Chapter 8
Soil Productivity and Nutrition

H. Hameed Khan and V. Krishnakumar

Abstract The natural habitat of coconut is the coastal belt of the tropics where sandy and red sandy loam soils predominate. This chapter describes the major coconut growing soils around the world, their characteristics and management. An understanding of the role of major, secondary and micronutrients and their interactions is discussed in relation to the yielding ability of palms. As a general rule, it is advised that at least a quantity of nutrients exported through harvested produce and above-ground parts are replenished to maintain a balance between export and import of nutrients. For a perennial palm like coconut, a fertilizer management programme should consider soil nutrient reserves, plant nutrient status and nutrients stored in the plant system and evolve a system in preference to a blanket recommendation. Productivity and sustainability of yields in the light of integrated nutrient management are emphasized. A balanced approach evolved through the physiology-related growth parameters and their significance is presented in an integrated approach in the nutrient management of coconut. A review of fertilizer practices in coconut growing countries is provided, and a basis for fertilizer formulations to coconut palms is indicated in the wake of knowledge of DRIS, DFR and other models tested in coconut nutrition. Research results on leaf analysis and diagnostic techniques for site-specific nutrient recommendation to coconut gardens are indicated. A refinement of these models is suggested with respect to different agroclimatic regions. Soil and nutritional aspects associated with certain diseases and disorders across coconut growing regions are also presented.

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8.1 Introduction

The coconut palm grows on different soil types provided; they are reasonably deep and free draining to allow for unrestricted root development and aeration. Examples of major world producing areas indicate that the soils range from coarse sand, which contains up to 97% sand (0.2–2.0 mm), to heavy soils with about 70% clay (Child 1974). It is also observed that coconut grows very well in lower slopes, piedmont slopes of hills and, most importantly, coastal areas, where subsurface moisture drains down slope, which makes them to retain moisture for appreciably longer periods. Since coconut is grown in the tropical condition, most of the soils under coconut are deficient in organic matter except the soils of the humid tropics like lateritic soil of the hilly region and the alluvial soils. Manciot et al. (1979b) suggested a threshold value of 1% organic carbon for coconut soils. The soil nitrogen supply is directly related to the soil organic fractions. However, it varies with soil type.

On the west coast of India, coconut is grown on laterites, coastal sand and red sandy loam, while on the interior areas of the east coast, coconut is grown on deltaic alluvium, coastal sandy areas and localized patches of red and black soils. The morphological and some of the physico-chemical characteristics of typical coconut growing soils from different agroclimatic regions of India have been discussed by Khan et al. (1978). They classified soils under alfisols, entisols, ultisols and vertisols, and soil taxonomy up to subgroup level has been provided. Sankaranarayanan and Velayutham (1976a, b) have described in detail about soils that support coconut in the west coast and east coast of India.

It is commonly observed that coconuts along coastal areas are more productive than those growing inland. Strong reasons for this are more humid conditions and narrow temperature fluctuation and better subsoil water supply kept in constant movement by the ebb and flow of the tide of the sea (Menon and Pandalai 1960). It is claimed that sodium abundant in such coastal areas substitutes partially for the potassium needs of the coconut (Nartea and Reyes 1973).

8.2 Major Coconut Growing Soils and Their Management

The principal soil types that support coconut cultivation in the world are red and laterite, sandy, alluvium, coral, volcanic, clay and peat soils.

8.2.1 Red and Laterite Soils

In India, Sri Lanka and many other countries, coconut farming is seen on the red and laterite soils to a large extent. These soils are highly leached with varying depth of solum and are deficient in bases. Physically, red and laterite soils are loose, porous and well drained, but the water retention power is rather poor. Chemically, these soils are acidic and contain excess amounts of aluminium, iron and manganese. They are also deficient in many of the essential plant nutrients, particularly potassium and phosphorus. Since the nature of soil colloids in these groups of soils is dominantly 1:1 lattice silicate minerals intermixed with non-expanding 2:1 types, they have low cation exchange capacity and poor nutrient retention power. The dominant cations in these types of soils are Al and Fe which would convert the soluble phosphates into insoluble forms. The organic matter content is also low. Consequently, these groups of soils exhibit many production problems for coconut in the absence of appropriate management practices. Nevertheless, they respond well to manuring and support a good stand of productive coconut plantations.

8.2.2 Sandy Soils

The second major soil group on which the coconut is cultivated is the coastal sands. It is commonly found in the coastal belt of almost all coconut growing countries in the world. In India, it is found along the coastal belt both in the east and west coast of the peninsular India. In Sri Lanka, the sandy soils occur all along the west coast from Kalpitiya to Dondra head and are known as “cinnamon” sands. However, on the east coast of Sri Lanka, coarse sandy deposits overlie coral hard pans and are often shallow in depths. Practically, all coconut plantations in West Africa and Madagascar are observed on coastal sandy soils. Similar type of soil is found in Mozambique, in the Philippines and in the east coast of Malaysia. Consequently, this group of soils is deficient in almost all essential nutrients. The soil in general has a single-grained structure, poor silt and clay contents, poor in organic matter and deficient in almost all nutrients. The leaching loss of applied nutrients is heavy in high rainfall areas. Management of these soils requires liberal additions of almost all sources of organic matter, and that generated within the system for successful cultivation of coconut palms.

8.2.3 Alluvium

The third major soil group is the alluvium. Among all the soils, the river or estuarine alluvial deposits with sufficient amount of coarse and fine sand are considered to be the best for coconut cultivation. In India, coconuts are cultivated extensively in the deltaic regions of Cauvery,Godavari, Krishna, Mahanadi, Brahmaputra and Ganga where the soils are deep and loamy. In Sri Lanka, the best estates are located on the tidal loams of the alluvia of the Ma Oya, Deduru Oya and Batholu Oya rivers and their tributaries in the North-West Province and the estuarine deposits of the silted up Negombo, Madampe, Mundel and Puttalam lagoons on the west coast (Child 1974). In the Philippines, the alluvial limestone-derived soils are exceptionally fertile (Cooke 1936). In Indonesia excellent plantations are found on marine alluvial soils. Almost a similar situation is met with in other coconut growing countries of the world. These soils are well-drained, deep and highly fertile. The supply of organic matter and essential plant nutrients is usually more than adequate. As a result, alluvial soils support highly productive coconut groves.

8.2.4 Coral Soils

Coral soil is yet another group of soils extensively cultivated to coconut. This group covers most of the atolls (Polynesia). It is a mixture of coral, sand and rock, almost entirely calcareous, which poses unique problems of nutrient assimilation and deficiencies (Newton 1967). It is considered to be an extreme soil condition where the coral fragments are mixed with sand and pH reaching as high as 8.5–9.0 rendering some critical nutrients to be unavailable.

Their fertility depends on the amount of organic matter content and the degree of weathering. Many studies on these soils have been carried out under the auspices of the South Pacific Commission and the *Institut de Recherches Pour les Huiles et Oleagineux* (IRHO), particularly at the research station at Rangiroa in the Tuamotu Archipelago (Pomier 1964). Deficiencies of iron and manganese as well as potassium and nitrogen have been commonly noted in these soils. In the Solomon Islands and in New Hebrides, these soils are overlaid by alluvial deposits of varying depths, which makes them very fertile, and excellent coconut groves are found there. In India, the soils of Lakshadweep, some parts of Andaman and Nicobar and soils of Maldives Islands also belong to this group. Although these soils are poor in organic matter and major plant nutrients barring phosphorus, calcium and magnesium, the coconut production is excellent due to the supply of almost all plant nutrients through partially saline underground water. Potassium is the most limiting nutrient in such soils. The management of these soils is very difficult due to the highly sensitive ecosystem prevailing in the island habitats.

In Lakshadweep, India, 80% of the geographical area of 3270 ha of the Islands is cultivated to coconut. Krishnan et al. (1997, 2004) observed the soils are entirely derived from coral limestone and are predominantly sandy and loamy sand and majority of soil is classified *as carbonic isohyperthermic family* of *Typic ustipsamments* and in some island locations as *orthants* under soil taxonomy (Soil Survey Staff 1999). A chemical analysis of soil profile is presented in Table 8.1.

8.2.5 Volcanic Soils

The volcanic soils cultivated with coconut are generally fertile. They are found mainly in Indonesia and the Philippines. In Indonesia, coconuts grown on the so-called plains of Anggio on Sangihe Island which were built up from the dejects of

Table 8.1 A model profile of coral soil series with its characteristics (series A)

(a) Mechanical composition

Depth (cm)	**Horizon**	**Sand (%)**	**Silt (%)**	**Clay (%)**	**Texture**	**E C dS/m**	**pH (1:2.5)**
0–16	Ap	90.6	5.3	4.1	S	0.23	8.5
16–43	C1	92.6	2.4	5.0	S	0.17	8.5
43–84	C2	94.3	2.8	2.9	S	0.16	8.9
84–122	C3	97.1	2.8	1.5	S	0.13	9.1
122–164	C4	97.1	2.9	0.0	S	0.12	9.1

(b) Chemical constituents

Depth (cm)	**O.C (%)**	**Ca CO_3 (%)**	**Exchangeable cations C (mol) kg^{-1} soil**				**CEC c (mol) kg^{-1} soil**	**Base saturation (%)**
			Ca	**Mg**	**Na**	**K**		
0–16	0.78	93.1	5.88	0.47	0.32	0.1	1.0	100
16–43	0.59	95.5	5.37	0.48	0.29	0.6	0.6	100
43–84	0.19	96.0	4.47	0.33	0.33	0.5	0.5	100
84–122	0.11	9.8	4.34	0.39	0.29	0.4	0.4	100
122–164	0.13	96.0	4.67	0.37	0.31	0.4	0.4	100

(c) Available nutrients

Depth (cm)	**O.C (%)**	**Available nutrients (kg ha^{-1}) micronutrients (ppm)**					
		P_2O_5	**K_2O**	**Fe**	**Mn**	**Zn**	**Cu**
0–16	0.78	125	105	1.26	1.11	0.62	1.20

two neighbouring craters of Mount Awu are found to produce about 3 tonnes of copra ha^{-1}. In the Philippines, good coconut plantations are found in Southern Luzon surrounding Mount Banahaw in Tayabas and Mount Mayon in Albay which are volcanic in origin (Child 1974).

8.2.6 *Clay and Peat Soils*

The clays are generally regarded as the least suitable for coconut cultivation, and those with stiff clay subsoil should, as a rule, be avoided. In Sri Lanka, estuarine clays formed by the silting up of estuaries and lagoons are considered to be unsuitable for coconut. These soils become waterlogged during monsoon season and baked and cracked during dry weather (Child 1974). Similar situations are also found to exist in Mozambique. In contrast to other coconut growing countries, large coconut areas in Malaysia come under heavy clays and peat soils. Cooke (1936) reported a type of clay soil in the Philippine Island, Basilan, with a striking resemblance to the clay soils of the west coast of Malaya. Deep ploughing, husk burying, draining and raising leguminous cover crops are some of the practices suggested for improving such areas (Child 1974). In the southern state of Tamil Nadu, large areas of heavy soils are cultivated with coconut.

Peat soils in Malaysia are studied by Cooke (1930), and he concluded that soils containing more than 80% of organic matter are not really suitable for coconut cultivation. In India, peat or Kari soils are found in some parts of Alappuzha and Kottayam districts of Kerala. These soils are characterized by strong acidity (pH 3.0–4.5) and high content of organic matter. They are very rich in total nitrogen but often deficient in phosphorus and calcium. The level of potassium is generally satisfactory. Coconuts are usually grown on raised bunds(mounds). With regular soil reclamation and management practices, the crop performs well on such soils.

8.3 Soil Suitability for Coconut Plantation

Most of the plant species need well-drained, moderately fine to medium textured soils having optimum physical and chemical properties. Soil resource maps, based on such parameters, can aid in predicting the behaviour and suitability of soils for growing different crops and forest species, once the suitability criteria for each crop is established. The National Bureau of Soil Survey and Land Use Planning, India, has proposed land suitability criteria for selecting soils for coconut cultivation (Naidu et al. 2006). Climatic parameters and land quality characteristics as required for a perennial crop like coconut are considered, and the suitability of the site has been rated as S1, S2, S3 and N (Table 8.2).

8.4 Soil Fertility Management

The performance of coconut palms under cultivation is closely linked to the health of the soil, and high yield is tied up with the fertility status of the soil. According to Pandalai (1953), at least six principal soil factors, viz. soil moisture, soil nutrients, soil air, soil temperature, root space and soil toxins, govern the productivity of coconut of which the soil water and nutrient supply regulate the productivity of more than 80%. Soil physical properties are more important as it is more difficult to modify them than to correct mineral deficiencies.

Sharing his experiences from Brazil, Sobral et al. (2007) observed a base saturation of the soil of 60–70% as ideal for coconut. At this level, it is probable that exchangeable Al^{+++} becomes insoluble and exchangeable Ca^{++} and Mg^{++} should exceed 20 mmol/dm^3. It has been observed that although these values have been reached, the levels of Ca and Mg in the leaves remain below the critical level and such lands require application of calcium sulphate and a magensium source to correct the deficiency.

Where the Al, Ca and Mg levels are low, Ca and Mg should be applied to correct the deficiency. In this case, lime should be applied in a circular area, with the trunk at the centre and the edges at the crown projection as the outer limit (Sobral 1998). The quantity of lime to be applied per plant is obtained by the proportion between the quantity hectare^{-1} and the calculated area of the crown projection. In all cases, incorporation of lime is important to correct acidity and place Ca and Mg near the

Table 8.2 Soil-site suitability criteria for coconut cultivation

Soil-site characteristics			Ratings			
Parameters		Units	Highly suitable	Moderately suitable	Marginally suitable	Not suitable
			S1	**S2**	**S3**	**N**
Climatic regime	Mean temperature in growing season	°C	26–29	23–25, 30–32	20–22, 33–34	
	Total rainfall	mm	1500–2500	1000–1500	500–1000	<500
	Dry months (months with <50 mm rainfall)	Months	<3	4–5	6–7	–
Land quality		**Land characteristics**				
Oxygen availability to roots	Soil drainage	Class	Well drained	Moderately well drained	Imperfectly drained, excessively drained	Poorly drained
	Depth of water table	M	2–3	1–2	0.5–1	–
Nutrient availability	Texture	Class	cl, scl, sc, sicl, sil	sl, c (non-swelling), sic	c (swelling), ls, s	
	pH	1:2.5	5.1–6.5	6.6–7.5, 4.5–5.0	7.6–8.5, 4.0–4.4	
Rooting condition	Effective soil depth	Cm	>100	75–100	50–75	<50
	Coarse fragments	Vol %	<15	15–35	35–50	>50
Erosion hazard	Slope	%	<8	8–15	15–30	

Note: *c* clay, *cl* clay loam, *sicl* silty clay loam, *sic* silty clay, *sil* silt, *ls* loamy sand, *sl* sandy loam, *s* sand

roots. Where fertigation is not practised, the interval between liming and fertilization should be at least 60 days.

Very pronounced effect of drainage, soil depth and soil series on coconut yield was noticed by Cosico and Fernandez (1983) in the Philippines. Yield was the highest in soil that is well-drained, with at least 80 cm deep, and whose texture is coarse to medium. Similarly, yield was highest in relatively flat areas and where the climate has only a short dry period. Compaction of the subsoil rather than the topsoil adversely affected yields.

Issaka et al. (2012) reported that soil physical properties did not cause any major limitation for good coconut growth and yield in Western and Central regions of Ghana. However, the soils suffer from multi-nutrient deficiency with nutrient levels of the soils being low to very low and will not support good coconut growth and yield. Except for soil pH, nutrient levels generally showed a decreasing trend in the order top soil > subsoil and below, a feature commonly observed in soil profiles. For growth and productivity, liming to improve the exchangeable basic cations and pH of the soils is recommended. Use of rock phosphate is also recommended for raising the levels of both phosphorus and some basic cations.

8.4.1 Depth of Soil

The depth of the soil is one of the important physical criteria to promote sustained productivity of the palm. Around 73% of roots of coconut are found within a 2 m radius, and most of them were confined to 30–120 cm in depth (Kushwah et al. 1973). Root distribution pattern was also studied by Dhanapal et al. (2000). The presence of hard soil pan, bed rock, a plinthite layer or permanent water table within 1 m depth should be considered as unsuitable soil physical conditions for satisfactory growth of coconut palms. Under such situations, the initial growth would be satisfactory, probably only up to 10–15 years, beyond which the palms show quick decline both in vegetative growth and yield-related parameters unless intensive fertilization is resorted to. Hence, sufficient depth of soil is a prerequisite for planting coconut which gives a good physical support and better anchorage against gusts of winds. Ganarajah (1953) emphasized the necessity of at least 1 m of fertile soil for healthy coconut growth. A minimum depth of 80–100 cm was observed as ideal by Fremond (1964).

8.4.2 Soil pH and Management

The optimum soil pH range is 6.4–7.0, though the palms can also thrive under soil pH range of 5.5–6.3 and 7.1–7.5. Soil pH values below 5.4 or above 7.5 provide marginal condition for the growth of the palms (Child 1974). The acidity of samples of Philippine coconut soils showed a pH range between 6.2 for poor yielding clay and 7.0 for high-yielding volcanic alluvium to 8.3 for high-yielding coral sand (Cooke 1936). The pH of representative Indian soils is reported to be in the range of 5.2–8.0 (Menon and Nair 1952). Manciot et al. (1979b) suggested a pH range of 5.0–8.0 as normal for coconut. According to Fremond (1964), the ideal soil pH for coconut growing soils ranges between 5 and near neutral. However, soil acidity frequently changes depending up on management practices. Continuous application of acid-forming chemical fertilizers reduces the soil pH due to the acid residues. On the other hand, continuous application of organics such as forest leaves, farmyard manure, compost and green manures tends to buffer the soil pH. The soil acidity varies depending on the parent materials from which the soils are formed. Besides the basic pedogenic processes, the presence of dominant cation in the exchange complex determines its acidity. Almost all red and lateritic soils have very low pH, while it is towards neutral for alluvial soils. In the case of sandy soils, the pH is near neutral, whereas the coral soil (Krishnan et al. 1997), which contains calcium as the dominant cation followed by Mg, is in the pH range of 7.8–8.5. The soils of volcanic origin are generally acidic and have a low pH. The measure of soil acidity generally gives an indication about the status of nutrient availability and the possible production-limiting factors prevailing in such soils.

Soil Acidity Most of the red and lateritic soils, where coconut is predominantly cultivated and is formed under humid tropical conditions, have Al^{+++} as the dominant cation, and consequently their pH is very low (4.2–5.8). These highly leached soils are deficient in many of the essential plant nutrients, particularly potassium and magnesium. The presence of high Al and Fe reverts the soluble phosphates into insoluble forms.

Soil Salinity In low-lying areas where the soils are frequently inundated by seawater or submerged with brackish water during certain seasons of the year, excess salinity may create some production problems. Drainage facilities and check bunds can reduce the inundation. Coconuts cultivated in nontraditional saline/alkaline areas face considerable limitation due to the dominance of sodium, carbonates and bicarbonates.

The management practices that are appropriate for problem soils are liming to correct acidity and gypsum application to correct alkalinity as per the lime or gypsum requirement of the soil.

Soil acidity can be managed by applying liming material based on the lime requirement of the soil. Often, the acid-forming cations such as Al^{+++} could be inactivated by using excess of phosphate or organic manures. But in the case of acid sulphate soils, the correction of acidity and suppression of aluminium could be achieved only by using magnesium silicate. This facilitates inactivation of Al as aluminium silicate, and the magnesium sulphate thus formed can be leached out of the system. Thus, the problem of Al^{+++} and sulphate can be tackled by the single application of magnesium silicate. According to Nambiar et al. (1975), the application of seaweed manure reduced the acidity to a certain extent. In acid sulphate soils of Malaysia where coconut is intercropped with cacao, Chew et al. (1984) reported that liming from pH 3.9–4.5 in the top soil increased copra content and copra yields by 10% and nearly doubled the cacao yields. The application of acid-forming chemical amendments such as sulphur or gypsum helps in reducing the salt problem. Application of more organic matter in the planting pits along with soil-sand mixture in equal amounts was also observed to reduce the salt problems. Similarly coir pith has been found to be a good amendment to correct soil alkalinity.

8.4.3 *Electrical Conductivity*

The total soluble salts in the soil are not a serious problem as far as coconut cultivation is concerned. This is mainly because coconut is a semi-halophytic palm and can tolerate salinity to a greater extent. According to Sankaranarayanan et al. (1958), the palm could tolerate a salinity up to 0.6% which is beyond the tolerance limits of many other crops. Majority of the soils where coconut is cultivated are acidic and highly leached, and as such, the salt problem is not a matter of concern. However, in low-lying areas where the soils are frequently inundated by seawater or submerged with brackish water during certain seasons of the year, excess salinity may create some production problems. Excess salt concentration also enhances the osmotic potential of soil matrix which restricts the water uptake by plants. Na, being a toxic ion under such conditions, interferes with K uptake disturbing stomatal regulation which ultimately causes water loss and necrosis. The application of acid-forming chemical amendments such as sulphur or gypsum would also help in reducing the salt problem. Application of organic matter in the planting pits along with soil-sand mixture will have an ameliorative effect under conditions of excess salinity.

8.4.4 Organic Matter

Soil organic matter is the source and sinks for plant nutrients. Coconut growing soils, in general, are deficient in this component. Among the major soil groups, the lateritic soil on the hilltops and slopes and the alluvial soils tend to contain fairly higher amount of organic matter than the coastal sandy soils. The build-up of soil organic matter under tropical humid condition is rather difficult due to faster disintegration and degradation/oxidation. In the case of soils of volcanic origin and marshy and acid sulphate soils, the total soil organic matter content is high, but the humic and fulvic acid fractions which are the active components contributing to soil fertility are low. Manciot et al. (1979b) suggested a threshold value of 1% organic carbon for coconut growing soils.

