trials are still under observation although some of the test materials were already infected by the CSPWD.

4.11.13 Tanzania

The Mikocheni Agricultural Research Institute (MARI) is currently testing six hybrids with the local East African Tall (EAT) as sole pollinator. Mother palms involved are from Malayan Green Dwarf (MGD), CRD, Pemba Red Dwarf (PRD), MYD, MRD and improved EAT populations. In addition to determining their yield performance, the F_1 progenies are also being evaluated for their resistance to lethal disease and tolerance to drought stress.

4.11.14 Mexico

Coconut research at the Instituto Nacional de Investigacion Agropecuaria Y Forestal is focused on developing hybrids resistant to lethal yellowing disease. Initial hybrids were mainly derived from crosses between MYD and improved Pacific Tall populations. Intra-population crosses of selected Pacific Tall were also done, and these are currently being tested.

4.11.15 South Pacific Region

Though composed of tiny islands, they all put together a substantial area (600,000 ha) with coconut. In Western Samoa and Tuvalu, there are seed gardens to produce hybrids of MYD as well as RMD × RLT to meet the demand for replanting programme. Cocoa and Coconut Research Institute (CCRI) carries out national research on coconut in Papua New Guinea. A good collection of varieties have been made, and it also hosts the International Gene Bank for the South Pacific. The tall and dwarf varieties in ICG are being used for breeding work. Malayan Red Dwarf and Malayan Yellow Dwarf × Rennell Tall are the ruling planting materials. One of the main programmes is production of Malayan Dwarf × Rennell Tall hybrids for replanting. There is a seed garden in Omuru for mass production.

In Fiji, a seed garden to produce MYD or RMD and RLT or Rotuma Tall (RTT) is functional. In Vanuatu, work started from 1962. The Vanuatu Research and Training Centre has produced hybrids involving the local cultivars, viz. Vanuatu Tall (VTT) and Vanuatu Red Dwarf (VRD), with the introduced varieties Rennell Island Tall (RIT) and Brazilian Green Dwarf (BGD). The Malayan Red Dwarf (MRD) × RIT was also produced. These hybrids as well as exotic introductions, though slightly better in yield, were found to be susceptible to coconut foliar decay (CFD), whereas the local varieties are tolerant. The VRD × VTT hybrids had lower copra yields (3.3 to 3.7 mt ha^{-1}) but were found to be more tolerant against CFD. So emphasis is laid on selection of local material. The local talls are found to produce 2.5 mt copra ha^{-1} $year^{-1}$, whereas the dwarf × local talls produce 4.0 mt copra ha^{-1} $year^{-1}$ (Duhamel 1993). In the Solomon Islands, where controlled pollination began in the 1960s, a replanting programme is being carried out with the Malayan Red Dwarf × Rennell Tall hybrid.

4.12 Future Strategy

1. Increasing the availability and accessibility of quality planting materials.
2. Emphasis on evolving resistant/tolerant varieties to biotic and abiotic stresses specific to the concerned area.

3. Evolving coconut idiotypes suitable for inter/mixed cropping.
4. Strengthening international germplasm exchange strictly adhering to the quarantine protocols. Sustaining/strengthening the existing national and international coconut gene banks.
5. Adoption of a comprehensive breeding strategy.
6. Diffusion of information to farmers and steps to narrow down the potential and realised performance of coconut varieties.
7. Developing micropropagation protocol using adult palm tissues and genome sequencing of coconut to complement the breeding efforts.
8. Establishment of an International Coconut Research Institute (ICRI).

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