The underlying productive capacity of the soil is determined by the organic matter status through its beneficial influence on soil physical, chemical and biological environments. This is particularly true for sandy or coral soils. One such beneficial effect has been reported by Nambiar et al. (1983) in the case of littoral sandy soils of west coast of India where it was successfully demonstrated that coconut seedlings can be well established by the application of different organic sources. Their studies also revealed favourable changes in the soil physical and chemical environments which in turn improved the health of the palm. In cases where organic manures are in short supply, on farm availability of organic sources of nutrients could be ensured, through green manuring, cover cropping and conservation of farm biomass. Wherever feasible it is advantageous to generate sufficient organic matter within the plantation.

8.5 Mineral Nutrients on Growth and Productivity of the Palm

The vital aspect of mineral nutrition is to ensure the availability of the essential mineral elements in the soil in the required levels and in the right proportion to the palm, for its sustained growth/productivity throughout its life. The two important approaches for achieving this are (1) to assess the nutrient demand of the palm for expressing its full production potential and (2) to assess the capacity of the soil medium to supply the nutrient.

8.5.1 Soil Nitrogen

The soil nitrogen varies with soil type. Generally, the sandy soils contain very low amount of soil nitrogen, while it is high in the case of swampy, Kari (peat) and alluvial soils. Heavy soils with high amount of clay such as alluvial, black and heavy red soil, tend to retain N in the ammoniacal form dominantly in their exchange complex compared to sandy and red sandy loam soils depending upon the pH of the soil. Swampy and marshy soils contain high amount of organic nitrogen.

The nitrate concentration in arable soils, in general, does not exceed 20–30 ppm. It is highly mobile and susceptible to loss by leaching. The initial showers of the monsoon rain tend to leach most of the nitrate accumulated in the coconut gardens. Such a loss is very high in sandy soil followed by sandy loam and red soils. The nitrate concentration is generally high in the alluvial, forest and black soils. It undergoes reduction process in soils submerged in water at least for a period of 1 or 2 weeks. Thus, all the coastal soils subject to inundation by seawater tend to lose the nitrate by this process. Even some of the upland soils, which receive torrential rain continuously for a week, are susceptible for nitrate reduction. This is especially true for situations like West Coast and North Eastern parts of India.

The soil N is also subjected to loss by volatilization process. Although most of the coconut growing soils are acidic in nature, the N loss through volatilization would take place due to localized changes in soil pH caused by the hydrolysis of urea. This loss varies among soils depending on the H^+ ion buffering capacity, the presence of easily decomposable organic matter content, etc. The volatilization loss from applied urea can be reduced to a large extent by covering with 5 cm soil after fertilizer application. Upadhyay et al. (2007) evaluated N mineralization potential of predominant coconut growing soils, viz. sandy (Oxic quartzipsamments), red sandy (Arenic Paleustults), laterite (Oxic haplustults) and Kari (Tropic fluvaquents) type of soils of Kerala, India, and found it to be more in Kari soils (0.543 μg N day^{-1}) followed by red sandy loam (0.042 μg N day^{-1}), sandy (0.027 μg N day^{-1}) and laterite (0.024 μg N day^{-1}) soils.

Bopaiah et al. (1998) studied the effect of slow-release N and P fertilizers (different combinations of urea, urea formaldehyde, neem-coated urea, lac-coated urea blended along with coir dust, tar, single superphosphate, Mussoorie rock phosphate and muriate of potash). Among the slow-release N fertilizers, urea form (urea formaldehyde), neem cake-coated urea and coir dust mixed with urea have been found to remain for a long period in the sandy soil, thus facilitating availability of N in the more permeable soil, and among the P carriers, Mussoorie phosphate was equally efficient as superphosphate. Dissanayake and Rajapaksha (2016) observed that in the sandy regosols of Sri Lanka, urea blended with neem cake is more suitable to reduce nitrate losses than use of neem extract.

It is inevitable that soils which receive high doses of nitrogenous fertilizers suffer, in the long run, from decreasing base saturation, acidification and a significant drop in soil pH. Organic manures such as green manure crop residues, compost, cow dung, etc. are known to alleviate the negative effects of inorganic fertilizers. Among the different management practices, mixed cropping with cacao and banana, intercropping including pineapple, etc. and mixed farming in coconut gardens as well facilitate recycling of nutrients and more so of nitrogen.

8.5.2 Soil Phosphorus

The P distribution in the soil varies with geomorphology and parent material of the soil as well as soil chemical constituents. In sandy soil, the total as well as available soil P is very low, whereas it is high in alluvial, black and swampy soils. The P status of laterite, lateritic and red soils is medium. However, the P retained in the soil is made available to the crop in course of time. Soils formed under the process of laterization contain high amounts of sesquioxides that revert the soluble P into insoluble complexes. In these soils, the Al^{+} Fe labile P forms are relatively higher than that of saloid-bound and calcium phosphates, whereas the soils of semiarid regions contain dominantly the Ca-P. In the case of alluvial and swampy soils, the organically bound P is higher than that of inorganic fractions. Organic P content was found to increase due to introduction of mixed farming and multiple cropping in coconut gardens. Nambiar et al. (1989) recorded considerable change in the P fractions of red sandy loam soil of Kasaragod, India, due to continuous P fertilization (Table 8.3), and Khan et al. (1985b) reported distribution of P fractions as influenced by P carriers, viz. single superphosphate, nitro-phosphate, ammonium phosphate and rock phosphate on their application to laterite soil.

In a discussion on P requirement of coconuts cultivated in New Zealand in soils derived from limestone, Baseden and Southern (1959) opined that though the soils are low in available P, it is not likely to be a serious factor for coconuts.

The coconut growing soils in Sri Lanka are generally deficient in total as well as the active and available forms of P. Although soils of the ultisols had marginal to moderate amounts of total P, the active and available fractions were extremely low (Loganathan and Balakrishnamurti 1983). Leaf analytical data from the joint FAO/CRI/CCB study revealed that about 85–90% of the holdings have adequate levels or an excess of P. Accordingly, P is placed fourth in the order of priority of nutrients

Table 8.3 Effect of P fertilization on phosphorus fractions (ppm) in red sandy loam soil

Year	Depth (cm)	Saloid-P	Al-P	Fe-P	Ca-P
1983	0–25	2.67	38.9	92.6	3.5
	25–50	2.03	15.1	52.4	3.9
1986	0–25	47.50	217.6	97.7	40.3
	25–50	34.40	277.7	85.8	27.0

for adult coconut in Sri Lanka (Anon 1989). Available P in the Boralu and Pallama soil series of Gampaha District of Sri Lanka was at a medium level of sufficiency, with a mean of 16 mg kg^{-1}, even in unfertilized coconut plantations (Jayakody et al. 2007).

The mobility and diffusion of soil P is very much limited and also its loss from soil through leaching. The loss of P through surface run-off is quite high, particularly during heavy rains. Nevertheless, P build-up would take place due to continuous application of fertilizers containing phosphates (Muliyar and Wahid 1973). On a sandy loam soil in the dry zone of Sri Lanka, the downward movement of P from concentrated superphosphate was greater than from rock phosphate (saphos) (Loganathan and Nalliah 1977). The surface layers (0–15 cm) of soil when applied with concentrated superphosphate had higher P values (60 and 89 mg kg^{-1} for the 8th and 9th year, respectively) than those given rock phosphate (3 and 16·5 mg kg^{-1}). At 40 cm depth, the concentrated superphosphate treatment had 6 and 30 mg P kg^{-1}, but the rock phosphate treatment had almost zero P at and below 40 cm.

There have been many evidences of P build-up in the soil due to continuous fertilization. The studies of Khan et al. (1992) showed that the available soil P (0–30 cm) increased from 84 ppm to 121 ppm when annual fertilization of P was done at 320 g P_2O_5 $palm^{-1}$ for 14 years, whereas in the treatment where P was not applied, it decreased from 84 ppm to 21 ppm during the same period. Khan et al. (1985b) further reported a general build-up of available soil P irrespective of sources of phosphatic fertilizer applied to a typical laterite soil of Malabar area of Kerala, India (Table 8.4). They recommended rock phosphate as the ideal carrier of P in coconut mineral nutrition, as soil contents receiving rock phosphate gave a better reflect on plant P contents and enriched all P fractions in the soil and influenced the yield. The study further revealed that plant P content in coconut can be built up only gradually over a period of time compared to N and K. They also observed mobility of applied phosphorus to lower depths as a result of cultural practices associated with fertilizer application and mobility of P increased with increase in the level of its application. As Kushwah et al. (1973) demonstrated that > 80% of coconut roots were seen below 30 cm depth, and P moved to the roots mainly by diffusion (Barber 1962), they suggested deeper placement of P for better utilization as a rational approach to tree crops such as coconut.

Table 8.4 Influence of P carriers on the available P (Bray I) status in the coconut basins

	Available P status (ppm)					
	1975–1976 (pretreatment)			1980–1981 (posttreatment)		
P-carriers (to supply 320 g P_2O_5 $palm^{-1}$ $year^{-1}$)	0–30 cm	30–60 cm	60–90 cm	0–30 cm	30–60 cm	60–90 cm
Single superphosphate	34.7	38	1.3	132.8	3.7	3.1
Ammonium phosphate	36.0	Traces	Traces	152.7	3.5	3.1
Nitro-phosphate	29.3	Traces	Traces	148.1	5.8	1.3
Rock phosphate	40.7	Traces	Traces	91.1	3.5	2.7

Table 8.5 P budget and balance (kg ha^{-1}) in coconut-based high-density multispecies cropping system

Fertilizer levels	1983–1984			1985–1986		
	Budget	Removal	Balance	Budget	Removal	Balance
*F	198	8	190	395	20	375
2/3 F	170	8	162	315	18	297
1/3 F	148	8	140	243	20	223

*F = Recommended dose of N, P_2 O_5, K_2O (500:320:1200 g $palm^{-1}$ $year^{-1}$); 2/3 F = 2/3 of the recommended dose; 1/3 F = l/3 of the recommended dose

Bavappa et al. (1986) have recorded a phenomenal build-up of P (Table 8.5) in the high-density multispecies cropping system involving 18 crops over a period of 3 years. They have also observed similar trend in mixed farming and coconut-cacao mixed cropping systems at the experiments at ICAR-CPCRI.

A review of P fertilization trials in coconut in many Asian and African countries (Wahid et al. 1977) indicated that P application had no desired effect on yield and growth parameters. Where responses were observed, they occurred after many years of continuous P application (Muliyar and Nelliat 1971; Ouvrier and Ochs 1978). Nevertheless, Fremond (1966) and Muliyar and Nelliat (1971) found P response in the presence of K. Chew (1978) indicated that response to P fertilizers could have been due to the generally low levels of fertilizers. With continued use of P fertilizer and consequent build-up in soil, the need for it could be lower. Furthermore, in soils high in P, there would be no P response (von Uexkull 1972); the leaves of coconut palms on these soils reflected sufficient P levels (0.15%). For coconut, Cordova (1965) considered 10 ppm available P in soil as the critical level, and Khan et al. (1985a) observed that an available P status (Bray 1) of 15 ppm might be sufficient in maintaining the palms at sufficiency levels (0.110%) of phosphorus. Limbaga (1986) considered 15–20 ppm as the critical level and 30–35 ppm Olsen P as the optimal P level in surface soil.

The P fixation measurements are very useful for determining the P-deficient and P-sufficient conditions in soil and finding out the amount of P fertilizer to be added to a particular soil in order to supply adequate amount of P nutrient to coconut palm. Asara et al. (2011) studied the P fixation capacities of coconut growing soils from 20 coconut estates in the low country intermediate zone of Sri Lanka. They observed that 14 series showed higher fixation capacities which can be categorized as P-sufficient soils as the soils recorded higher available P and other 6 series showed lower fixation capacities which can be categorized as P-deficient soils as the soils recorded lower available P compared with critical value. The amount of P fertilizer to be added to P-deficient soils to supply adequate amount of P for coconut was 170, 80, 60, 130, 35 and 120 mg kg^{-1} for Kuliyapitiya, Tambarawa, Welipelessa, Ambakele, Sudu and Kiruwana soil series, respectively.

The analysis of Eppawala rock phosphate (a phosphate deposit in Sri Lanka) indicated that the total P content was about 30% and the water-soluble P content was about 0.02% (Perera 2007). Compared with other soluble phosphates, it is low in solubility level, but its solubility increases in acidic media. The low solubility of locally available Eppawala rock phosphate (ERP) makes it unsuitable for direct application for coconut palms in dry zone. In order to increase the solubility, incorporation of goat manure was suggested in the fertilizer schedule (Kulasingh et al. 2013). The Coconut Research Institute, Sri Lanka, recommends 100% of the P requirement of adult and young coconut palms in wet and intermediate zones with locally available ERP.

Phosphate-solubilizing microorganisms were found to be widely distributed in coconut growing soils (George Thomas et al. 1991), and the predominant bacteria solubilizing phosphate were *Pseudomonas* spp. and *Bacillus* spp. (Nair and Subba Rao 1977). Priya George et al. (2012) evaluated phosphate-solubilizing potential of bacterial isolates from rhizosphere soil and roots of coconut palms growing in Kerala, Karnataka, Tamil Nadu, Andhra Pradesh and Maharashtra states of India and, based on their phosphate-solubilizing potential and the ability to produce IAA, ACC-deaminase and siderophores, reported *E. cloacae* 267, *P. putida* Biotype B HSF 132 and *P. plecoglossicida* KnSF 227 as prospective candidates for use as bio-inoculants for organic farming of coconut.

Dwivedi et al. (1981) examined the efficiency of different methods of plant injection and soil placement techniques using carrier-free ^{32}P tagged to single superphosphate and ^{86}Rb, with coconut as test crop. By plant injection technique, radioactivity was detected in a 10-m-tall coconut palm after 4,8,12 and 18 hours of application through cut end of roots, stem, leaf axils and growing root tips, respectively. Out of 4 soil placement methods, the quickest recovery of ^{32}P in palms was detected after 7 days of placement when applied through hole method, 8 days of application by trench method and strip methods and after 11 days in basin method. They observed that the quickest recovery of radioactivity was noted through hole method and the average highest accumulation of activity (CPM/g dry matter), among all the methods, soil placement techniques, was recorded in trench method, where roots were exposed to root activity at 20 cm and 40 cm depths around the bole at a distance of 0.5 m and 1.0 m, respectively. Based on the above findings, circular trench method of nutrient application containing P can be recommended in the fertilizer application programmes (Khan and Bavappa 1986). Nethsinghe (1976) reported that roots of coconut were most active up to a depth of 45 cm and nutrients placed around the bole to a distance of 1.2 m are absorbed quickly.

8.5.3 Soil Potassium

The K content is relatively low in almost all acid soils due to leaching and surface run-off as a consequence of heavy rainfall. The soil K content depends on the nature and composition of the parent material (Graham and Fox 1971). It is low to medium in coconut growing soils of humid tropics but high in alluvial soils and those formed under semiarid conditions such as black soils. The swampy soils also contain moderately high amount of soil K. The potential reserve of soil K in the fixed or non-exchangeable form is an important source of K to coconut. The physico-chemical dynamics of soil K determines its fertility status and supplying power. The quantity-intensity relationship and the potential buffering capacity of soil K virtually regulate its availability to coconut.

Vegetative production appears to have priority over dry matter storage in the inflorescence and nuts when resources are limiting. A shortage in K availability will, therefore, first affect nut size, number of nuts and finally vegetative growth. With severe K deficiency, the rate of new leaf production is reduced, leaves are smaller (fewer and shorter leaflets) and duration of leaf production is less. Young palms supplied with low amount of K take much longer to develop a trunk and to come into bearing. Ouvrier (1984) noticed perfect correlation between K levels in the leaf and husk. Therefore, leaving the husks in the palm basins will help to restore the soil excess K. Fremond and Ouvrier (1971) in the Côte d'Ivoire tested the effect of withholding K on the development of young palms (Table 8.6).

Seedlings which received KCl fertilizer from field planting stage showed progressive improvement in all growth parameters and better partitioning of nutrients over the years, resulting in a consequent increase in the copra production of adult palms significantly, compared to those palms which received KCl fertilizer from bearing stage only.

Compared to the soil threshold value of 179 mg kg^{-1} for exchangeable K for the coconut palms, the status of exchangeable K of most of coconut growing soils is not sufficient for coconut cultivation, and, therefore, potash fertilizer application is necessary.

Pillai (1975), based on the ratings of Muhr et al. (1963), reported that all the soil groups of Kerala, India, under coconut are generally deficient in available K, and no soil group followed high ratings. The deficiencies of N and K are the most common in coconut plantations (Sobral 1998), and the quantities of nutrients removed by the coconut palm are high, since nutrient mining by coconut is a continuous process linked to growth. The nutrient removal ratio of N: K of 1:1.2–1.75 is indicative of

Table 8.6 Effects of periods of first potash fertilizer application on the performance of young coconut palms

Year	Characteristics observed	Time of KCI application		**B** as % of **A**
		A – from field planting	**B** – from bearing stage only	
1956	Number of fronds	8.89	7.69	86.5
1958	Length of frond (cm)	256.00	223.00	87.1
1959	Circumference of trunk	124.10	105.40	69.9
1960	Number of fronds in 1 year	11.70	10.70	91.4
1962	kg of copra ha^{-1}	944.00	272.00	18.7
1966	kg of copra ha^{-1}	2560.00	2272.00	88.8
1970	kg of copra ha^{-1}	2480.00	2096.00	84.5
1961–1970	Cumulative yield, kg ha^{-1}	17344.00	12704.00	73.2

its influence being exerted on the crop (Khan et al. 2000). Silva et al. (2005) observed that, in the nonirrigated area, the N and K for nuts harvested at 7 months were 23 and 76 kg ha $^{-1}$ year $^{-1}$, respectively, whereas in irrigated area, the removal was 74 and 243 kg ha^{-1} year^{-1}.

The nutritional limitations of two coconut growing soils, viz. Wariyapola and Maho series in Sri Lanka for the production of coconut, were inadequate supply of K and plant availability of Ca (Herath et al. 2008). Low soil N, Mg and Ca levels indicated their potential to be limited, if they are not replenished adequately. However, Ekanayaka et al. (2011) observed that high potential buffering capacities of potassium (PBCk) was in coconut growing soil series of Kuliyapitiya, Boralu, Madampe and Melsiripura, belonging to S1, S2, and S4 land suitability classes, indicating that they can buffer K and release it slowly to the soil solution. The Coconut Research Institute, Lunuwila, Sri Lanka (Anon 2008), recommends muriate of potash at 1600 g and 1800 g palm^{-1} year^{-1} for local and improved varieties, respectively, without split application for coconut palms grown in such soil series.

Khan et al. (1982) found that K adsorption was comparatively more and uniform in laterite soils than in red sandy loam, river alluvium and coastal sands cultivated to coconut. The magnitude of the constants K and 1/n and the difference in the values of Freundlich adsorption isotherm were attributed to the contents and nature of clay minerals in these soils. Potassium is likely to get depleted more easily from the root zone around the palm, and the K pool also cannot restore much K needed. As the coconut palm has a heavy demand for K, there is a need for evolving a more suitable way of K management.

The influence of clay minerals in K supply to the nutrient pool was also indicated by Ramanathan and Krishnamoorthy (1976). In the incubation experiments with different coconut growing soils, the highest water-soluble K fraction was obtained in sandy soil followed by laterite, red sandy loam and alluvial soils. The exchangeable K fraction was the highest in red sandy loam than in laterite, alluvial and sandy soil. The non-exchangeable K fraction was the highest in alluvial followed by laterite, red sandy loam and sandy soil (Anon 1967). This variation in the fractional distribution of K is on account of the variation in the mineralogical constituent of the soil and the initial soil K status. The presence of plenty of K-bearing minerals like mica would tend to regulate the release of K into the soil solution. The availability of K in soils is regulated by the levels of other cations like Ca, Mg and Na. Bastin and Venugopal (1986) indicated that the alfisols, which are intensively cultivated with coconut, are generally low to medium in potash status.

Many researchers (Shanmuganathan and Loganathan 1976; Somasiri and Liyanage 1996; Fernando 1999; Giritharan et al. 2000, 2002) studied on K status of the coconut growing soils, and they concluded that exchangeable K appeared to be a better measure of K availability as this form correlated better with leaf K values. However, they further reported that total K was not related to leaf K status because K minerals do not become available for a long-lived crop like coconut. The studies showed that the exchangeable K levels are different with the soil types irrespective of the agroclimatic zones and most of soils have exchangeable K levels below the threshold value. Upadhyay et al. (2005) observed that the optimum K application to maximize the soil solution K for optimum plant nutrition ranged from 662 ppm (full dose) to 692 ppm (No fertilizer). The quantity of K fertilizer required to optimize the soil solution K concentration in red sandy soil was 1150 g K_2O palm^{-1} year^{-1}, which very well matches with the general K recommendation (1200 g K_2O palm^{-1} year^{-1}) for coconut in India.

As K is one of the most essential nutrients to coconut, any damage caused in the early stages of its growth due to its deficiency would be difficult to be corrected in the later stages of growth. Hence, adequate K supply is essential right from the planting of coconut in the main field. The K supply can be regulated by suitable management practices. For example, Nambiar et al. (1983) observed higher build-up of available K in littoral beach sand by blending inorganic fertilizers with different organics. The maximum build-up was obtained when K was applied along with cattle manure followed by coir dust (Table 8.7).

Cultivation of grasses, cacao, banana, pineapple and other compatible crops in coconut gardens tend to recycle large amount of K to the soil (Bavappa et al. 1986). The results of studies conducted at ICAR-CPCRI, Kasaragod, India, showed that the potassium balance and budget considerably increased in the high-density multispecies cropping system involving 18 crops over a period of 3 years (Table 8.8). The management of soil K is not as difficult as that of nitrogen. Regular fertilizer application combined with possible recycling of organic residues would help to build up the soil K sufficient enough to meet the continuous requirement of coconut.

Table 8.7 Effect of blending organic sources with inorganic fertilizers on available potassium (0–50 cm depth)

Organic sources	Available K (ppm)			
	1971	1972	1976	1980
NPK* alone	7.6	9.1	11.6	44.0
NPK+ Coir dust	6.3	12.2	30.8	108.0
NPK. + Coconut *sheddings*	8.2	10.8	39.6	73.0
NPK+ Forest leaves	5.7	10.0	32.4	44.0
NPK+ Cattle manure	9.0	13.0	52.0	95.2

*K was supplied as muriate of potash at 2.0 kg palm^{-1} year^{-1}.

Table 8.8 K budget and balance (kg ha^{-1}) in coconut-based high-density multispecies cropping system

	1983–1984			1985–1986		
Fertilizer levels	Budget	Removal	Balance	Budget	Removal	Balance
*F	610	110	500	1403	488	915
2/3 F	455	100	355	1025	335	690
1/3 F	300	80	220	740	428	312

*F = Recommended dose of N, P, K (500:320:1200 g palm^{-1} year^{-1}); 2/3 F = 2/3 of the recommended dose; 1/3 F = l/3 of the recommended dose.

8.5.4 Secondary Nutrients in the Soil

Among the secondary nutrients, Mg and S are very important as far as coconut productivity is concerned. Both the nutrients are generally in short supply in many of the coconut growing areas in the humid tropical soils. They are either deficient or tending towards deficiency in most of the soils in Kerala, Karnataka, Maharashtra and North Eastern States of India. The deficiency of S has been reported from Papua and New Guinea (Southern 1969) and some of the East African and South East Asian countries (Ollagnier and Ochs 1972). In the Philippines, even coconut grown on soils derived from volcanic origin could suffer from S deficiency under high rainfall condition throughout the year. The contents of Mg and S are fairly high in black and alluvial soils. Both magnesium and sulphate ions are highly mobile, and, hence, they are easily lost from the soil by leaching.

Ollagnier et al. (1983b) considered an exchangeable Mg level of 0.46 meq % as high. The critical values for exchangeable K and Mg in the Philippines are 0.45 and 2.9 meq %, respectively (Santiago 1978). Margate et al. (1979b) did not observe a K-Mg antagonism in a long-term KCl fertilizer study on a clay loam soil in the Philippines in spite of high application of KCl (8 kg palm^{-1} year^{-1}), with soil levels of 0.45 meq % K and 5.3 meq % Mg.

Bavappa et al. (1986) have reported that the Mg budget and balance in coconut-based high-density multispecies cropping system declined very fast to the extent of 50% over a period of 3 years (Table 8.9). Further, the systems involving coconut-grass and coconut-cacao also showed a similar pattern of decline with respect to Mg.

Nethsinghe (1963) suggested that the exchangeable Mg content of soils had no diagnostic value for predicting Mg availability to coconut and according to him the 0.01 M $CaCl_2$ extractable Mg would give a more reliable estimate of Mg availability. Manciot et al. (1979b) suggested a threshold level of 0.2–0.5 m.e 100 g^{-1} of exchangeable Mg out of 1.0 m.e. 100 g^{-1} of total exchangeable cations. They have further suggested an exchangeable Mg/K ratio of 2.5 as ideal for coconut soils, while Cecil (1981) found a minimum value of 2.0 for the satisfactory supply of Mg to the palm. Field trials conducted in Sri Lanka (de Silva 1966), Côte d'Ivoire (Brunin 1970; Coomans1977), India (Cecil 1981) and other coconut growing countries (Manciot et al. 1979c) have clearly demonstrated the correction of Mg

Table 8.9 Mg budget and balance (kg ha^{-1}) in coconut-based high-density multispecies cropping system

Fertilizer level	1983–1984			1985–1986		
	Budget	Removal	Balance	Budget	Removal	Balance
*F	95	10	85	73	28	45
2/3 F	93	10	83	75	28	47
1/3 F	93	10	83	78	30	48

*F = Recommended dose of N, P, K (500:320:1200 g palm^{-1} year^{-1}); 2/3 F = 2/3 of the recommended dose; 1/3 F = l/3 of the recommended dose.

deficiency by the application of magnesium salts/minerals like Kieserite/Epsom salt or magnesite/dolomite. Cecil (1981) has recommended the application of 500 g MgO palm^{-1} year^{-1} as Epsom salt ($MgS0_4.7H_20$) for correcting Mg deficiency in the coastal sandy soils of the Onattukara series of Kerala, India.

Although calcium is one of the essential secondary nutrients, its concentration beyond a certain limit would decrease the coconut yield probably due to its interaction effects with other nutrients. The Ca content in most of the coconut growing soils of the world is satisfactory, and no improvement in growth or yield was obtained by Ca treatments. Besides, the indirect addition of Ca through phosphatic fertilizers is considered to be quite adequate for sustaining the Ca demand of the palm. However, for acid soils, regulated additions of liming materials are needed for correcting the soil acidity and other related problems. The availability of Ca in coral soils is very high and often reaches a concentration where it would interfere with the uptake of K, Mg and Na by coconut. Liberal organic amendments are generally recommended for improving the fertility of such calcareous soils. As fairly high amount of Ca is being recycled through litter fall and prunings of cacao and other intercrops grown in coconut gardens, the management of Ca is not a serious problem in coconut growing soils.

Analysing the nutrient contents of coconut leaves in the gardens of Tanzania, Thomas (1973) indicated that the yield was related to the ratios such as N /P, N /K and Ca/ Mg, but the level of K had to be interpreted in terms of a balance between K and Ca. When the individual nutrients were considered, the levels of N and Ca alone had a positive relation with the yield. The study also revealed that the nutrient composition of the leaves reflected to some extent the nutrient status of the soil. Hence, application of fertilizers having N and Ca might possibly correct the nutrient ratios and thereby improve the productivity of low-yielding coconut palms.

Potassium is not always necessary and responses to KCl often result from the effect of chlorine. It was shown from numerous experiments that leaf Cl levels are nearly always closely linked to those of Ca, K, Mg or even N cations. Thus, in soils with a high exchangeable Ca content, KCl is frequently inadequate to correct a K deficiency, whereas, where there is a low exchangeable Ca level, on the contrary, KCl appears to be one of the best forms for the correction of a Cl deficiency as well as the K deficiency which may be associated with it. Where there is no chlorine deficiency, chlorinated fertilizers, particularly KCl, can be used without problem.

Sulphur is either deficient or approaching to deficiency in most of the coconut growing soils barring acid sulphate soils, alluvial and black soils where the soil S content is medium to high. The deficiency is mainly due to the leaching of soluble sulphates from the soil solution. The anion adsorption capacity of most of the acid soils is also low. Soils very low in organic matter and continuously cropped without S fertilization are likely to suffer from deficiency of S. The use of high analysis fertilizers in modern agriculture restricts the addition of S as an incidental component to the soil. However, the S management can be effectively achieved by suitably selecting some of the S-containing fertilizers like superphosphate, ammonium sulphate, diammonium phosphate, magnesium sulphate, etc. while formulating the fertilizer schedule for coconut. The organic matter is one of the potential sources of S, its management and release pattern is almost similar to that of N from organic matter. As the major fraction of S is held in the organic form, the S management in the soil can be best achieved through proper organic farming practices.

8.5.5 Micronutrients

The tropical acid soils are in an advantageous position with respect to most of the micronutrients especially iron, manganese, copper and zinc. These cations are easily soluble and readily available under acid conditions. The availability of Fe and Mn is generally high in acid laterite and red soils; moderate in alluvial, volcanic, peat and clay soils; low in coastal sandy soils; and very low in coral soils.

The high calcium carbonate content of the coral soils blocks the assimilation of Fe and Mn by the palm. Severe deficiencies of Fe and Mn were reported in the coral tolls of Oceania which were not corrected by soil application of Fe and Mn salts (Pomier 1964, 1969). In acid laterite and red soils, their contents may often reach to toxic levels, particularly under anaerobic conditions.

The concentrations of Cu and Zn are moderate in acid laterite and red soils, high in the case of alluvial soils and low in black and coral soils. However, these nutrients are not generally found limiting in the nutrition of the palm. The requirement of Mo for coconut is very small, and its deficiency has not been felt in coconut farming anywhere in the world. On the other hand, the problem of B deficiency is becoming more and more conspicuous in most of the acid laterite, red, alluvial and coastal sandy soils. The "crown choke disorder" of coconut is considered to be due to boron deficiency which can be corrected by judicious application of borax depending on the severity of the symptoms as well as the age of the palm. Baranwal et al. (1989) recommended soil application of borax decahydrate at 50 g palm^{-1} just after the appearance of crown choke symptom. In slightly advanced stages, two applications of borax, 50 g each, at an interval of 3–4 months were found necessary for the redemption of the disorder.

8.5.5.1 Sodium

Though coconut consumes fairly high amount of Na, its specific function is yet to be established. Sodium is not really indispensable, but it is known that it can replace K to a certain extent when the latter is in short supply. Almost all coconut growing soils of humid tropics are fairly well supplied with Na. The soils originated under semiarid condition like the black and red soils are rich in Na. The soils near coastal belt are also well supplied with Na due to continuous salt spray from the sea. Under no circumstances, Na becomes a limiting element for coconut production. However, under brackish water ecosystems, the marshy soils are frequently inundated with seawater, and they tend to contain very high concentration of Na which might cause its toxicity. Since coconut is a semi-halophytic plant, it can tolerate fairly high amount of Na concentration in the soil solution.

There is not much information available on the soil Na in literature except some sporadic studies. The management of Na as a plant nutrient has not been attempted in greater detail. Nevertheless, it is being used as a soil ameliorant in the hard lateritic soils as common salt. The common salt enhances the crumbling and weathering of hard laterite and, in due course, softens the soils favouring the coconut roots to penetrate deep into the soil easily.

8.5.5.2 Chlorine

Chlorine is generally considered as an essential micronutrient for cultivated crops. Recent research has shown that coconut has a high requirement of Cl and that its deficiency causes detrimental effects on growth, yield and disease resistance in the palm. However, the specific functions of Cl in coconut have not been well established. The Cl content in most of the soils is medium to high. It is being added indirectly to the soil through muriate of potash which contains about 47% of Cl. The soils near coastal belt are well supplied with Cl due to continuous salt spray from sea through aerosol which would be deposited on the soil surface. In semiarid regions, the Cl content in the soil is high due to the chloride-bearing minerals from which the soil has been formed. The amount of Cl in the soil also depends on the amount of chloride brought down by the rain. The highly leached soils located far away from the sea coast usually show deficiency of Cl.

Ollagnier and Ochs (1971a, b), von Uexkull (1972) and Mendoza and Prudente (1972) strongly suggested that chloride must be considered as an essential macronutrient for coconuts. Chlorine deficiency appears to be widespread in many inland areas, especially on well-drained soils (volcanic soils). A survey conducted by the Philippine Coconut Authority revealed that 24 out of 54 coconut-producing provinces have widespread Cl deficiency (Magat 1988). In many cases, responses to applied KCl may be due to chlorine than potassium. Studies conducted in the Philippines (Magat et al. 1975; Magat and Pardones 1984), in the New Hebrides (Daniel and Manciot 1973) and in Indonesia (Manciot et al. 1979c) have clearly demonstrated the correction of Cl deficiency by the addition of Cl-bearing salts like muriate of potash, common salt and ammonium chloride.

Deficiency of Cl affects nut size, number of fruits palm^{-1}, copra yield, nitrogen uptake and the water economy of the plant. Combined application of N, Cl and S was found to increase nut yield, copra nut^{-1} as well as copra yield palm^{-1} year^{-1} by 32–34 nuts palm^{-1} year^{-1}, 27–34% and 10–11 kg palm^{-1}, respectively (Magat et al. 1979). They also observed that Cl and S are both strongly and positively correlated with nut production and copra yields, while only leaf Cl and Ca were highly correlated with copra nut^{-1}. They suggested application of (a) 1.8 kg ammonium sulphate (21–0-0) + 2 kg common salt (sodium chloride) or (b) 1.8 kg ammonium sulphate +2 kg potassium chloride (0–0-60) palm^{-1} year^{-1}.

Coconut palms grown far away from the sea at *Côte d'Ivoire* were found to exhibit Cl deficiency with reduced growth, yield and resistance to drought and increased susceptibility to fungal diseases (Ollagnier et al. 1983a). The manifestations of Cl deficiency seen on coconuts in the Côte d'Ivoire and Indonesia were interpreted as the inability of the plant to maintain its water potential at sufficiently low values because of the deficiency in monovalent anions (Ollagnier et al. 1983b).

The Cl critical level is 0.42–0.45% for young PB 121 hybrids (leaf 4) and 0.5% for adults (leaf 14). Though NaCl fertilizer is very effective and much cheaper than KCl, but it cannot be used alone because of K-Na antagonism (Bonneaux et al. 1993). In order to maintain good K and CI contents at the same time, it is necessary to use a combination of KCl and NaCl.

Prema et al. (1987) studied the effect of NaCl on growth and yield of 24-year-old coconut palms in a laterite soil of Kerala and reported the possibility of substituting 50% of KCl by NaCl as the palms applied with 100% of the recommended dose of KCl and that receiving 50% substitution of KCl by NaCl gave similar nut yields, which were higher than other treatments. Coconut palms were found to display a considerable response to NaCl applications as regards all the yield variables (growth, flowering, number of nuts, nut size, phytosanitary condition, resistance to water stress), at all stages (from the nursery to a bearing plantation) and under a wide variety of soil and climatic conditions (Bonneaux et al. 1997). The cost-effectiveness of NaCl applications, which exists virtually everywhere in Indonesia, increases in zones with a water deficit, since NaCl attenuates the effect of water stress, thereby regularizing production in coconut plantations. NaCl, which is much cheaper and readily availabe, can be used to largely replace KCl. NaCl is, therefore, set to become the main component in fertilization for coconut plantations in Indonesia.

Attention was first paid to the K ion, and its effect on coconut palm growth, right from an early age, was very quickly recognized. Later on, agronomists realized its presence alone could not suffice under water stress conditions and found that when Cl was combined with K, it played a synergistic role in growth and yields of coconuts and had an exclusive role with an increase of resistance to water stress (Ollagnier et al. 1983a). In trials in the Côte d'Ivoire and Indonesia, Ollagnier (1985) found that Cl had a specific effect on drought resistance in coconut as the stomata of Cl-deficient palms do not function normally. A close correlation occurs between potassium and chloride fluxes during stomatal opening. In chlorine-deficient plants, stomatal opening is delayed by about 3 hrs (Marschner 1995). Impairment of stomatal regulation in palms is considered to be a major factor responsible for growth depression and wilting symptoms in chlorine-deficient plants (von Uexkull 1985). Braconnier (1988) studied the physiology of Cl nutrition in coconut palms and provided a clearer picture of the physiological role of the Cl showing that this ion was involved at two levels: in stomata control mechanisms and osmotic phenomena. Osmotic adjustment in response to water stress occurs well before stomata closure and helps to maintain cell turgor, improving cell growth and stomata opening, among other things. Mialet-Serra and Bonneau (2004) observed that (i) Cl and K had an exclusive effect on leaflet size and are increasing their area of 6-year-old PB 121 hybrid coconut palms in Southern Lampung, South Sumatra, Indonesia. Potassium primarily affected petiole length, thereby the total frond length; (ii) synergy between these two ions was found to occur only for the number of leaflets; (iii) Cl and K acted independently on stem diameter, and synergistically on height of coconut palms receiving K or Cl had significantly more voluminous leaf crowns; and (iv) when K and Cl were supplied in a balanced manner, the crown area and leaf area index of coconuts increased leading to early bearing and higher nut yields.

Intensive basic and applied field studies on the usage of NaCl on tall variety and hybrids at PCA-Davao Research Centres gave consistent results that NaCl is a general and ideal fertilizer for coconut, both for corrective and maintenance fertilization. On local tall varieties like the Laguna tall, for a 5-year period, the average annual response to NaCl application at 2 kg palm^{-1} year^{-1} on bearing palms was about 31%, 30% and 69%, respectively, for nut yield, copra weight nut^{-1} and copra yield palm^{-1} (Magat and Margate 1990), while on coconut hybrids as CATD × LAGT, the respective average annual response was 65%, 31% and 65% (Secretaria et al. 2006). Magat (2009) reported that application of NaCl increased coconut yield by 25% and 50% over the unfertilized conditions during the first and subsequent years (2–5), respectively. In terms of copra, average annual yield of 1.78 tonnes ha^{-1} is achievable by application of NaCl over the unfertilized palms. Increasing chloride levels of coconut growing sandy regosol soil (Aquic Quartzipsamments) was found to reduce the leaching losses of nitrate N (Dissanayake et al. 2016) indicating the inhibitory effect of NaCl on soil nitrification.

8.6 Removal of Nutrients by the Palm

The coconut palm is an extreme type of perennial and is unique in that once it starts flowering, the productive phase lasts throughout the year and all through its economic life, which may average 70 years. The palm has many distinct developmental stages in its vegetative and reproductive cycles of growth. Once these are carefully identified and defined, then it should be possible to plan systematic studies covering every stage in its ontogeny. An evaluation and integration of these studies could then be expected to provide a reliable foundation for taking a complete nutrient inventory of the crop. To ensure a full appraisal of the nutrient status of the crop in all its bearings, and a thorough knowledge of all its growth manifestations, a three-pronged approach is in fact envisaged (Nathanael 1961). The *first phase* would constitute the establishment of norms for selected palms of comparable age and optimum performance grown under standard or typical conditions of cultural management and fertilizer regime. The *second phase* would be the study of reactions to known changes in fertilizer regime and levels of nutrient supply on the basis of long-range field experiments on differential manuring, involving single and multiple elements. The *third phase* would be the institution of plant nutritional surveys for the diagnosis of causative factors of deviations from established norms. The three phases of the proposed investigations would combine fundamental long-range work with short-term studies covering seedlings in the nursery stage and adult palms in their vegetative and productive stages of the life cycle. In addition, collateral sand culture experiments would be carried out on seedlings and young palms less than 5 years of age.

Nathanael (1958) suggested three approaches to study the mineral nutrition of the palm, viz. (i) to assess the mineral needs of the palm with the help of field fertilizer trials and by successive approximations, (ii) to analyse the soil for its nutrient-supplying capacity and (iii) to analyse the coconut water and leaf for understanding the level of nutrition of the palm in relation to its productivity and also the available nutrient status of the soil. Nathanael (1969) further elaborated the conceptual basis of assessing the nutrient requirement of the palm by the equation: F = R-S + L, where F is the quantity of the fertilizer nutrient, R is the quantity of the nutrient required by the crop for unrestricted growth, S is the quantity of the nutrient supplied by the soil and L is the portion of the fertilizer nutrient not utilized by the crop. He calculated the annual removal of the major nutrients by a middle-aged palm of the ordinary tall variety as 0.59 kg N, 0.26 kg P_2O_5 and 0.86 kg K_2O for palm yielding 40 nuts year^{-1}. When the yield level increases to 60 nuts, the calculated removal would be 0.72, 0.33 and 1.08 kg N, P_2O_5 and K_2O, respectively.

Conventional soil analysis is difficult to be adopted because a large volume of soil and subsoil is used by the coconut roots. Very often the composition of the leaves is not related to soil contents as the depth of effective soil and its structure are found more important than the nutrient concentrations. The sustained argument against soil testing is its inability to provide information on the nutrient absorption capacity of the palm. The soil analysis indicates only the potential capacity of a soil to supply nutrients to the palm, but it neither characterizes sufficiently the mobility of nutrients in the soil nor it provides any information on the plant factors, such as the extent of root growth and root functions which are of decisive importance for nutrient uptake under field conditions.

Visual deficiency symptoms usually appear when the deficiency is acute, possibly after passing through stages of hidden hunger, and the growth rate and yield are severely depressed. Moreover, the occurrence of multiple deficiencies, pest and disease attack, unfavourable environmental conditions, etc., makes the diagnosis complicated. The most widely adopted method is foliar analysis and recommending fertilizer applications based on established critical levels. This method has limitations as it fails to differentiate between metabolically active and inactive fractions of the elements in the tissue samples. The synergistic/antagonistic interaction between elements may lead to misinterpretation of foliar values. Environmental factors, type of cultivars/hybrids and the yield levels of the palm alter the critical levels of the nutrients. Therefore, an integrated approach giving a meaningful interpretation of different methods based on practical experience with respect to each situation is very much needed for making a realistic assessment on the nutrient requirement of the palm. The results of various approaches made to understand the mineral requirement of the palm are described in the following sections.

For the continued growth and productivity of the palm, an understanding of the nutrient demand and nutrient supply in the soil-plant system is essential. The major nutrient demand in the coconut plantation arises due to (i) the nutrients removed by the palm for its growth and yield, (ii) the nutrients lost by leaching and volatilization and weed growth, as well as (iii) the nutrients immobilized by the soil.

Table 8.10 Annual mineral export by the coconut palm

Sl. No	Basis	Nutrients (kg ha^{-1})					References
		N	P	K	Ca	Mg	
1	Annual removal ha^{-1}	63.9	29.10	95.3	–	–	Jacob and Coyle (1927)
2	6900 nuts ha^{-1} year^{-1}	91.9	41.50	136.7			Copeland (1931)
3	Annual removal ha^{-1} (tall type, 7400 nuts)	63–90	10.50–19.00	81–250	3.5–22	5.4–32	Georgi and Teik (1932)
4	Annual removal ha^{-1}	90.8	40.40	131.1	–	–	Eckstein et al. (1937)
5	156 mature palms ha^{-1}	116.6	40.40	141.2	–	–	Carvalho (1947)
6	150 palms ha^{-1} with 50 nuts palm^{-1} year^{-1}	58.3	17. 90	53.8	29.1	44.8	Cooke (1950)
7	70 palms ha^{-1}	10.2	2.40	12.9	–	–	Nethsinghe (1960)
8	173 palms ha^{-1} with 40 nuts palm^{-1}	56.0	11.90	70.0	33.9	12.5	Pillai and Davis (1963)
9	173 palms ha^{-1} with 40 nuts palm^{-1}	96.0	20.80	120.0	61.8	21.9	Ramadasan and Lal (1966)
10	60 nuts palm^{-1}	72.0	39.00	108.0	–	–	Nathanael (1969)
11	100 nuts palm^{-1} (nuts-whole palm)	120.0	18.00	85.0	–	–	Khanna and Nair (1977)
		157.0	28.00	346.0			
12	Annual removal ha^{-1} (1.5 t copra ha^{-1})	95.0	9.00	117.0	65.0	–	Ouvrier and Ochs (1978)
13	Annual removal ha^{-1} (6.7 t copra ha^{-1})	174.0	20.00	249.0	70.0	39.0	Manciot et al. (1979b)
14	Annual removal ha^{-1} (200 palms ha^{-1})	142.0	17.00	202.0	82.0	28.0	Omoti et al. (1986a)
15	Dwarf coconut (200 nuts palm^{-1} year^{-1}	87.71	12.44	169.8	6.02	9.48	Sobral (1998)
16	15,000 nuts ha^{-1} year^{-1}	50.0	6.00	106.0	–	14.0	Somasiri et al. (2003)
17	Coconut yield 7500 nuts ha^{-1}	32.6	4.2	80.1	–	4.4	Gunathilake and Manjula (2006)

At a given soil-plant environment, the export of nutrients by the palm is an indicator of its nutrient requirement in addition to other related soil environmental parameters. In perennial plantation crops such as coconut, it is often difficult to measure nutrient removal since all parts of the plant cannot be analysed for their nutrient contents periodically. However, estimates of annual removal of nutrients by the palm reported by workers from different coconut growing countries of the world are presented in Table 8.10.

An insight into the nutrient exhaust data shows that though there are variations in the absolute values reported by different workers, the results generally indicate that the quantitative sequential order of importance of the major mineral nutrients for the adult coconut palm is $K > N > P \geq Mg > Ca$ (Nathanael 1967). Reports on chemical analysis of the various parts of the palms in Nigeria showed the predominance of $K > N > Ca > Mg > P$ in the export of nutrients (Omoti et al. 1986a).

The sequence of nutrient export by hybrid PB 121 as K > Cl > N > Ca > Na > Mg > S > P shows the predominant requirement of chlorine (Ouvrier and Ochs 1978). Quoting the above data and those of Copeland (1931), Manciot et al. (1979b) reported that for the same yield of copra, there is no difference in the quantity of uptake between hybrid and tall coconuts. The uptake of different nutrients by coconut seedlings is also more or less in the same order (K > N > Cl > Ca > Mg > P) with K as the greatest and P the least absorbed (Santiago 1978). It is obvious that the dominant requirement in the nutrition of the palm is for K, while the least required nutrient is P.

The importance of a soil nutrient for the palm changes as the palms grows as demanded by its physiological requirements. The order of nutrient requirement for young palms is N > P > K > Mg, while that for adult palms (fruit-bearing trees) is K > Mg > N > P (Tennakoon 2004). In the coconut belt of south-western Ghana, the order of nutrient requirement for restoration of nut yield potential in mature coconut is K > P > N > Mg (Andoh-Mensah et al. 2003). According to Khan et al. (1986b), Tennakoon (2004) and Okeri et al. (2007), coconut palm responds positively to fertilizer, and the response is normally higher when Mg is included.

Detailed studies were conducted by Pillai and Davis (1963) on the removal of nutrients by West Coast Tall palms in India and that for the hybrid PB 121 in West Africa by Ouvrier and Ochs (1978). Even though the differences in the absolute values reported by these authors are large, there is agreement in the pattern of removal. The percentage removal of nutrients through different parts of the tall palm and the annual export of nutrients by the hybrid PB 121 are presented in Tables 8.11 and 8.12.

Table 8.11 Percentage removal of nutrients by different parts of WCT palm

Parts of the palm	Nutrient removal (%)				
	N	P	K	Ca	Mg
Nuts	43.0	40.0	63.0	15.3	25.0
Peduncles	4.2	7.0	12.1	3.3	11.4
Spathes	3.5	2.9	2.7	4.5	4.9
Leaf with stipules	41.2	45.1	12.4	73.8	56.5
Stem	8.1	5.0	9.8	3.1	2.2
Total	100.0	100.0	100.0	100.0	100.0

Table 8.12 Annual exhaust of major nutrients (kg ha^{-1}) by the hybrid PB 121

Particulars	N	P	K	Ca	Mg	Na	Cl	S
Total uptake for yield (6.7 t copra ha^{-1}) and growth of stem and leaves	174	20.0	249.0	70.0	39.0	54	249	30.0
Uptake for yield alone (6.7 t copra ha^{-1})	108	14.7	193.1	9.3	15.4	20	125	8.5
Difference (uptake for the growth of stem and leaves)	66	5.3	55.9	61.0	23.6	34	124	21.5

Table 8.13 Partitioning of nutrients; percentage removal of nutrients for the yield of nuts and for the growth and development of stem and leaves

Cultivar	Plant part	N	P	K	Ca	Mg	Na	CI	S
West Coast Tall	Stem + leaves	49	50	22	77	59	–	–	–
	Nuts	51	50	78	23	41	–	–	–
Hybrid PB 121	Stem + leaves	38	25	22	87	62	63	50	70
	Nuts	62	75	78	13	38	37	50	30

For a comparative assessment, the percentage removal of nutrients for the development of bunches with nuts and for the growth of stem and leaves is computed and presented in Table 8.13. For both the tall and the hybrid, the quantity of K exhausted through the harvest of bunches is 78%, and that used for the growth of stem and leaves is only 22%. Among all the nutrients, the largest removal as well as the highest proportion in the nut harvest is K which suggests that maximum utilization of K is for the productivity of the palm irrespective of the variety.

The hybrid palms (PB 121) require more N and P as compared to tall palms and utilize higher proportion of absorbed N and P for the production of more nuts. In tall palms these nutrients are utilized more or less equally in the production of nuts and for growth. For both cultivars, the K removal through bunches is 78% of K uptake. Calcium is utilized more for the production of leaves and stem and least for nuts. Since Ca is not a very mobile element and its concentration in the leaf tissues increases with maturity, it is quite probable that a higher proportion of this element is exhausted through the shedding of leaves. Unlike K, the proportion of Ca used for the development of bunches is the least, while the one used for the growth and development of stem and leaves is the highest suggesting the importance of Ca for the proper growth and functioning of the leaves and stem. Moreover, Ca plays a major part in the formation of cell walls. Thus, among the nutrients, Ca is the least involved in increasing the nut yield of bearing palms, but it helps in the healthy growth of leaves.

In the case of Mg, the quantity removed for the growth of stem and leaves is about 60%, while that exhausted through the harvest of bunches is about 40%. Magnesium is the only metal constituent of the chlorophyll molecule and is concerned in a variety of enzyme reactions in which it acts as the most effective activator. Thus, Mg is an important element in the nutrition of the palm and is mostly required for the effective functioning of the leaves, and through its photosynthetic function, it very much regulates the growth as well as the productivity of the palm.

Though the total quantity of Cl export by the hybrid is equal to that of K, the quantity used for the development of bunches ranks second, next to K, which makes it the second most required nutrient for productivity as reported for PB 121 hybrid. Its requirements for vegetative and reproductive growth are equal, and hence Cl-bearing fertilizers assume significance in coconut nutrition as opined by Oguis et al. (1979). However, its role in the physiology of the palm is not clearly understood in spite of its high requirement. Sodium and sulphur are more utilized for the growth of stem and leaves than for the development of nuts. Pillai and Davis (1963) from India and Ouvrier and Ochs (1978) from Côte d'Ivoire suggested that the dominant requirement of the palm is for potassium and probably chlorine.

The high productivity of the hybrid is invariably accompanied by a proportionate increase in the uptake of nutrients, particularly N and K, from the soil. The above data further suggest the importance of adequate nutrition to hybrids for higher yields and that regular fertilizer application is necessary to maintain a balanced supply of nutrients for sustained productivity (Khan et al. 1986a; Khan 1993).

According to von Uexkull (1978), around 10.5 g K is lost and immobilized for every nut harvested. Low yields (below 40 nuts palm^{-1} year^{-1}) can usually be sustained by the soil reserves of nutrient without replacing the K removed. At about 150 nuts palm^{-1}, yields can usually only be maintained if the total amount removed is replaced by soil application. At the highest yield levels, application should exceed actual removal because applied K is used less efficiently at that level and K concentration in the soil solution should be raised.

The PB 121 is capable of producing up to 6.0 t of copra ha^{-1} year^{-1}. The determination of annual exports of mineral elements (Ouvrier and Ochs 1980) revealed that a yield of 6 t of copra removed a fertilizer equivalent of 1450 g of urea (46% N), 600 g of tricalcium phosphate (38% P_2O_5), 2500 g of KCl (60% K_2O) and 500 g of Kieserite (33% MgO). These exports, however, represent only a part of the total requirements of the palm.

The removal of K from the soil by a coconut plantation with a population of 150 palms ha^{-1} at a production level of 7500 nuts ha^{-1} year^{-1} (50 nuts palm^{-1} year^{-1}) given by Mahindapala and Pinto (1991) indicates that husk removes 34% and nut water 27% of K (Table 8.14).

The annual exhaust computed from 1 hectare of 173 palms in sandy loam soil was 65.6, 29.7, 84.5, 47.4 and 20.3 kg of N, P_2O_5, K_2O, CaO and MgO, respectively, taking into account the nuts, fallen leaves, spathes and the stem growth (Pillai and Davis 1963). The amounts of macronutrients lost through the removal of plant components from the field of Typica × Typica coconut palms yielding an average of 17380 nuts ha^{-1} year^{-1} in Sri Lanka were 116.79 kg N, 14.02 kg P, 245.43 kg K, 40.47 kg Ca and 33.66 kg Mg ha^{-1} year^{-1}. The amounts of micronutrients lost were 1.14 kg Fe, 0.63 kg Mn, 0.13 kg Cu, 0.44 kg Zn and 0.26 kg B ha^{-1} year^{-1} (Somasiri et al. 2003). Potash

Table 8.14 The removal K from a coconut plantation having 150 palms ha^{-1}

Component		Amount of K removed	
		kg ha^{-1}	g palm^{-1}
Flower parts		1	7
Frond	a) Petiole	7	47
	b) Leaflets	32	213
Nut	a) Husk	45	300
	b) Shell and kernel	11	73
	c) Nut water	36	240
Total		132	880

was found to be removed the most, followed by nitrogen, calcium, magnesium and phosphorus. The quantity of nutrients removed varies with the soil type and yield. Palms growing on coastal alluvium removed 70 kg K_2O ha^{-1}, but the average removal from red sandy loam and laterite was around 53 kg K_2O ha^{-1}.

As the trees grow older, the total amounts of P and other nutrients immobilized in the system increase. Chew (1978) and Omoti et al. (1986b) reported that over a 25-year life cycle, about 9–10 kg P ha^{-1} is immobilized in the trunks each year. The removal of P in nuts (husks, shells, albumen and water) varies with yield. Immobilized nutrients are important for palms as they sustain the growth of the palm, and as assimilates increase in the system, the nutrients are partitioned towards vegetative and reproductive needs.

8.7 Long–Term Impact of Fertilization on Nutrient Status

In all coconut growing countries, fertilizer application and its impact on sustainable yields has been demonstrated. Fertilizer application over years has given sufficient lessons to understand its impact on management of groves considering the physical and chemical changes it has brought on soil health, plant nutrient contents and tailor management practices for sustainable yields.

Annual application of NPK fertilizers over an 18-year period to coconut on red sandy loam soil in a high rainfall region of Kerala, India, resulted in a marked increase in soil available P and K but only a minimal increase in mineralizable N (Khan et al. 1986a). In monitoring the healthy coconut groves, they suggested that leaf analysis gives a better reflection of the effect of N fertilizer than soil analysis and slightly lower values even in fertilized plots compared to the critical level of N established elsewhere (Table 8.15). The study also suggested that maintaining 15 ppm available P (Bray I) in soil in the manuring circle is sufficient to maintain optimum P nutrition of palms.

Table 8.15 Effect of different levels of fertilizer on plant (14th leaf) nutrient status of three genotypes

		Percent						ppm			
Genotype	Fertilizer level	N	P	K	Ca	Mg	Na	Zn	Mn	Cu	Fe
WCT	M_0	1.4	0.11	0.7	0.23	0.23	0.25	20	593	6	93
	M_1	1.7	0.11	1.0	0.33	0.17	0.23	18	711	6	86
	M_2	1.7	0.11	1.1	0.27	0.15	0.13	17	648	7	90
CDO × WCT	M_0	1.4	0.11	0.6	0.26	0.22	0.24	19	599	6	99
	M_1	1.6	0.11	1.0	0.26	0.13	0.11	16	585	8	108
	M_2	1.7	0.11	1.1	0.27	0.11	0.10	15	620	9	108
WCT × CDO	M_0	1.4	0.11	0.6	0.25	0.26	0.27	24	521	10	96
	M_1	1.6	0.11	1.0	0.26	0.16	0.14	18	615	8	86
	M_2	1.6	0.11	1.1	0.30	0.15	0.11	16	678	8	73

M_0: No fertilizer, M_1: 500 g N, 220 g P and 830 g K, M_2: 1000 g N, 440 g P and 1660 g K

Table 8.16 Long-term effect of fertilization on available potassium status of red sandy loam soil (Arenic Paleustults) at different soil depths

Fertilizer level N/P/K (g palm^{-1} year^{-1})	Irrigated condition Available K (ppm)		Rainfed condition Available K (ppm)	
	0–25 cm	25–50 cm	0–25 cm	25–50 cm
M_0 (No fertilizer)	79	38	66	66
M_1 (500:218:833)	110	69	202	153
M_2 (1000:437:1667)	212	129	318	235

Fertilizers applied to coconut for longer periods (1965–1984) also lowered the soil pH (5.17–4.13) probably as a result of increase in Mn content, and it also decreased the plant Zn status, however, insignificantly. The superiority of COD × WCT hybrids over the reciprocal cross and WCT palms was also indicated (Khan et al. 1986a). In an extension of the above study, a modified treatment structure with irrigation to palms was introduced (1984–1985), and the findings were reported by Srinivasa Reddy et al. (2002). They observed that after 32 years of fertilizer application, the available soil K content was 66 ppm in M_0 plot under rainfed condition, which increased to 202 ppm and 318 ppm, respectively, at 0–25 cm soil depth with M_1 (500:220:830 g) and M_2 (1000:440:1660 g N, P, K palm^{-1} year^{-1}) levels of fertilizer application. Under irrigation, a reduction in soil available K was observed in M_1 and M_2 plots (Table 8.16). Application of K fertilizers raised the leaf K levels to 1.14% (M_1) and 1.25% (M_2) compared to 1.07% in M_0 under rainfed condition probably because of ready availability under the moisture regime. Under irrigation, leaf K content was 1.07% under M_1 and 1.20% under M_2 compared to 0.90% under $M_{0.}$

Application of K fertilizer at M_1 level was found to maintain K content of leaves above critical level (0.8–1.0%). This study suggests that doubling the K levels had little effect indicating that rates beyond 830 g K (1000 g K_2O) year^{-1} are probably not needed. Thus, a soil available K (1 N NH_4OAc) content of 50–60 ppm (0.128–0.153 meq 100 g^{-1}) is adequate for maintaining sufficiency levels in coconut palms. Annual application of fertilizers also resulted in a marked increase in available phosphorus and potassium status in soil, but a marginal change in soil available nitrogen status was observed. Foliar contents of N remained below the critical levels of 1.8–2.0%. Phosphorus build-up in the soil due to fertilizers did not reflect in the P contents of diagnostic leaf under both rainfed and irrigated conditions. Application of K fertilizer at M_1 level maintained K content of leaves at 1.07%, i.e. just above the critical level.

Manciot et al. (1979b) reported that 0.15–0.20 meq 100 g^{-1} (59–78 ppm) and Loganathan and Balakrishnamurti (1980) suggested that 0.13 meq 100 g^{-1} (51 ppm) of exchangeable K is sufficient for satisfactory growth of coconut palm.

In another long-term study in littoral sandy soil at Kasaragod, India, the available K status of the soil (0–100 cm depth) increased from 50.2 ppm at K_1 level (750 g K_2O palm^{-1} year^{1}) to 95.9 ppm at K_2 level (1250 g K_2O palm^{-1} year^{-1}) to 105.56 at K_3

level (1750 g K_2O palm^{-1} year^{-1}) (Srinivasa Reddy et al. 1999). These values of soil available K corroborate with the statement by Biddappa et al. (1993) that a soil available K content of 50–60 ppm is adequate for maintaining the sufficiency levels in coconut. Joseph and Wahid (1997) have observed that the application of KCl resulted in a large increase in K reserves in soil to depth of 100 cm. The increase in K content was nearly 200 ppm within this depth. Relatively less accumulation of K was noticed in the 0–50 cm root zone than below it.

Smith (1968) emphasized the importance of K not only for the faster development and vigorous growth but also for reducing the pre-bearing period of palms. The palms, which received adequate nutrition from the beginning, produced more yield than those supplied after maturity. In coconut experiments in the Côte d'Ivoire (Fremond and Ouvrier 1971), the effect of applying K and the time of field planting was compared to withholding K applications until the age of bearing. The latter practice was inferior for all palms. Thus, the yield potential and also the precocity of fruiting of coconut palms depended much on the K supply of the young palms.

In a sandy loam soil at Kasaragod, Kerala, palms which received 1.0 kg N and 1.5 kg K_2O flowered first (Nelliat et al. 1978). Similarly, palms fertilized with KCl and N or NP from transplanting time in an inland-upland area of the Philippines recorded initial flowering in less than 4 years and significantly higher nut and copra production than those palms, which did not receive KCl (Mendoza and Prudente 1972).

In a 5-year study in a high rainfall laterite soil region with different carriers of phosphorus for coconut, viz. single superphosphate, ammonium phosphate, nitrophosphate and rock phosphate, Khan et al. (1985a) suggested rock phosphate as the ideal carrier of P and use of ammonium phosphate, to be discouraged as continued use may lead to extreme acidic conditions in the rhizosphere region though it is a soluble P carrier. They further observed that build-up of P in the plant system could be achieved only over a period of time compared to N and K.

Studying the residual effect of applied phosphorus to coconut palms after 14 years, Khan et al. (1992) observed that though the available P levels reduced to a mean value of 12.72 ppm (0–90 cm depth) from 43.88 ppm, it maintained the leaf P levels (frond 14) as 0.119% without bringing any reduction in yield. In the P-skipped plot, the mycorrhizal infection might have played a significant role in P nutrition (mobilization) of palms (Table 8.17).

Table 8.17 VA mycorrhizal association in different P treatments

Treatment	Per cent colonization	Intensity of infection (%)	Spore count (g^{-10} soil)
P_0	79.29	38.14	128.86
P_1	52.14	20.14	94.00
P2	47.86	17.43	81.86

8.8 Role of Mineral Nutrients

The perennial nature of the coconut palm as well as its extensive root system poses considerable challenges in carrying out plant nutritional studies. However, various studies have been carried out in the different coconut growing countries of the world, and the present state of knowledge on the role of individual nutrients on growth and productivity of the palm is presented in this section.

8.8.1 Nitrogen

Nitrogen is one of the primary nutrients which is universally limiting the growth and yield of crops including that of coconut. It is an essential constituent of amino acids, proteins and nucleic acids and also of the green colouring matter chlorophyll. The shortage of nitrogen results in retarded growth and chlorosis.

8.8.1.1 Behaviour in the Palm

A basic understanding of nitrogen in the coconut plant system was presented by Ohler (1999). Braconnier et al. (1992) analysing 4-year-old coconut trees, 3.5 months after applying isotopically labelled nitrogen (^{15}N), found that total nitrogen distribution in the plant is related to the distribution of dry matter. Thus, leaves contained 66% of total nitrogen of aerial parts. Differences between these findings are probably due to age differences between groups. The highest labelled N percentages were recorded for the spear, bud and green spathes, indicating that developing organs are considerable sinks of nitrogen. By contrast, stipules and dry spathes, which did not grow and had low physiological activity, had low-labelled N percentages. However, the percentage in the stem was surprisingly high, although growth of this organ was nil. The same situation was found in older leaves. Apparently N fertilizer was distributed in all leaves, indicating that labelled N in different organs has rather rapid turnover. These observations confirm the existence of an influx and afflux of nitrogen in each leaf, whatever its rank. The proportion of nitrogen in coconut seems to be in continuous flux. Labelled N was distributed in all parts of coconut, except in stipules and dry spathes, indicating N distribution throughout the tree. Little nitrogen fertilizer was distributed into mature bunches, indicating that N nutrition of albumen comes mainly from the husk and shell. Thus, N fertilization would influence production only 8–10 months after fertilizer application.

The N concentration in the leaf varies with its position on the crown. It progressively increases up to the sixth or seventh leaf and then decreases with maturity and drops down to a low level when senescence advances. It also shows marked seasonal and diurnal variations. Its content is invariably high during cooler and wet periods than hot summer months. The N flux in the crown is minimum during summer months due to the low water content in the soil. Diurnally the N content increases up to 10–11 AM, and then it decreases as the day progresses.

The critical level of 1.8–2.0% N in frond 14 is widely accepted as a guide for regulating the N nutrition of the palm. Thus, leaf analysis is found to be the best diagnostic method for predicting the N demand as well as the possible N deficiency in the palm. The interaction between N and P, N and K and N and S are generally positive on growth and productivity of the palm. In case of nitrogen deficiency, heavy doses of nitrogen fertilizer may result in rapid improvement of leaf colour and photosynthetic capacity, giving yield responses compared with other elements. Ohler (1999) observed that both in the heavy soil (Port Bello) and on a minerally poor sandy soil (Barra) in Mozambique, palms reacted strongly within 1 year for fertilizer application, the canopy colour changing from light yellowish to dark green. The reactions to other elements, when applied without N, were rather insignificant. Manciot et al. (1980) reported that only after N levels in the palms had normalized, potassium deficiency became apparent. Khan et al. (1986a) observed that N content of leaf gives a better indication of fertilizer application with nitrogenous fertilizers than soil analysis.

8.8.1.2 Deficiency Symptoms, Causes and Correction

Visible symptoms of N deficiency on coconut were described by different workers (Fremond et al. 1966; Manciot et al. 1979b). The specific symptoms are yellowing of foliage in varying degrees and stunted growth. In the initial stages, the palm loses the healthy green colour, and the whole foliage exhibits a slight and continuous yellowing. When the deficiency advances, the older leaves are affected the most and may develop uniform golden yellow colour, while the younger leaves turn pale green giving the leaflets a dull appearance with a diffuse underlying yellowing. This is accompanied by the abortion of many of the inflorescences, and the number of female flowers per inflorescence becomes less. N deficiency limited female flower production, rate of bunch production and yield (Smith 1969).

Nitrogen deficiency is commonly observed, under dry climatic conditions which inhibit nitrification and N absorption, on calcareous soils where alkalinity impedes mineralization of organic matter and on sandy soils that are deficient in organic matter and also in waterlogged situations. Deficiency can also result from exhaustion of the soil by continuous mining of nutrients for longer periods without adequate replenishment. The size of the leaves gradually gets reduced, and the number of functioning leaves becomes less. In the advanced stages, the stem below the crown narrows to a “pencil point”-like appearance with few short leaves on the crown. Inflorescences fail to emerge, if any emerges will have very few or no female flowers and ultimately the palm becomes unproductive (Fig. 8.1). In potted seedlings under N deficient condition, the newly emerged leaves appear pale, abnormally short and non-succulent. Nitrogen deficiency is more common in young palms.

Fig. 8.1 Symptoms of nitrogen deficiency. (Photo: Jacob John)

Coconut responds well to the application of nitrogenous fertilizers and organic manures in almost all soil types, and the response is maximum in light-textured sandy soils and lateritic soils. Field experiments conducted in different parts of the world have demonstrated a response to manuring with nitrogenous fertilizers. It increases all the growth parameters of young palms, reduces the pre-bearing age and increases the rate of frond and bunch production. The female flower production and the number of nuts palm^{-1} are increased significantly. The full expression of the beneficial effect of N occurs in the presence of adequate levels of P, K and S in the soil. In New Guinea, the application of S and urea together produced spectacular response on vegetative growth and foliage colour of young palms (Charles 1968). In Jamaica, Smith (1968) found significant increase in growth characters of young palms due to application of nitrogenous fertilizers. A further study in Jamaica showed that N increased the production of bunches (Anon 1967). In India, Muliyar and Nelliat (1971) observed about 17% increase in yield of nuts, but the copra weight nut^{-1} was depressed by N (Table 8.18). It is generally experienced that when nitrogen considerably increased the number of nuts produced, it very significantly lowered the copra content of the nuts (Manciot et al. 1980).

Similar responses to nitrogen applications were reported in different coconut growing countries (Manciot et al. 1979b). In an experiment on quartz sand soil from 1987 to 1992 in north-eastern Brazil, Sobral and Leal (1999) observed that N influ-

Table 8.18 Effect of different levels of N on yield of nuts and copra content

N levels (kg palm^{-1} year^{-1})	Mean annual yield (nuts palm^{-1})	Copra weight (g nut^{-1})
N_O - (0.0)	47.8	179
N_1 - (0.34)	55.9	165
N_2 - (0.68)	54.7	162

enced the number of nuts and considered 1.718% as the critical N level. Sobral (2004) observed an increase in the number of nuts in dwarf green coconut palms when the plant was receiving nitrogen in the form of urea in the fertilizer programme.

8.8.2 Phosphorus

Among all the major nutrients, the quantitative requirement of P is the least. According to Manciot et al. (1979b), P uptake is nearly one tenth of total uptake of potassium and that of chlorine as well. It is not usually a limiting factor in most of the coconut growing areas of the world. Although generally known as a macroelement, phosphorus is taken by coconut in modest quantities. Phosphorus is an essential constituent of many vital cellular compounds like ATP, ADP, AMP, RNA, DNA and other phosphorylated sugars and fats. It is mostly concentrated in the growing points like tender leaves and root tips of the palm. The leaf P content decreases with maturity as evidenced by the leaf content across the crown. It is high during cooler and wet periods and low during dry summer months. Both seasonal and diurnal variability influence the leaf P concentration.

8.8.2.1 Behaviour in the Palm

The beneficial role of P on adult coconut palms has always been a debating question as far as its direct role in the yield of palms. Eden et al. (1963) in Sri Lanka, Pandalai and Marar (1964) in India, Smith (1968) in Jamaica, von Uexkull (1972) and Barile and Azuceana Jr (1972) in the Philippines did not realize much improvement in the yield of adult coconut palms due to the application of P-containing fertilizers. Wahid et al. (1975) observed no reduction in either soil or foliar levels of P when fertilizer with phosphorus was discontinued for 1 year. Application of P was found to increase leaf production, girth at collar and root density of coconut seedlings, lower the age of flowering and reduce the incidence of leaf disease caused by the fungus *Helminthosporium incurvatum* in young palms (Loganathan et al. 1984). The growth as indicated by leaf production and age of flowering was largely influenced by application of P. Discussing the influence of Mg on assimilation of phosphorus, Nethsinghe (1963) observed that when Mg was deficient, the movement of P within the plant is hampered and under such conditions the palm may experience double deficiencies of P and Mg and according to de Silva (1973), this could occur even if the palm is supplied with an available source of phosphorus.

8.8.2.2 Deficiency Symptoms, Causes and Correction

Specific instances of P deficiency were rarely reported. There was no characteristic visual symptom apart from slowing down of growth and shortening of fronds (Manciot et al. 1979b). Phosphorus deficiency in young palms in sand culture manifested stunted growth and rosette appearance. The leaves were dark green and they could not come out fully from the stipules. The older leaves showed severe drying (Velasco et al. 1960). The delayed flowering in certain palms in Bandirippuwa (Sri Lanka) was attributed to an induced lowering of P in fronds caused by a lower uptake of Mg by the roots (de Silva et al. 1973). In a global review on mineral nutrition and fertilization of coconut, Manciot et al. (1979b) reported that there are only a few instances in Madagascar, India, Sri Lanka and Côte d'Ivoire in which the favourable effect of P manuring on coconut yield was noticed and that too after several years of continuous P application to palms. Commenting on P manuring of coconuts in Sri Lanka, Halliday and Sylvester (1954) stated that there was no response to P application at Bandiruppuwa where the soil contained adequate reserves of P, but experiments on poor lateritic soils of Veyanagoda and Ahangama with low P resources in the soil gave response to P application at 275 g P_2O_5 palm^{-1} once in 2 years. Summarizing the contribution of. IRHO on the study of mineral nutrition, Fremond (1964) reported that P did not show much beneficial effect in increasing either the yield of nuts or copra content. But in the presence of K, P was found to have beneficial effects. However, nuts were larger where P was applied (Smith 1969).

Being the least mobile element in the soil, the loss of P by leaching is the minimum among all major nutrients. Various studies have shown that the continued use of P fertilizers can substantially increase the available soil P, and the residual effect was observed a number of years later. In Sri Lanka good responses were obtained on very poor latosols containing only traces of available P, when P was applied at 0.12 kg palm^{-1}. The soil P potential was then built up to a level, at which discontinuance of P application did not lead to any reduction in yield for at least 5 years (Child 1974).

Reduction of soil available P from 84 to 59 ppm at 0–30 cm depth and 24 to 13 ppm at 30–60 cm depth in the coconut basins was observed over years by Khan et al. (1983) in India when application of P fertilizer to adult coconut palms was resorted to. Neither a reduction in soil available P nor an increase consequent to fertilizer application at two levels for about 6 years had significantly influenced foliar P levels and yield. The palms, however, were receiving regularly fertilizers containing N and K as per schedule. The possibility of withholding application of phosphate fertilizers to adult coconut groves in soil where available P is around 24 ppm at 30–60 cm depth was suggested. Subsequent studies by Khan et al. (1990) showed that skipping P application for 14 years did not show any adverse effect

Table 8.19 Foliar P content (frond 14) and yield of nuts as influenced by levels of P application

P fertilizer as levels (palm^{-1} year^{-1})	Foliar P (%) (1989)	Yield (nuts palm^{-1}) 1985–1986	1986–1987	1987–1988	1988–1989
P_O (Zero P)	0.12	127	97	89	109
P_1 (160gP_2O_5)	0.12	130	85	98	102
P_2 (320 g P_2O_5)	0.11	138	93	96	109

either on yield or leaf P levels which suggest that utilization of built-up reserves in soil is the most ideal and economic way of management of coconut groves. Addition of green manures may further assist in dissolution and availability of P to palms. It also suggests the importance of soil testing in the P nutrition of palms (Table 8.19).

Based on the above study, it has been recommended that when the available soil P (Bray I) in the 0–90 cm soil is less than 10 ppm, apply the full recommended dose of 320 g P_2O_5, and if it is between 10 and 20 ppm, a maintenance dose of 160 g P_2O_5 palm^{-1} year^{-1} may be applied. If the available P is more than 20 ppm, P application can be skipped for a few years and monitored through soil analysis (Khan et al. 1992). A foliar content of 0.11–0.12% P (frond 14) can be regarded as sufficiency level for coconut under Indian conditions. The interaction between N and P and P and K is generally positive on growth and productivity of the palm, while that between P and Mg is positive on foliar P levels. Though the requirement of P is low compared to other nutrients, its role in interaction with other elements and its physiological functions cannot be undermined.

8.8.3 Potassium

Potassium is usually the least needed major nutrient in low-yield agriculture but rises to a dominant position when yields are maximized (von Uexkull 1985). The severity/frequency of K deficiency has been found to be one of the most limiting factors in the economic production of coconut all over the world, and conspicuous increases in yield have been obtained by its correction through potassium fertilization. The coconut palm is a K-demanding crop as large quantities of K are removed by the nuts of the palm (Fremond et al. 1966). A low-yield level of 40 nuts palm^{-1} year^{-1} in case of coconut can be sustained without replenishing the K to the soil; however, at yield levels of 150 nuts, all the K removed must be replenished. von Uexkull (1985) opined that the higher K demand may be due to the coarser root system and midday heat and moisture stress suffered by fully exposed leaves.

Potassium improved all the nut characters, viz. weight of whole nut, weight of husked nut, volume of husked nut and copra weight nut^{-1}, whereas nitrogen had an adverse effect. For palms yielding less than 60 nuts annually, the optimum dose of N ranged between 400 and 650 g and that of potash between 890 and 1210 g palm^{-1} year^{-1} (Muliyar and Nelliat 1971). In a long-term fertilizer experiment in red sandy loam soil in Kerala, significantly higher nut yield besides early bearing was achieved with increased levels of K application. The yield was 7, 68 and 77 nuts palm^{-1} year^{-1} in the 21st year after planting under no fertilizer, 450 g K_2O and 900 g K_2O palm^{-1} year^{-1}, respectively (Wahid et al. 1988).

8.8.3.1 Behaviour in the Palm

Potassium positively influences the number of inflorescences, increasing the production by increasing the number of fruits and the quantity of copra nut^{-1}. Coomans (1974) demonstrated that the K content in the leaf is influenced by production in view of the large quantities exported. Thus, plants of low productivity may have a high K content in the leaf, giving the impression of good nutrition. It is also observed that palms with higher yield load may have a slightly lower K content. Anilkumar and Wahid (1989) found that application of K caused a decrease in Ca and Mg in the leaf. Manciot et al. (1980) proposed as critical level for K on leaf 14 values between 0.8 and 1.0%.

The coconut palm is highly responsive to K which increases resistance to drought and disease, hastens maturity and increases fruit set and the number of harvested nuts (von Uexkull 1985). An adult palm (more than 10 years) yielding 1.8 t ha^{-1} of copra removes between 90 and 130 kg K ha^{-1} in 1 year. The number of coconuts required to produce 1 kg of copra was 4.5 with adequate K nutrition and 8 where palms were under K stress.

Potassium chloride is the most widely used fertilizer for both coconut and oil palms. It increases the size (weight) of the nuts and the copra yield, as well as the Cl and Ca concentration, but slightly decreases K in the leaves (von Uexkull and Sanders 1986).

Potassium is taken up by the palm as K^+ ions, and its absorption is antagonized by the presence of high concentrations of Ca, Mg and Na. The annual removal of K by the palm varies with the cultivars as well as the soil conditions. Total removal of K by the high-yielding varieties and hybrids is generally higher than that of low-yielding types. As mentioned earlier, 78% of the K exhaust is through the harvest of coconut bunches, out of which 60% is present in the husk (Ouvrier and Ochs 1978). That is, about 47% of the total K removed by the high-yielding hybrid is present in the husk.

The K concentration in the leaf varies with its position on the crown. It is high in young leaves which progressively decrease with maturity, indicating mobility of K to the younger leaves. The middle leaves do not show much seasonal variations in their K contents. However, in the young leaves, the K content is more during dry seasons and less during wet seasons, while in the older leaves, this trend is found reversed.

The widely accepted critical levels of K for traditional varieties and high-yielding hybrids are 0.8 to 1.0 and 1.4%, respectively (Manciot et al. 1979c). The K content in the index leaf often shows good correlation with nut yield. As the foliar K levels or the yield of nuts does not generally show significant correlation with soil K levels, leaf analysis is found to be the best diagnostic method for predicting/regulating the K nutrition of the palm. The critical level of K is about 1 g kg^{-1} DM (von Uexkull and Sanders 1986).

Manciot et al. (1979b) reported that there exist strong antagonisms between K-Ca, K-Mg and K-Na in coconut. Often, a higher quantity of fertilizer application was found to decrease Mg level in the tissue. Application of K led to a significant drop in the content of Ca, Mg and Na in the leaf. Further, Mg fertilization is beneficial only when the K is adequate in supply or the K deficiency is corrected. The results showed that Mg application had a beneficial effect on the copra yield only if K fertilizers were also applied. Similarly higher levels of K manuring increased the yield only in the presence of Mg. In fact, higher levels of K application had a depressive effect on copra yield in the absence of Mg fertilization. Wahid et al. (1974) found that the foliar content of K + Na decreased with increase in root CEC while Ca + Mg increased with increase in root CEC. The uptake of cations by the palm was found to be governed by their ratios in soil. Highly significant correlations were obtained between K/Na, K/(Ca + Mg) and K/Mg in soil and their corresponding ratios in the leaf. The negative correlation of root CEC and positive correlation of both soil and leaf potassium with yield indicated the role of potassium in improving the yield of coconut. Coomans (1977) observed that application of K had induced the Mg deficiency in coconut hybrid palms, but Mg application had no effect on leaf K level. However, Brunin (1970) reported that in tall cultivars when the leaf K levels were between 0.7 and 1.2 g kg^{-1}, application of high rates of Mg significantly reduced K contents.

Nutrient interaction studies have clearly demonstrated the antagonism between K-Ca, K-Mg and K-Na in the palm, among which the K-Mg antagonism is more severe and has been well documented (Manciot et al. 1979c; Khan et al. 1986a; Wahid et al. 1988). Heavy rates of K application induce Mg deficiency wherein both the absorption and functional antagonisms are operating in the palm. On the other hand, higher rates of Mg application in poor soils induce K deficiency conditions. The effect of higher application of potassium chloride on foliar nutrient levels is shown in Table 8.20.

Though the foliar contents of all the three cations, viz. Ca, Mg and Na, are depressed by higher doses of K (Khan et al. 1986b), the effect is highly pronounced on Mg ($r = -0.68^{**}$). While formulating higher fertilizer doses, particularly of K, for hybrids and other high-yielding genotypes, it is necessary to include proportionate quantities of Mg fertilizer salts to maintain a proper balance between K and Mg in the soil.

Table 8.20 Effect of higher levels of KCl application on foliar nutrient levels

	Foliar nutrient level (%)					
KCl (kg $palm^{-1}$ $year^{-1}$)	N	P	K	Ca	Mg	Na
Control	1.80	0.091	0.20	0.50	0.57	0.17
5	1.75	0.097	0.98	0.51	0.19	0.29
10	1.74	0.094	1.38	0.40	0.16	0.23
15	1.74	0.097	1.55	0.39	0.13	0.18

8.8.3.2 Deficiency Symptoms, Causes and Correction

The deficiency symptoms of K are usually perceptible only when the soil K levels are below 0.15 meq 100 g^{-1} and the leaf K level (frond 14) falls below 0.4%. The first visible symptom is the development of rusty spots in two longitudinal bands on either side of the midrib with their diameter ranging from 0.5 to 4.0 mm, which is accompanied by slight yellowing of the lamina. The yellowing is more marked towards the tip of the leaflets. When the yellowing intensifies, the older leaves assume an orange-red tinge, while the younger leaves remain green. The yellowing is never uniform. It is more intense along the edges of a leaflet leaving a central band along the midrib green. The individual leaflets are also greener at the base than towards the distal ends where necrosis sets in and the rusty spots coalesce into numerous irregular brown blotches. As the deficiency advances, the yellowed surface becomes necrotic resulting in more of a necrotic appearance than of yellowing (Fig. 8.2).

K deficiency leads to development of poor crown with short fronds. The growth is reduced, the trunk becomes slender, leaflets become short and the number of inflorescences, nut set and nuts $bunch^{-1}$ gets reduced (Salgado 1953; Menon and Pandalai 1960; Fremond et al. 1966; Smith 1969; Anon 1970; Manciot et al. 1979c, 1980; Liyanage 1999). An increase in the level of K in the leaves improves the precocity of flowering and increases number of female flowers, setting percentage, thereby increasing the number of bunches $palm^{-1}$, average copra nut^{-1} and total copra production $palm^{-1}$ (Anon 2010). Severe K deficiency in coconut has been noted on tertiary and quaternary sands of West Africa, on the coastal sands of Sambava (Madagascar), on the coral soils of the Oceania atolls, on the exhausted lateritic soils of India and on the sandy soils of the east coast of Sri Lanka (Manciot et al. 1979c).

Baseden and Southern (1959) in New Ireland observed that K was the main factor limiting coconut production. They reported K deficiency in coconuts on soils

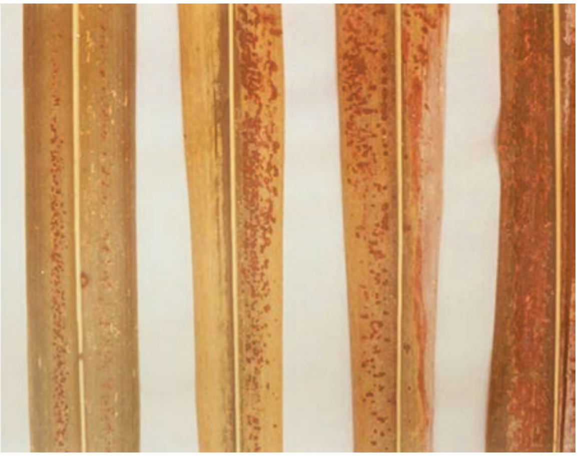

Fig. 8.2 K deficiency symptoms. (Photo: Jacob John)

developed over coral limestone, because of an imbalance in cations and the considerable amount of K removed with the husks and nuts. The wide range of productivity (from <5 to >60 nuts palm^{-1}), occurring among coconut palms on the coral-derived soils of eastern New Ireland, and the intensity of symptoms, such as chlorosis, smallness and sparseness of fronds, is closely related to the K levels found in nut waters, husks fronds and the soils. The better palms, with higher K status, occur on a narrow coastal strip of shallow, neutral to slightly acid, red-brown clay loams, and the poorer palms, with low K status, on much deeper, acid, yellow-brown clay, present on the inland side of the strip. On these soils, coconuts showed a dramatic response to K applications (Charles and Douglas 1965) which was also found in soils with high Mg/K ratios (Sumbak and Best 1976). Dootson et al. (1986) reported significant reduction in all growth parameters of MYD × WAT hybrid coconut in Thailand, except trunk length, due to non-application of K. Nitrogen and K were mutually antagonistic, and antagonism among cations was also observed.

Experiments in Sri Lanka by Salgado (1952) have shown that K has an effect on the earliness of bearing in the palm. Palms receiving K flowered in the fifth year of planting while those without K application flowered in the eighth year. When N application caused an 8% increase in copra yield, K application gave an increase of 25–39% (Salgado 1947).

The spectacular response to K fertilizer application on the yield of nuts at the Coconut Research Station, Balaramapuram, Kerala, on red loam soil (Wahid et al. 1988), showed the importance of K in augmenting coconut yield (Table 8.21). More than tenfold increase in yield was obtained with 450 g K_2O palm^{-1} year^{-1}, while it was about 13-fold increase with 900 g K_2O palm^{-1}year^{-1}.

Responses to K fertilization were reported from different coconut growing countries of the world (Prevot and Fremond 1961; Eden et al. 1963; Foale 1965). Fremond (1964) and Manciot et al. (1979c) observed that the application of K resulted in the improvement of all production factors such as the number of bunches

Table 8.21 Effect of K fertilization on the nut yield of West Coast Tall palms planted in 1964

	Mean yield (nuts palm^{-1})		
Year	K_0	K_1	K_2
1976	0.3	12.2	18.7
1977	1.0	21.3	29.1
1978	0.9	21.4	27.5
1979	0.8	28.1	38.2
1980	1.5	27.9	33.3
1981	4.6	36.1	41.8
1982	6.3	46.3	52.6
1983	3.4	33.5	40.0
1984	2.1	23.9	33.6
1985	6.7	67.7	77.0
Cumulative yield (1976–1985)	27.6	318.4	391.2

K_0 No potassium, K_1 450 g K_2O palm^{-1}year $^{-1}$, K_2 900 g K_2O palm^{-1} year^{-1}

palm^{-1}, number of female flowers bunch^{-1}, fruit setting, number of nuts bunch^{-1}, copra nut^{-1} and ultimately the total copra outturn palm^{-1}. Potassium application also improved all nut characters studied, viz. weight of whole nut, husked nut volume and copra weight nut^{-1} (Muliyar and Nelliat 1971).

The foliar K levels were also increased simultaneously to the sufficiency level. Fremond and Ouvrier (1971) found that the damage caused by K deficiency in the early stages was not fully corrected by subsequent K additions. Although later additions of K enabled the re-establishment of the palm in good physiological functioning, the palms which suffered K deficiency during the pre-bearing stage remained, on an average, 15% less productive than those never suffered. Therefore, it is necessary that, for maximum productivity, adequate K nutrition should be ensured early from the time of field planting.

8.8.4 Calcium

Calcium is a less mobile element in the plant, and it functions mainly outside the cytoplasm in the apoplast. In contrast to other macronutrients, a high proportion of Ca in plant tissues is present in the cell walls. It is very much concerned in membrane stability and cell integrity and helps the maintenance of acid-base equilibrium in the sap. In contrast to K or Mg, Ca activates only a limited number of enzymes in plants. In coconut palm, Ca is mainly concerned for the proper growth and functioning of stem and leaves rather than the productivity of nuts. Cecil (1981) observed that when all the major nutrients had been regularly applied since field planting, the length and width of the leaflets were significantly increased only with Ca treatment. Its concentration is low in young leaves, which progressively increases with maturity of the fronds. The remobilization of Ca is low in the coconut crown because of the relatively immobile nature of the element. Cellular distribution studies indicated that Ca was found to be high in polar compounds followed by cellulose and lignin fractions of leaf tissues of the palm.

The Ca content in most of the coconut growing soils of the world is satisfactory. The calcium added through phosphatic fertilizer is considered to be quite adequate for sustaining the Ca requirement of the palm. In very acid soils, regulated additions of liming materials are needed for ameliorating the soil acidity and other related problems. Concentration beyond certain limit would decrease the coconut yield probably due to its interaction effects with other nutrients.

8.8.4.1 Behaviour in the Palm

Only limited reports are available on the responses of coconut to Ca treatment. Manciot et al. (1979c) remarked that application of calcium carbonate to tall coconut in Côte d'Ivoire for 4 consecutive years had no beneficial influence on yield. On the other hand, lime dressing alone (Wilshaw 1941) and lime with fertilizers (Vertueil 1934) were reported to have beneficial effects on nut yield in Malaya and Trinidad, respectively, but it is not clear whether the beneficial effects reported by them were the direct influence of Ca in the nutrition of the palm. Cecil (1984) observed some favourable effects of liming on growth as well as foliar Ca levels of young palms, but the foliar levels were not correlated with growth/flowering or initial yields. The foliar Ca content even without Ca treatment was above 0.3% (frond 14) which is considered to be the critical level of Ca by Magat (1979).

The critical level of Ca initially suggested by IRHO was 0.5% for the tall variety (Fremond 1964). But values lower than this have been very widely reported on healthy plantations without any adverse effect on yield or foliar conditions. Manciot et al. (1979c) suggested that 0.3–0.4% Ca content in frond 14 was satisfactory and no improvement on growth or yield could be expected from application of fertilizers containing calcium. In Malaya, Kanapathy (1971) proposed an optimum level of 0.15–0.30% Ca for talls, semi-talls and dwarfs. Magat (1979) opined that the critical level of Ca initially suggested by IRHO appeared to be too high for the Philippine conditions. According to him, the critical level of Ca followed in the Philippines is 0.3%. Cecil (1984) also suggested 0.3% Ca in frond 14 for regulating the Ca requirement of the palm under west coast conditions of India. The leaf Ca contents are generally increased by nitrogen and Ca-bearing phosphatic fertilization, while it is depressed by higher levels of K and Mg fertilizers.

8.8.4.2 Deficiency Symptoms, Causes and Correction

Calcium deficiency in coconut was rarely reported. Visual symptoms of Ca deficiency were recently reported in Côte d'Ivoire on Malayan Yellow Dwarf with leaf Ca levels below 0.1% (Manciot et al. 1979c). The symptoms are yellowing of leaflet tips with yellow to orange ring-shaped spots, spread on the leaflets which later become necrotic and brown, and the leaf dries up. Middle leaves are affected before the oldest. The first symptoms of Ca deficiency appear on leaf numbers 1, 2 and 3, and they become yellow and rounded, turning brown at the centre. The spots are isolated in the early stages, joining and drying later on. In young leaves, the spots are uniformly distributed; however, starting from leaf number 4, the spots are concentrated at the base of the leaf. Plants with such symptoms contained only 0.85 g kg^{-1} Ca in leaf number 4 (Dufour et al. 1984).

Salgado (1947) reported that the lime requirement of coconut in Sri Lanka could be adequately met by the Ca present in Ca-bearing fertilizers. It is suggested that heavy liming is not needed for the management of the palm which is known to grow well under a wide range of soil pH ranging from 3.5 (peat soil) to 8.5 (coral soil). Nevertheless, regulated additions of Ca through Ca-bearing fertilizers or light addition of liming materials may be followed for supplying the Ca requirement of the palm (Cecil 1981). This is all the more important, in view of the heavy loss of Ca by crop removal and also by excessive leaching under high rainfall conditions in the tropics.

8.8.5 *Magnesium*

Magnesium is considered as the fourth important major nutrient in coconut nutrition. Its major function is as the central atom of the chlorophyll molecule. It is actively involved in Mg-dependent ATPase activity in the plant membrane where proton pumping operates. It also has an essential function as a bridging element for the aggregation of ribosomal subunits which is necessary for protein synthesis. When the level of Mg is deficient, in the presence of excessive levels of K, protein synthesis is impaired. Chlorosis of matured leaves is the most obvious visible symptom of Mg deficiency.

8.8.5.1 Behaviour in the Palm

The concentration of Mg is low in younger leaves which gradually increases reaching the maximum in the fully expanded leaves and then decreases with the progress of senescence of the leaves. This shows a high order of Mg fluxes in the coconut crown. Under normal growing conditions, the leaf number 14 or 15 is found to be the buffered leaf where the influx and efflux of Mg are equal. Leaves younger to the buffer leaf import considerable quantity of Mg, while older leaves export it. The Mg content in the leaf is highly influenced by diurnal as well as seasonal variations.

8.8.5.2 Deficiency Symptoms, Causes and Correction

Symptoms of Mg deficiency in coconut were reported by different workers (Coomans 1977; de Silva 1966; Fremond et al. 1966; Manciot et al. 1979c; Jeganathan 1990). Mg deficiency symptoms appear first in the old leaves. When the deficiency becomes severe, there is a necrosis on the extremities of the leaflets, which become dark yellow. At this stage translucent spots become visible. The visual symptoms are characterized by yellowing of the leaflets on the oldest leaves, going from the tips towards the rachis of the leaf. When the deficiency is fairly severe, the leaflet is almost devoid of pigmentation, but the parts nearest the rachis remain green. As the deficiency advances, yellowing becomes intense near the periphery of the leaf blade leaving a narrow longitudinal green band parallel to the midrib on either side of the leaflet. When the deficiency gets worse, yellowing further intensifies, the number of green leaves become less and necrosis sets in at the tips of the leaflets. Magnesium-deficient leaves are more sensitive to sunlight as the part exposed to sunlight shows intense yellowing, while shaded part of the same leaflet remains green (Fig. 8.3).

When the deficiency becomes severe, intense yellowing accompanied by severe necrosis and browning develop, and the mature leaves wither away prematurely leading to a lesser number of functioning leaves on the crown. The frond production rate is reduced, onset of bearing is delayed in young palms and the productivity is adversely affected.

Fig. 8.3 Magnesium deficiency symptoms. (Photo: Jacob John)

Magnesium is observed to be one of the important elements in the nutrition of seedlings and young palms especially when the soil supply is low (Khan et al. 1994). Magnesium deficiency is more common in acid sandy soils in view of their low Mg status and imbalance of K, Mg and Ca. Specific instances of absolute Mg deficiency situations are found in West Africa (Brunin 1969), Sri Lanka (De Silva 1966) and India (Cecil 1969). Nethsinghe (1959) reported Mg deficiency in lateritic soils of high rainfall areas where palms responded to foliar spray with magnesium sulphate. Prolonged use of K fertilizers, especially at higher rates, has been found to depress foliar Mg content and induce Mg deficiency conditions in the palm.

Application of Mg-containing fertilizers (Kieserite ($Mg\ SO_4\ H_2O$)/Epsom salt ($Mg\ SO_4$)/dolomite($Ca\ Mg(CO_{3)2}$ /magnesite ($Mg\ CO_3$)) corrects the deficiency very well resulting in the regreening of chlorotic foliage/prevention of chlorosis accompanied by increase in foliar Mg levels and improvement in growth and yield of nuts. Child (1974) suggested that the application of Mg was necessary for the successful nursery culture of coconut in Sri Lanka. Fremond et al. (1966) recommended 60 g $Mg\ SO_4$ seedling^{-1} in the nursery along with similar quantities of double superphosphate and muriate of potash. Balanced application of N, K and Mg from the time of field planting was indispensable for the successful cultivation of hybrid coconut in Côte d'Ivoire (Coomans (1977), and he obtained highly significant response with 600 g Kieserite palm^{-1} year^{-1}. Varkey et al. (1979) obtained 87% decrease in foliar yellowing and 95% increase in yield of affected palms by the application of 500 g $Mg\ SO_4$ palm^{-1} year^{-1}. Kamalakshiamma et al. (1982) applied two levels of Mg, viz. 500 and 1000 g MgO palm^{-1} year^{-1} as $Mg\ SO_4$ along with three levels of NPK to D × T hybrids since planting. The second level of Mg did not generally show any significant increase over the first. Cecil (1981) observed highly significant response on growth, flowering and initial yields of young palms with 500 g MgO palm^{-1} year^{-1}. Nethsinghe (1962) obtained complete recovery of yellowing in 3–5 months by fortnightly spraying with 1–2% solution of Mg SO_4. He further suggested that soil application of Mg SO_4 was more effective than dolomite, while the latter could be used for long-term remedy. It was observed that the main effect of Mg on yield could be as much as 40% when K was in the sufficiency level, but unlike K, magnesium influenced only the number of nuts palm $^{-1}$ and had no effect on the copra nut^{-1} (Manciot et al. 1979c; Cecil 1981). A review of nutrition experiments in Sri Lanka involving magnesium was discussed by Jeganathan (1993).

As a preventive measure against occurrence of Mg deficiency of coconut palms, it is recommended to apply 1 kg of dolomite palm^{-1} year^{-1} along with NPK fertilizers. But when Mg deficiency symptoms appear in palms, 1 kg of Kieserite palm^{-1} has to be applied biannually until the disorder is corrected (Mahindapala and Pinto 1991). Nevertheless, the planters' experience is that it takes a long time to correct Mg deficiency even by application of Kieserite along with NPK fertilizer mixtures, particularly in palms on red-yellow podzolic soils with laterite in the wet zone which are highly leached.

The critical level of Mg initially suggested by IRHO was 0.3% (frond 14) for the tall variety (Fremond 1964). However, lower values have been found in healthy palms without any foliar symptoms of deficiency. In Côte d'Ivoire, the application of Mg showed a highly significant effect in increasing the yield of nuts palm^{-1} and copra palm^{-1}, and the foliar Mg level was also simultaneously increased at a highly significant level from 0.098 to 0.23%. In Sri Lanka, Nethsinghe (1963) suggested that deficiency symptoms could be expected when the Mg content (frond 6) was less than 0.2%.

There has been a general decline in Mg levels, probably due to the potassium chloride applications necessitated by the severe potassium deficiency in the Côte d'Ivoire coconut plantations. The critical levels proposed by the IRHO, 0.3% for Mg, are confirmed by Brunin (1970).

In India, Kamala Devi et al. (1973) observed a mean foliar content of 0.18% Mg in three high-yielding genotypes, viz. high-yielding talls, dwarf × tall and tall × dwarf hybrids. Cecil (1975) recorded 0.08% Mg in palms showing severe Mg deficiency symptoms and 0.18% Mg in apparently healthy palms without any visual symptom of deficiency. Cecil (1981) and Dufour et al. (1984) proposed an optimum level of 0.3% Mg for talls, semi-talls and dwarfs, while 0.2% Mg was reported to be critical under the Philippine conditions (Magat 1976). Manciot et al. (1979c) suggested 0.24% Mg for talls and 0.2% Mg for hybrids during the initial bearing periods. Cecil (1981, 1988) suggested that a critical level of 0.2% (frond 14) may be adopted as a diagnostic aid for regulating Mg nutrition of the palm under west coast condition of India until specific critical levels for each variety/type are established.

8.8.5.3 Interactions

Nitrogen fertilization often depresses the leaf Mg levels, possibly due to the antagonistic effect of NH_4^+ ions on Mg absorption by the palm. On the other hand, phosphatic fertilization generally increased foliar Mg levels and vice versa, indicating a close synergistic relation between P and Mg in the nutrition of the palm. Potassium fertilization generally depresses Mg uptake by the palm. Cecil (1981) observed a depressive effect of K on leaf Mg content when the soil and the leaf Mg contents were low and an effect when the Mg levels were improved due to regular Mg additions. On the other hand, Smith (1967), von Uexkull (1972), Barrent (1977) and Rosenquist (1980) reported an increase in foliar Mg levels by K fertilization. The results of Margate et al. (1979b) showed that even up to a level of 8.0 kg KCl palm^{-1} year^{-1}, the leaf Mg content (frond 14) remained more or less stationary (0.216%). Cecil (1988) suggested that the action of K fertilizers on leaf Mg content largely depends on the balance between K and Mg in the soil. The depressive action is severe when the exchangeable Mg/K ratio in the soil is less than 2.0–2.5. At higher Mg/K ratios, the action is not significant. A negative linear relationship between K and Mg in the soil was found (Limbaga 1986; Giritharan et al. 2000). Khan et al. (1986a) and Goh and Sahak (1988) reported that Mg leaf levels decreased significantly and linearly to increasing rates of K. It has been observed that application of high levels of K fertilizer induces Mg deficiency in coconut palms particularly on red-yellow podzolic soils with laterite in the subsoil (Jeganathan 1990). It has been a general observation that application of NPK coconut fertilizer mixture without application of dolomite induces Mg deficiency in palms on most of the soils. Brunin (1970) and Coomans (1977) reported that it was only after K deficiency has been corrected that Mg manuring was found to have a positive effect on production.

Application of potassium fertilizer decreased the quantity of both exchangeable and water-extractable Mg, and magnesium fertilizer decreased the quantity of exchangeable K in soils (Somasiri 1997). The mutual decreasing effect on the exchangeable fraction of each nutrient is attributed to low cation exchange capacity and base saturation of the soils. The close association of the coconut leaf nutrient contents with soil nutrient status implies that poor chemical characteristics of red-yellow podzolic soils bring about imbalance of K and Mg nutrition in coconut palms. The results showed that application of potassium fertilizer to the coconut palm would drastically affect the magnesium status of the palm on lateritic soils despite Mg fertilizer application. In the presence of K fertilizer, even the application of Kieserite at 1.2 kg palm^{-1}was not sufficient to raise the Mg status of the palm to the sufficiency range. It is very difficult to balance K and Mg nutrition of coconut palms grown on highly leached red-yellow podzolic soils with laterite, just by application of inorganic fertilizers due to their poor soil characteristics such as low cation exchange capacity and base saturation. This problem could be overcome by improving cation exchange capacity of such soils by increasing the humus content of the soils by organic matter incorporation. According to Somasiri et al. (2003), the dolomite supplied in fertilizer schedule does not necessarily meet the Mg lost from a coconut land, and Tennakoon and Bandara (2003) opined that organic manures only have the ability to partially supply the requirement of Mg demand of coconut palm.

8.8.6 Sulphur

Sulphur is an essential component of organic structure like sulpholipids in cell membranes and is a constituent of amino acids cysteine and methionine. It is also a constituent of several coenzymes and prosthetic groups such as ferredoxin, biotin and thiamine pyrophosphate. It also plays a key role in the redox systems in plants. Sulphur deficiency inhibits protein synthesis and causes a reduction in the chlorophyll content.

8.8.6.1 Behaviour in the Palm

S is an important secondary nutrient for coconut. It is involved in oil synthesis, copra quality as well as chlorophyll synthesis; coconut takes up considerable amount of S from the soil for its annual growth and productivity. The S distribution in the coconut crown follows a similar pattern as that of nitrogen. This is primarily because of the close interrelationship between these elements in the biosynthetic processes in coconut. However, unlike nitrogen, S is more uniformly distributed between old and young leaves. Young leaves generally have low concentration of S which is gradually increased up to middle-aged leaves beyond which the concentration is decreased.

8.8.6.2 Deficiency Symptoms, Causes and Correction

In coconut, S deficiency exhibits some similarity to that of N deficiency. Major observations on the S requirement of the palm and its deficiency symptoms were reported by Southern (1969) and Ollagnier and Ochs (1972). Sulphur deficiency symptoms are easily differentiated from those of N deficiency since the latter does not affect the young leaves unless the deficiency is very severe. The colour of affected leaves is yellowish orange to orange in S-deficient palm, while under N deficiency the colour of the foliage is pale green to yellow. The nut size of N-deficient palms may become small, but it produces normal copra on drying. In the case of palms with S deficiency, the kernel becomes rubbery (rubbery copra). S improves oil percentage, protein content and marketability of copra.

The most important source of S is the sulphate present in the soil which is taken up by roots even though atmospheric SO_2 is taken up and utilized by the aerial parts. Soils very low in organic matter and continuously cropped without adequate S fertilization are also likely to suffer from S deficiency. In the Philippines, coconuts grown even on soils derived from volcanic materials could suffer from S deficiency under high rainfall conditions. In India, up to the 1970s, S was added to coconut indirectly through S-containing fertilizers such as superphosphate and ammonium sulphate. Thereafter, the use of sulphur-free fertilizers like urea and rock phosphate was found to cause shortage in supply of sulphur to the palm. Regular use of S-containing fertilizers could take care of the sulphur needs of the palm. Organic farming is an alternate approach for S management. In situ organic recycling and/or additions of organic manures in the coconut basin would improve the organic S status of the soil which is further released into the inorganic form on mineralization. This process also checks the possible loss of S through leaching.

Coconut palms respond well to S fertilization. Maximum response to S is obtained when other nutrient anions, particularly NO_3 and Cl, are also applied at the required levels. Sulphur application increased the total yield of fruits and weight of copra but decreased the weight of kernel nut^{-1} (de Silva et al. 1985). The combined action of S and NO_3 and that of S and Cl is positive on growth as well as on yield of nuts and copra outturn. Ammonium sulphate is found to be a good fertilizer for correcting field conditions of S deficiency which is generally associated with foliar S content below 0.13%. The most frequently recommended fertilizer is ammonium sulphate which raises N and S levels at the same time (Wuidart 1994). Magat et al. (1991) using the data on yield and leaf nutrient contents from a gypsum-fertilization experiment derived a quadratic equation where 74.6% of the variation in yield of nuts palm^{-1} was accountable to the level of sulphur in the leaves. The critical and optimum levels of leaf S in the reference leaf were 0.12 and 0.19%, respectively. They opined that the leaf S deficiency level of 0.13% pointed out by Manciot et al. (1979c) is actually the critical level. It was also indicated that the value of 0.15% S suggested by Southern (1969) in foliar diagnosis is higher by 0.02%, while the range mentioned by Manciot et al. (1979c) as critical level (0.15–0.20% S) covers the optimum level of leaf S (0.19%) obtained in their study.

8.8.7 Sodium

The specific role of Na in plant is not yet established. However, it participates in non-specific functions in plants such as maintenance of cell turgor, electrical neutrality, osmoregulation and detoxification of excess of phenols. In recent years, it has been postulated that Na could release the locked-up K in cell vacuoles under K stress conditions and, thus, make available limited amounts of K for vital metabolic functions.

Briones (1931) made a study on the salt requirement of coconut seedlings in pots and found that moderate quantities of sodium chloride were invigorating, while higher doses were harmful. Addition of NaCl at 0.5 kg young plant^{-1} month^{-1} on a rocky laterite soil gave a distinct difference in vigour, size and colour after 15 months compared to untreated palms (Salgado 1951). The coconut grows well on soils rich in Na although there is no direct relationship between the Na content of soil and that present in the leaves (Fremond 1964). Harmer, quoted by Manciot et al. (1979c),

Table 8.22 Effect of NaCI on growth and flowering of young D × T hybrid and on yield of bearing West Coast Tall palms

Treatments (g adult palm^{-1} year^{-1})	D × T hybrid		West Coast Tall
$K_2O + Na_2O$	Fronds produced 1976 to 1985	Early flowering index	Mean posttreatment yield (nuts palm^{-1} year$^{-1)}$adjusted
0 + 0	73.9	1.0	69.7
1000 + 0	73.3	1.9	86.8
750 + 250	78.3	2.6	73.8
500 + 500	79.3	2.4	84.8
250 + 750	72.7	2.6	83.0
0+ 1000	77.5	2.4	75.0

grouped coconut among the plants which give a moderate response to Na even when there is plenty of potassium, while Jacques (1932) suggested that NaCl was also needed in the nutrition of the palm. Results obtained from young coconuts in the early stages of production showed that application of NaCl could significantly increase the number of inflorescences, the number of female flowers and the number of nuts palm^{-1}. Prema et al. (1987) in their studies in laterite soil region of Kerala observed that performance of palms in terms of yield was at par with palms receiving full dose of K_2O and 50% K_2O substituted with Na_2O. Preliminary studies indicated that Na to a certain extent substitutes the role of K when its supplies are inadequate. The copra content was also increased. Field studies conducted in India showed that addition of 50% of K requirement as NaCl and the rest as KCl did not show any difference in the growth of young palms or the productivity of bearing palms (Table 8.22). The early flowering index of NaCl-treated palms was higher than that of KCl-treated palms (Wahid et al. 1988). Irrigation with seawater and sweet water did not show any difference in the performance of the palms (Menon and Pandalai 1960).

Either as direct manure or as an indirect soil ameliorant, the addition of NaCl in coconut gardens has been a very old and popular practice among coconut growing farmers in Kerala, Java and Colombia (Child 1974; Manciot et al. 1979a). In Kerala, farmers apply it to the soil as well as in the crown of the palm, often admixed with wood ash, on the belief that it could increase the productivity of the palm. However, there is not much evidence on the direct effect of Na in increasing the yield of coconut. Since Na was applied in all the related studies in the form of NaCl, it is quite probable that the improvements in growth and yield obtained might be the effect of Cl which has been considered recently as an important nutrient in the nutrition of the palm for its effect on enhanced growth and productivity.

Fremond et al. (1966) suggested a maximum level of 0.40% Na (frond 14) beyond which adverse effects would be expected. The foliar Na contents reported by different workers normally range from 0.1% to 0.5%. The foliar level of 0.4% Na may be taken only as a rough guide as many coconut groves giving excellent yields have low Na levels around 0.1%. The leaf Na concentrations are generally depressed by K fertilization. Khan et al. (1986a) reported the relationship between K and Na as $r = -0.87^{**}$ in their studies involving tall and hybrid palms.

8.8.8 Chlorine

The specific functions of Cl in plants are not well understood. It is readily taken up by plants as chloride ion. It functions mainly as a highly mobile inorganic anion in processes related to charge compensation and osmoregulation. There is evidence to assume that Cl is required for the *photosystem II* in photosynthesis and it stimulates the membrane-bound proton-pumping ATPase activity. Chlorine can also influence photosynthesis and plant growth indirectly through stomatal regulation. Wilting of leaves, especially the leaf margins, is a typical symptom of Cl deficiency.

The essentiality of chlorine for higher plants was first established by Broyer et al. (1954), but its importance in the nutrition of two tropical oil-yielding crops, oil palm and coconut, was brought to light by Ollagnier and Ochs (1971a, b). They reported that oil palm and coconut gave significant yield increase due to Cl. They further emphasized the high requirement of this element and suggested to rank Cl as a major nutrient for coconut and oil palm. The high requirement of Cl for coconut was established later by Ouvrier and Ochs (1978), and they reported that for the high-yielding hybrid PB 121, the removal of Cl was equal to that of K, and Manciot et al. (1979c) ventured to rank Cl as the second most important nutrient, next to K, for coconut.

The response of coconut to other Cl-containing salts like KCl has also been noted, but the importance of Cl in coconut nutrition in certain countries was reported only in the 1970s (Ollagnier and Ochs 1971a, b; von Uexkull 1972; Magat et al. 1975). Chlorine in the form of either KCl or NaCl is easily absorbed by palms (Magat et al. 1975), and the amount of Cl in the soil depends on rain and seawater (Manciot et al. 1979c).

Chlorine increases the thickness of kernel and copra weight nut^{-1} as a result of a bigger cell volume. It also accelerates plant development in terms of girth and frond production rate. It enhances better absorption of other nutrients like K, Ca and Mg which contributes to accelerated growth and early flowering in coconut. von Uexkull (1972) found that Cl was the only foliar nutrient that was significantly correlated with growth of young palms and yield of bearing palms. He also demonstrated the importance of Cl for coconut when the application of KCl increased the weight of kernel from 117 to 216 g and the composition of Cl, from 0.40 to 2.33 g kg^{-1} in 14th leaf. Multiple regression analysis showed that 55.5% of increased nut production, 74.3% of increased copra yield nut^{-1}and 80.3% of increased copra palm^{-1} were due to chlorine (Margate et al. 1979b).

Similar highly significant correlations between Cl content in the leaves and growth/production of nuts of young/bearing palms were also reported by Magat and Prudente (1975). According to Prudente and Mendoza (1976), Cl is the most likely factor that limits production of inland coconut areas, especially in Davao, followed by N. The addition of 1.6 kg ammonium sulphate plus 1.8 kg muriate of potash tremendously increased production by 191%, 58% and 314% in terms of nut yield, copra weight nut^{-1} and copra production, respectively, over the palms with N fertilizer only. Nitrogen levels in the leaves are highly correlated with nut and copra production, while Cl levels with copra weight nut^{-1}, copra and nuts palm^{-1}.

Coconuts growing near seashore (where Cl is sufficient) are generally more productive than those growing on inland, supposed to be low-Cl areas. Studying the effect of long-term fertilization with different levels of KCl on bearing coconuts in the Philippines, Margate et al. (1979b) concluded that application of KCl at 2.0 kg palm^{-1} year^{-1} gave the highest production of nuts. Though copra weight nut^{-1} correspondingly increased with increasing levels, copra production did not follow a definite trend of response beyond 2.0 kg level of application. The palm receiving with 2.0 kg KCl palm^{-1} year^{-1} showed an increase in leaf Cl status from 0.04 to 0.55% and yielded 128 nuts against 87 nuts by the control palms, an increase of about 47%. The copra weight nut^{-1} was significantly increased with increased rate of KCI, and the response followed a linear pattern up to the highest level of 8.0 kg KCl palm^{-1} year^{-1}. It is very interesting to observe that even up to a treatment level of 8.0 kg KCl palm^{-1} year^{-1}, no significant correlation was obtained between foliar K levels and nuts palm^{-1}, copra nut^{-1} or copra palm^{-1}. The response of coconut in the study was due to the chlorine component and not to K. Mineral nutrition studies in the Philippines indicate that as a source of chlorine, NaCl can effectively replace KCl which is an expensive fertilizer.

The use of NaCl and seawater is an ancient and very common practice among coconut growers in many parts of the world (Bonneaux et al. 1997), and sufficient evidence supports the contribution of Cl to oil palm production. Palms contain little starch that can produce malate as the accompanying anion for K in their guard cells (von Uexkull and Sanders 1986), and, therefore, Cl plays a vital role in movement of stomata. Healthy coconut palms along the seashore usually contain Cl at a concentration of 7–10 g kg^{-1} DM in their foliage. The optimal Cl concentration is usually in the range of 4.5–5.5 g kg^{-1}. At Cl concentrations lower than 2.5 g kg^{-1}, coconut palms may exhibit some visual symptoms of yellowing and/or orange mottling of the older leaves and the leaf tips and edges (von Uexkull and Sanders 1986). For example, the threshold value for EC in a soil extract is 4.5 dS m^{-1}. Above this level, growth and copra yield begin to decline (Hassan and El-Samnoudi 1993). No copra yield was obtained when the EC value of the soil extract exceeded 23.2 dS m^{-1}, and salinity symptoms appeared on the leaves, but the trees survived. Soil salinity leads to an accumulation of Cl, Na and K in the leaves that of Cl was larger than that of Na and was highly correlated with salinity symptoms (Hassan and El-Samnoudi 1993).

Reports on Cl deficiency symptoms in coconut are limited. The visible symptoms are yellowing and/or orange mottling of the older leaves and drying up of the outer edges and tips of leaflets which are very similar to K deficiency. The nuts from Cl-deficient palms are smaller compared to nuts from palms well supplied with Cl. The number of leaves would be less with narrow leaflets, and the leaves are susceptible to leaf spot/blight diseases. The deficiency symptoms are associated with leaf Cl contents (frond 14 less than 0.3%) in adult palms.

Magat et al. (1977) suggested a critical level of 0.7–0.8% Cl in coconut seedlings (frond 3). Ollagnier and Ochs (1971b) proposed that for high yields of coconut, leaf level of 0.5–0.6% Cl was necessary. Magat (1979) suggested the critical level of Cl (frond 14) at 0.3–0.4% and optimum level of 0.5–0.6%. Chlorine is not generally found limiting in coconuts in Kerala, particularly when K is applied in the form of muriate of potash, in most cases leaf Cl levels range from 0.5% to 0.7%, which is well above the critical level.

Magat et al. (1986) noticed improvement in nut production, copra weight nut^{-1} and copra yield palm^{-1} over a 3-year period with the application of NaCl. They also found that only leaf Cl was highly correlated with the yield parameters studied, indicating that the increase in yield was mainly due to the correction of Cl deficiency by NaCl application. From their subsequent studies, Magat et al. (1988) suggested that NaCl could be used to replace KCl, which is an expensive fertilizer, the optimum economic NaCl rate for coconuts grown in the Tugbok clay loam and those grown in similar conditions being 3.8 kg palm^{-1} year^{-1} (yielding 25.9 kg copra), although the rate of 1 kg palm^{-1} year^{-1} already made it possible to obtain more than half of the positive effects corresponding to the optimum economic rate.

Findings at the Davao Research Centre of the Philippine Coconut Authority revealed that the annual application of fertilizer $(NH_4)_2SO_4$ and KCI significantly increased nut and copra yield of bearing palms (Mendoza and Prudente 1972). With the same fertilizer combination, genetically tall coconuts of the “Laguna” form were induced to flower in less than 4 years instead of the normal 6–7 years from field planting. von Uexkull (1972) reported that the response observed from KCl application is due to Cl and not to K, since Cl levels in the leaf were correlated with the growth of young palms and the production of bearing ones. On the other hand, separate studies on the use of NaCl, another Cl source, showed that its application improved the development and yield of the palms. However, the response was not attributed to the effect of Cl (Roperos and Bangoy 1967; Del Rosario 1972; Ramanandan 1973), whereas the positive response to KCI applications observed in earlier studies (Magat et al. 1975; Margate et al. 1979b; Magat et al. 1981b) is attributed to the Cl component of the fertilizer.

Practical recommendations for the application of chloride to coconut are available (IFA 1992). For coconuts under Malaysian conditions, the rate of application ranges from 0.11 kg Cl palm^{-1} at an age of 6 months and increasing progressively to 0.9 kg Cl palm^{-1}.

Positive residual effects of Cl-bearing fertilizers (KCl, NaCl and NH_4Cl) on the yield indices of coconuts were reported by Magat et al. (1991, 1993). They suggested that for every 5 years of regular Cl fertilization (0.80 kg Cl), the application of Cl fertilizers (and even N and S fertilizers) is not required for at least the next 3 years as production of nuts and copra is maintained at high levels. This was mainly attributed to the residual effects as a result of the concentration of Cl in the crop at optimum levels (0.50–0.60%) or above critical levels (0.30%) of leaf Cl. With NaCl application, the positive residual effects on copra (weight nut^{-1} and yield palm^{-1} year^{-1}) could last for a longer period (4–5 years) at fertilization rates of $>=$ 1.76 kg NaCl palm^{-1} (0.97–3.87 kg Cl palm^{-1} year^{-1}).

Drought and chlorine deficiency in Lampung province, Indonesia, were reported by von Uexkull (1992). Palms deficient in chlorine lose water at a much faster rate than those well supplied with Cl. Similarly palms deficient in chlorine require a much longer period to recover. On soils rich in K, NaCl or NH_4Cl can be used as a source of chlorine to palms.

8.8.9 Micronutrients

Micronutrients are mostly constituents of important enzyme reactions and involve themselves in the effective functioning of the nutrient system in the plants. The most important observations indicate that mineral nutrient deficiencies, mainly of micronutrients, cause reductions in the number of female flowers spathe^{-1} and the fruits, which eventually succeed easily drop off the plant, a condition generally referred to as “abortion of immature fruits” (Siqueira et al. 1997; Holanda et al. 2007).

8.8.9.1 Iron

Iron is an essential constituent of certain enzymes, especially the cytochromes, which participate in the electron transfer system. Iron is taken up by plants as Fe2^{+} ion and also as chelated iron molecules like Fe-EDTA. The distribution of iron in the coconut crown shows that its concentration is low in young leaves and increases gradually with maturity. The internal recycling of this nutrient is very much restricted. The subcellular distribution of Fe shows that the major fraction is in the immobile stage followed by proteins and polysaccharide fractions. Generally hybrids utilize iron into various functional sites better than tall variety of palms. The critical concentration of Fe is considered at 50 ppm in frond 14. However, lower values are found in palms growing on rich soils without exhibiting any visual symptoms of iron deficiency. Lime-induced chlorosis is the characteristic disorder in coconut on coral and limestone soils that are rich in calcium carbonate. Iron deficiency is also found on peat soils.

The characteristic symptom of iron deficiency in coconut is the gradual development of yellowing in all the leaves. The entire leaflet becomes yellow in longitudinal strips parallel to the veins, and the leaf becomes completely yellow in the advance stage. Necrosis is generally absent in any part of the leaflet. The rachis and leaflets become shorter. Symptoms of iron deficiency may appear similar to that of nitrogen deficiency. However, in the latter case, yellowing is uniform, while in the case of former, strip discolouration is noticed in the initial stages with yellowing becoming general in the advanced stage. The symptoms of Fe deficiency were described by Pomier (1969) on the Pacific Coralline Islands, where the high levels of calcium carbonate render the iron unavailable. Trewren (1987) reported that on coral line soils of Tuvalu (Pacific Ocean Island), stem injection with 30 g ferrous sulphate to palms is considered safe remedy against lime-induced chlorosis. Generally, in tropical soils the presence of iron oxides is adequate to satisfy the crop demand.

8.8.9.2 Manganese

Manganese acts as a cofactor in some of the oxidative enzymes in the plant. It also participates in the oxidation-reduction reactions in the plant. It is absorbed mainly as Mn^{2+} ion and is translocated predominantly as the free divalent cation from the roots to the aerial parts. Mn deficiency is characterized by generalized chlorosis. For coconuts grown in north-eastern Brazil, analysis of leaf number 14 showed great variability in the Mn composition. Sobral (1989), studying the nutritional state of coconuts in Sergipe, showed no direct relationship between Mn in leaves and the burned leaf symptom. It was observed, however, that there is a significant relationship between the composition of Mn in the soil and the leaf.

Davis and Pillai (1966) reported that Mn could increase the yield of nuts in coconut. According to Pomier (1967), the application of K is effective only when the needs of Fe, Mn, and N are satisfied. Kamala Devi et al. (1975) noticed enhancement in the availability of Mn, Fe and Al in soil with lowering of pH by NPK treatments. However, only Mn was taken up by the palm in larger amounts. Water-soluble Mn in soil was highly correlated with plant uptake. Mn has indirect effect in the chlorophyll formation (Mandal 2000), and, therefore, deficiency of Mn can result in reduction of photosynthetic material such as carbohydrates.

The distribution of Mn in the coconut crown follows a pattern similar to that of Fe. Its concentration is low in young leaves and increases with maturity. The critical level of Mn is considered as 60 ppm in frond 14. It is not found to be a limiting nutrient in acid tropical soils. On the other hand, concentrations as high as 700–800 ppm Mn in frond 14 have been reported on lateritic and red sandy loam soils. However, Mn deficiency is found on coral soils, which is corrected by the application of Mn salts as foliar sprays and through trunk injection. Addition of organics charged with Fe and Mn salts is yet another method of supplementing these nutrients in calcareous soils.

8.8.9.3 Boron

Boron is a relatively immobile element in phloem but highly mobile in xylem accounting for accumulation of B in older tissues and also in margins. It is very closely related to the activity of moisture stress especially apical-meristem. When in short supply, normal cell division does not proceed satisfactorily to complete separation of cells whose longitudinal walls remain short. This results in incomplete and irregular leaf expansion, the development of distorted leaves and lack of elongation of internodes. B deficiency occurs due to accumulation of super-optima levels of endogenous IAA, probably due to reduced activity of IAA oxidase.

It improves water relations and translocation of sugars in plants, enhances tissue respiration, and influences N metabolism and the oxidation-reduction equilibria in cells. Boron deficiency affects the cells of the growing regions, and the effects are observed on the differentiating cells leading to the death of the apical growing point preceded by abnormal/deformed growth of young leaves.

In the coconut palms, B deficiency decreases the photosynthetic capacity, since it reduces the electron transportation of *photosystem II* (−12.5%), photosynthesis (35.7%), sweating (−32.2%) and stomatal conductance (−45.6%) (Pinho et al. 2010). Boron deficiency also compromises the coconut palm's radicular system, decreasing the percentage of fine roots and increasing the percentage of thick roots, causing over sprouting, necrosis, darkening and thickening of roots (Power and Woods 1997). With the compromising of the radicular system, the plant can possibly present secondary deficiencies and be more susceptive to hydric deficit, blight and diseases.

In nature, B is moderately rare and occurs principally as borates of calcium and sodium. It occurs in soils in the form of tourmaline (*crystalline borosilicate mineral*). Its availability is maximum within the pH range of 5 and 7. Boron is less available above the pH of 7.5. Excessive liming accentuates boron deficiency.

Symptoms of B deficiency become visible as soon as the leaves emerge, which occurs 2 or more months after the occurrence of the deficiency. Boron deficiency can also be chronic, affecting a series of successive leaves as they develop. As an immobile element, B deficiency causes leaflet fusion and malformation, truncation and reduction in the size of newly emerging leaves (Broschat 2007a; Corrado et al. 1992; Kamalakshiamma and Shanavas 2002). These symptoms could be confused with deficiencies of other micronutrients, such as manganese, zinc or copper, herbicide toxicities or even bud rot diseases (Broschat 2007b; Elliott et al. 2004). Where visual deficiency symptoms are insufficient to diagnose chronic B deficiency, leaf nutrient analysis can be useful (Mills and Jones Jr 1996).

Boron deficiency can be extremely transient, affecting developing leaves for as little as a day or two before normal growth resumes. Under these conditions, the effects of a temporary deficiency only become visible when the affected developing leaf emerges 4 or more months after the deficiency occurred. Palms may experience multiple alternating periods of B sufficiency and deficiency during the time that it takes for the first affected leaf to emerge. Thus, visual deficiency symptoms are an indication that a temporary B deficiency has occurred before leaf emergence but provides no clues as to the current B status of the palm (Rajaratnam 1973).

B deficiency is manifested in the leaflets, which are joined at the extremities (Fig. 8.4). In severe cases the leaflets at the base of the stem are smaller and crest and may even disappear. When B deficiency is very severe, the point of growth completely deforms, preventing the development of the palm (Corrado et al. 1992; Kamalakshiamma and Shanavas 2002; Santos et al. 2003; Broschat 2005; Broschat 2007a). Boron deficiency, in general, reduces root growth (Lima Filho and Malavolta 1997; Viégas et al. 2004), and in the coconut palm, production of total roots is

Fig. 8.4 Boron deficiency symptoms in adult coconut palm (Photo: V. Krishnakumar)

reduced by 30% and of thin roots by 48% (Pinho et al. 2008a). According to Broschat (2009), B deficiency can be transient to chronic and mild to lethal in palms. If this temporary deficiency is severe enough, the entire tip of the leaf beyond the necrotic point will often fall off. This very temporary deficiency is believed to be caused by a single heavy leaching event lasting as little as one day. In rainy climates, this pattern may be repeated every time a heavy leaching rainfall occurs, and as many as 3, such events have been documented during the development of a single leaf of a coconut palm (Broschat 2007a).

Santos et al. (2004), in an evaluation of the nutritional status of a coconut palm, reported that the most important elements for coconut production in decreasing importance were K > Ca > B. Manciot et al. (1980); Rognon (1984) and Sobral (1998) observed that a critical boron level in plant leaves was 10 mg kg^{-1}. Boron deficiency may be limiting yield at high rates of application of sulphate of ammonia and muriate of potash (Rosenquist 1980). B deficiency has become a common and widespread disorder of palms throughout the world (Corrado et al. 1992; Elliott et al. 2004; Broschat 2007a). A deficiency symptom varies from palm to palm, and all the symptoms may not be expressed on a single palm (Kamalakshiamma et al. 2005).

General recommendations for the application of boron to coconut plants are that young palms should receive 30 g of borax applied to the fourth leaf axilla. For yielding palms, it is recommended that borax should be applied directly into the soil at 2 kg ha^{-1} of B as borax (Sobral 1998) when analysis indicates levels lower than 0.2 mg dm^{-3} (hot water soluble) (Teixeira et al. 2005b). The application of B directly into the soil is more efficient than foliar techniques due to the low mobility it shows in plant tissues. Boron applied to the soil has a more persistent effect than when it is deposited in leaf axillae (Pinho et al. 2008b; Broschat 2011). Recommendations about B dosages to be applied to coconut palms are limited in the literature (Teixeira and da Silva 2003; Santos et al. 2003).

Leaf B concentrations did not vary significantly among leaves within the canopy or among leaflets within a single leaf for coconut palm (Broschat 2011). Boron concentrations were significantly higher towards the tips of individual leaflets. Application of Solubor to the soil significantly increased leaf B concentrations in all leaves of coconut palm after 2 months as well as in new leaves produced up to 6 months later. Application of Solubor as a leaf axil drench was much less effective in increasing foliar B concentrations than soil treatment. Thus, there appears to be no advantage to applying B to the axils of palm leaves when soil application is both efficient and effective. In young coconuts, deficiency may be corrected by applying 30 g of borax at the axil of leaf number 4. In adult coconuts, B can be added as borax mixed with other fertilizers and added to the soil. Because the limits of deficiency and toxicity are very close, elevated doses of B may cause toxicity in the plant.

Soil applications of 40–700 g of borax palm^{-1} year^{-1} have been suggested by Dickey (1977), von Uexkull and Fairhurst (1991) and Kamalakshiamma and Shanavas (2002). Some of these workers also suggested applying borates in the leaf axils, but they provided no data on the relative effectiveness of these two methods. Healthy palms had higher B content (6.9–7.9 ppm) compared to (4.7–6.3 ppm) in diseased palms, and Ca/B ratio was found to be lower in healthy palms (Baranwal et al. 1989). They recommended soil application of Borax at 50 g palm^{-1} in Assam and West Bengal where boron deficiency was noticed on young palms.

A fertilizer dosage of N, P and K at 0, 1 and 2 kg ha^{-1} resulted in leaf boron concentration levels lower than the considered critical level (10 mg kg^{-1}) as indicated by Manciot et al. (1980), Rognon (1984) and Sobral (1998). Teixeira and da Silva (2003), in a study of 2-year-old coconut palm of 7 genotypes growing in Bebedouro, State of São Paulo, Brazil, found foliar B levels higher than 10 mg kg^{-1} (43.9–47.9 mg kg^{-1} of B in leaf 9).

An understanding of natural B distribution patterns within palm canopies and leaves is necessary to determine which leaves should be sampled for analysis. In the same context, Rajaratnam (1973) indicated that a temporary B deficiency has occurred before leaf emergence but provides no clues as to the current B status of the palm. Considering this, Oertli (1994) opined that leaf analysis for B content may not always be a good indicator of current B status. Nevertheless, boron contents indicated by leaf analysis are taken as a guide for understanding and boron application to palms (Broschat 1997).

Jayasekara and Loganathan (1988) noticed the symptoms as unsplit, crinkled nature of leaflets, stunted and withered apical leaves and lack of leaflets in some fronds of young palms of 1–3 years. The third leaf of the affected palms had 3.4–7.5 ppm B as compared to 7.6–10.0 ppm B for healthy palms in the same vicinity. Soil application of sodium tetraborate (Na_2 $BO_4.2H_2O$) at 28 and 56 g palm^{-1} to the affected palms at incipient stages improved the condition of palms within 6 months, and complete recovery was achieved at the end of 8 months. However, the symptoms in the untreated affected palms gradually became acute, and the palms died after 6–8 months. Results suggest that the critical nutrient concentration range for B in the third leaf is 8–10 ppm and the deficiency could be corrected only at the incipient stages by soil application of sodium tetraborate.

Table 8.23 Recommendations for correcting boron deficiency in coconut palms

Sl no	Area	Recommendation
1	West Bengal (India)	20 g palm^{-1} borax decahydrate (11.5%) *
2	Kerala (India)	200 g palm^{-1} borax decahydrate followed by irrigation*
3	Assam (India)	50 g palm^{-1} borax repeat twice in severe cases at an interval of 3–4 months*
4	Côte d'Ivoire (W Africa)	Borax pentahydrate (14.8% B) 15 g palm^{-1} once in 6 months*
5	Sri Lanka	28–56 g sodium tetraborate to incipient stages **

* Compiled by Khan (1993); ** Jayasekara and Loganathan (1988)

Recommendations for correcting boron deficiency in coconut palms is given in Table 8.23.

Some academic studies describe the distribution of B in the leaves of coconut palm. In palms not fertilized with B, the tendency is to have similar contents in young and in old leaves; in those fertilized, however, the content of B increases, but it does not follow a consistent pattern of distribution between young and older leaves (Pinho et al. 2008b; Broschat 2011). The correction of the deficiency in coconut palms is possible after application of B (Santos et al. 2003). Doses of 30 g and 60 g of boric acid palm^{-1}, applied without dilution at the leaf axils or in the soil, respectively, adequately nourish the palm and do not cause toxicity (Pinho et al. 2008b).

Santos et al. (2003) observed that applying boron in young coconut palms promoted the emission of normal leaves, but did not correct the symptom of leaves already affected by B deficiency. Thus, to reduce potential decline in productivity, management of fertilization with B should be done to prevent disability and prevent the formation of abnormal leaves.

Boron deficiency in coconut in the northern region of the State of Rio de Janeiro was found by Mirisola Son (1997) and Santos et al. (2003). For the correction of this deficiency, it was recommended the use of 30 g of borax in the axilla of fourth leaf of young plants. In adult plants, borax could be mixed with other fertilizers and soil (Sobral 1998). Santos et al. (2003) found that providing 30 g of borax, divided into 2 applications of 15 g in the axils of leaves 2, 3 and 4, promoted the emission of normal leaves of coconut dwarf green plants showing epinasty and deflections of the new leaves, symptoms attributed to B deficiency (Sobral 1998; Macêdo et al. 1999; Broschat 2005). The higher palm yield was associated to levels of 0.6 mg dm^{-3} of B in the soil and 23.5 mg kg^{-1} in leaves. The maximum production was obtained in 95% of palms with the use of a boron dosage of 2.1 kg ha^{-1} (Moura et al. 2013). The leaf and leaflets become deformed due to deficiency of B (Pinho et al. 2015). The deficient and sufficient contents of B varied significantly in the canopy but did not vary in leaves. To study the level of B in the coconut palm, they suggested to use samples taken from the youngest leaf and to calculate the relation between the B content in the apex of the leaflet and the content in the centre or in the bottom leaflets. Little is known about the trace element contents of Papua New Guinea soils, but some studies were carried out by Southern and Dick (1969) to diagnose characteristic symptoms of B deficiency through leaf analysis and critical level varied between 5 and 10 ppm, depending on the site.

8.8.9.4 Copper and Zinc

Both copper and zinc are associated in certain enzyme systems in plants. They are taken up by plants as Cu^{++} and Zn^{++} ions and also as chelated molecules. Their deficiencies are not commonly found in coconut.

Copper deficiency has been observed in coconuts, in the Philippines, in new plantings, especially with improved planting materials or hybrids on peat soils (Magat 1991). The characteristic symptoms include severe bending of rachis of the young leaves accompanied by yellowing and drying of leaf tip which appears rimmed with brown and yellow, while the middle portion remains normal green. When the deficiency is severe, new leaves are deformed and are abnormally short giving the palm a runty sagging appearance. Deficiency of Cu in coconuts was described by Ochs et al. (1993) when the palms were grown in peat soils in Indonesia. Firstly, the stems of the new leaves become flaccid and later bend. Almost simultaneously, the extremities of the leaflets start to dry, colour changing from green to yellow and, finally, to brown – appearing burnt. When the deficiency is serious, new leaves become small and chlorotic, and the plant may dry completely. Earlier Ochs and Bonneau (1998) studied Cu and Fe deficiency symptoms in peat soils of Indonesia and opined that leaf contents in commercial plantations gradually increase with age and deficiency is seen in young palms rather than in the older ones. In Brazil, Cu deficiency was found in coconuts planted in Quartz Neosols (SiBCS) (Sandy Quartz) (Sobral et al. 2007).

Zn deficiency causes abnormal growth of the young leaves (Mandal 2000). The abnormal growth of the leaves was observed on the palms under the Kish Island environmental conditions of south Iran (Arzani et al. 2005). These abnormal leaves become rough in the surface and not fully expanded might be due to reduction in the photosynthetic activity of such leaves and further reduction of carbohydrates and lower female flower production.

The optimum levels of copper and zinc in coconut nutrition are not known, and hence, their critical levels are not established. However, levels of 5–7 ppm Cu and 10–15 ppm Zn in frond 14 are found to be adequate for the normal growth of the palm. The foliar contents reported by Southern and Dick (1968) were 2–5 ppm Cu and 19–36 ppm Zn. Pillai et al. (1975) reported mean values of 6.5–7.7 ppm Cu and 8.8–11.9 ppm Zn.

The distribution of zinc in the coconut crown shows that in young leaves the concentration is relatively low which gradually increases in the middle-aged leaves and then it declines. In the case of copper, the concentration does not show much variation among the different leaves. However, the copper concentration is relatively higher in older leaves.

Table 8.24 Fertilizer recommendations for B, Cu, Mn and Zn based on soil and leaf analysis

Nutrient/Analysis method	Soil (mg dm^{-3})	Leaf number and nutrient content (mg kg^{-1})		Fertilizer (g $plant^{-1}$)
		9	14	
Boron (hot water)	0–0.6	<17	<20	Borax 50
	> 0.6	>17	>20	–
Copper (DTPA)	0–0.8	<5	<5	Copper sulphate 100
	>0.8	>5	>5	–
Manganese (DTPA)	0–5	<60	<65	Manganese sulphate 100
	>5.0	>60	>65	–
Zinc (DTPA)	0–1.2	<14	<15	Zinc sulphate 120
	>1.2	>14	>15	–

Source: Sobral et al. (2007).

8.8.9.5 Molybdenum

The requirement of molybdenum for coconut is very small, and its role has not been determined in coconut farming anywhere in the world. The optimum requirement and critical level are not known. The recommendation of fertilizers for B, Cu, Mn and Zn based on soil and leaf analysis is given in Table 8.24.

The importance of major, secondary and micronutrients has been discussed with respect to their role in the mineral nutrition of palms. The studies were specific to certain regions of the coconut world and focussed on the soil and plant health in relation to yield and sustainability. The studies have given meaningful interventions to be adopted as a policy to improve soil health and yield. Consolidating the information of all these interventions for each region is necessary and to be revisited and practiced in larger areas through site-specific recommendations. Studies have also given information on economizing nutrient applications. The importance of magnesium and chlorine is largely recognized and that of potassium, nitrogen and phosphorus in their order, besides role of boron in specific sites. This information is to be studied in relation to the mineralogy of soils of different regions and basic studies on the release mechanism of nutrients.

8.9 Diagnostic Techniques for Evaluating Nutrient Requirement

Fertilizer use for a crop could be recommended based on soil testing and leaf/plant analysis. These guidelines restrict overuse of fertilizer, imbalance in the nutrition of crops and contamination water resources with nitrates and other residues.

Furthermore, overuse of fertilizers means higher costs for farmers and waste of resources.

Four diagnostic methods can be used for coconut, viz. soil and plant tissue analysis, deficiency symptoms and field fertilizer trials. Soil testing and plant diagnosis make it possible for farmers to assess the nutrient status of the soil and crop, apply fertilizers for an expected yield and when there is a deficiency to be corrected. In countries where fertilizer applications are low because of economic constraints, soil and plant testing can guide the farmers on fertilizer applications and realize maximum benefit in terms of crop yield.

The diagnosis and recommendation of nutrients for a given stand of a perennial like coconut palm require considerable knowledge as one has to understand the complex nature of the soil at a given location, its nutrients, the storage of the nutrients in plant and the dilution that takes place in the system once it is absorbed and stabilized. Normally the absorbed nutrient becomes highly mobile in the system satisfying the physiological requirements of the sink and stabilizes. At a given day of the hour, leaf samples are collected from designated leaves of the plant following standard procedures.

Plant or soil analysis may be complementary, not competitive, and most of the modern laboratories are equipped to carry out both types of analysis. However, it is recommended to start soil analysis prior to plant testing to gather sufficient knowledge of the characteristics of the soils that support the crop which will receive the fertilizers, and then plant testing may be carried out for observing the effect of fertilizer application as for determining nutrient requirement of crops.

Modern laboratories are equipped with sophisticated instruments for analysis of major nutrients, secondary nutrients and micronutrients following the principles but setting aside the conventional procedures which are time consuming. The soil as a first step is analysed for pH, electrical conductivity, organic matter, moisture and in special cases for bulk density and carries out water analysis as per the need. Sufficient information is in the knowledge of the agronomists for soil sample collection from defined zones and the diagnostic leaf to sample which will reflect the best nutritional status of the crops. The laboratoires can also carry out mechanical analysis of the soil.

In foliar diagnosis, a composite sample of palms grown under similar conditions is collected at defined intervals. For a particular stage or age of coconuts, leaf sampling is done on the selected leaf rank (number) of the palm based on its phyllotaxy (Magat 1979) (Table 8.25), and maturity of the leaf will give best indication of the nutritional status.

All the studies on soil fertility and plant nutrition are mainly concerned in predicting the nutrient requirement of crops. Although some of the conventional methods have been employed in coconut, none of them in isolation has been found successful in predicting the specific needs under field conditions for achieving the desired yields. New approaches like Diagnosis and Recommendation Integrated System (DRIS) (Beaufils 1973), which was successful for tree crops (Sumner 1982) like rubber, were tested for coconut, oil palm, grapes, etc. Differential Fertilizer Requirement (DFR) (Jayasekara 1993) for coconut in Sri Lanka was useful in prescribing nutrient

Table 8.25 Leaf rank for analysis depending on growth stage of coconut palms

Living leaves average count (5–10 leaves)	Stage	Leaf rank to sample
4–6	Nursery	1
7–12	Nursery/field	3 or 4
13–18	Pre-bearing	9
19 or more	Bearing	14

schedules. Saldanha et al. (2017) evaluated the nutritional status and established nutritional standards for the cultivation of hybrid coconut in Moju, Pará, in northern Brazil using DRIS and presented order of nutrient deficiencies. Their study compared with the critical levels established for reference suggested the following critical levels for dwarf coconut as percentage of N 2.02, P 0.15, K 1.72, Ca 0.41, Mg 0.12 and S 0.13 and mg kg^{-1} for B 15, Cu 4, Fe 115, Mn 101 and Zn 21.

Rosa et al. (2011) developed a Lime and Fertilizer Recommendation System for Coconut Crop based on the nutritional balance. The system considers the expected productivity, plant nutrient use efficiency, effective rooting layer, soil nutrient availability as well as other nutrient inputs to estimate the nutrient supply. Comparing the nutrient demand with the nutrient supply, the system defines the nutrient balance. These new approaches, if tested further and refined, will benefit in evolving a meaningful fertilizer recommendation based on soil and leaf analysis.

8.9.1 The Soil Approach

In coconut, the assessment of nutrient requirement through field experimentation would take a longer period. Therefore for a quick recommendation, soil testing is comparatively rapid and less expensive. However, the effectiveness of the procedure is closely related to the extent to which the data could be calibrated with field trails or that could be correlated with productivity. For making soil analysis more effective for coconut, some fundamental aspects like the time (period) of sampling, intensity, nutrient extraction procedures, calibration, etc. have to be standardized. Besides, the effective soil depth and total volume of soil and ground water characteristics of the area are yet other factors which regulate the nutrient reserves left at the disposal of the palm. Variations in soil type also need critical consideration. Thus, the problem of establishing soil critical values is rather a difficult task. However, attempts have been made to find out certain threshold soil values for making fertilizer recommendation to the palm. For example, Nethsinghe (1965) suggested a critical value of 9 ppm available soil P in Sri Lanka, while in India, Khan et al. (1990) suggested that 10 ppm Bray I P (0–90 cm) could sustain adequate P nutrition of the palm. If such soil fertility rating (of nutrients) for coconut under different pedoecological situations is established, soil testing could be profitably used for predicting the nutrient requirement of the palm.

Table 8.26 Suggested P application rate for coconut based on soil available P level

Olsen P (ppm)	P application (g $palm^{-1}$ $year^{-1}$)
Up to 6	180
7–1 0	130
11–15	90
16–20	40
>20	0

For coconut, Felizardo (1982) suggested rates of P application based on soil P levels (Table 8.26). Rates applied in other countries vary, possibly because of differences in soil P, soil type and yield level.

Studies conducted at ICAR-CPCRI, Kasaragod, India (Anon 1985; Khan et al. 1986b), have shown that the P and K requirement in laterite and red sandy loam soils could be predicted with the help of desorption equilibrium models which were constructed taking into account the response or reaction of the soils to added fertilizers. These models were developed with the assumption that 20 ppm P_2O_5 (Bray I) and 80 ppm K_2O (1 N NH_4OAc) in 0–50 cm soil would be optimum for sustaining adequate P and K nutrition of the palm, respectively. The models can be prepared for a given region or province based on soil series level to guide fertilizer application in the absence of leaf analysis data than arbitrary blanket recommendation. The validity of the models has been tested, and the predictability has been satisfactory. However, it requires refinement for different ecosystems.

8.9.2 The Plant Approach

In tree crops like coconut, the plant diagnostic methods give more reliable information on the nutritional status of plants in relation to soil fertility potential. The methods involve both qualitative and quantitative procedures which are designed to correlate plant status with productivity. Among them, one of the earliest approaches is the nutrient deficiency diagnosis in which the plant exhibits characteristic visible symptoms under nutrient stress conditions, and such deficiency could be corrected through judicious application of the concerned nutrient. One such example in coconut is the crown choke disorder which is primarily due to boron deficiency, and the malady could be corrected by the application of boron to the soil. The deficiencies of nitrogen, potassium, magnesium and sulphur in coconut are easily identifiable under field conditions and correction of such deficiencies can be attempted. However, its application is limited because some of the deficiencies do not show clear cut diagnostic symptoms. Diagnosis becomes difficult and inaccurate when more than one element is deficient. Further, the symptoms become clearly visible only when the deficiency is acute and the growth rate and the yield are severely depressed.

During the 1950s, the interest in the use of leaf analysis as an index of crop nutrient status grew rapidly. The concept of foliar diagnosis (Prevot and Ollagnier 1957) led to great expectations that it could be widely used as a means to predict fertilizer needs of tropical oil crops (oil palm and coconut). The coconut lends itself particularly well to nutrient investigation based on tissue analysis because of regular production of foliage and fruit throughout the year. It was strongly felt that plant analysis must have the advantage over soil analysis as the former reveals amounts of plant nutrients absorbed by the crop and interpretation is not dependent on soil nutrient "availability" or "exchange". Hence, on the assumption that nutrient level or concentration within the leaves of the plant is related to crop growth or yield, leaf analysis was developed as a diagnostic tool. In the Philippines, the serious use of leaf analysis was pioneered in the early 1970s by the Philippine Coconut Research Institute, which has led to the finding of the essentiality of chlorine for coconut production (von Uexkull 1971; Mendoza and Prudente 1972). Now leaf analysis is widely used in many parts of the world to determine the nutritional development or effect of fertilizer application on the performance of coconut palms.

The method depends on the determination of critical nutrient levels and the relationship between nutrient concentrations in standard plant parts and the corresponding growth/yield response curves derived mainly from field fertilizer experiments using different nutrient levels. The foliar levels are then compared with the critical levels for assessing the nutrient needs of the palm. The critical level is defined as the concentration of the nutrient in the standard plant part below which the addition of that particular nutrient has every chance of giving an economic increase in yield. The critical levels of nutrients have been proposed providing a very useful guide for further detailed investigations of the palm that are evidently falling short of potential yield (Table 8.27). The following critical nutrient levels (per cent) proposed by Fremond et al. (1966) in Côte d'Ivoire and Magat (1978) in the Philippines, Cecil (1981) in India and revised sufficiency ranges by Loganathan and Atputharajah (1986) in Sri Lanka are presented.

Plant analysis, in association with soil testing, is a highly useful tool not only in diagnosing the nutritional status but also helps in formulating management decisions for improving the crop nutrition. Plant analysis is the quantitative analysis of the total nutrient content in a plant tissue, based on the principle that the amount of a nutrient in diagnostic plant parts indicates the soil's ability to supply that nutrient and is directly related to the available nutrient status in the soil. As leaf is the primary centre where the major synthetic processes of the plant take place, variations in the nutritional condition of the leaf can be related to the soil nutrient status and the level of fertilizers to be applied. Leaf analysis is used most commonly as material of a similar stage of maturity, such as 14th frond, which can be used as a standard source for collection of samples for mature coconut.

Even though there are certain limitations, the studies conducted by IRHO, Paris reported by Magat (1979) have illustrated that leaf analysis is a very useful tool for predicting the fertilizer requirement of the palm. The 14th leaf of an adult palm (8 years and above) has been accepted as the index or reference leaf for foliar diagnosis in coconut. In sampling the diagnostic leaf, the first fully opened leaf on the

Table 8.27 Coconut diagnostic leaf (frond 14) critical levels (% dry matter) tall cultivar

	IRHO*	Unilever Friend (1975)	Malaysia Kanapathy (1971)	P C A Magat (1979)	India Cecil (1981)	CRISL**	CRISL**
Nutrient	1	2	3	4	5	6	7
Nitrogen (%)	1.8–2.0	2.00	1.80	1.80	1.8–2.0	1.8–2.1	1.9–2.1
Phosphorus (%)	0.12	0.14	0.12	0.12	0.12	0.11–0.12	0.11–0.13
Potassium (%)	0.8–1.00	1.00	0.80	0.80	0.8–1.0	1.20–1.40	1.2–1.5
Calcium (%)	0.50	0.55	0.15–0.30	0.30	0.30	0.25–0.35	0.35–0.55
Magnesium (%)	0.24–0.28	0.26	0.30	0.20	0.20	0.50	0.25–0.30
Sodium (%)	0.40	0.20	–	–	0.40	0.4	–
Chloride (%)	0.50	–	–	0.30–0.40	0.15	0.3–0.6	0.3–0.40
Sulphur (%)	0.15–0.20	–	–	–	0.20	0.15–0.20	–
Boron (ppm)	–	14	–	9.0–11.0	–	–	–
Manganese (ppm)	60	185	60	–	–	–	–
Iron (ppm)	50	115	50	–	–	–	–
Zinc (ppm)	60	15	60	–	–	–	–
Copper (ppm)	–	12.5	–	–	–		–

*IRHO *Côte d'Ivoire*, Fremond 1966; **CRISL, Loganathan and Atputharajah (1986).

crown is considered as 1, and subsequent leaves are counted to reach the 14th leaf considered as diagnostic leaf. This leaf is regarded as the one which has reached physiological maturity but has not entered the phase of senescence. For young palms up to 4 years of age, the fourth leaf and, for 5–7 years, the 9th leaf are taken for the purpose. For the details on sampling and sample preparation, the reader is directed to refer Prevot and Bachy (1962), Ziller and Prevot (1962) and Taffin and Rognon (1991).

Manuring recommendations should be aimed at the maintenance of the tree's mineral status at an optimum or its correction to that level, so that it is able to cover its needs for its production in the following years. Precisely, leaf analysis enables this status to be appraised and is therefore a good approach to the problem (Ouvrier 1982). The optimum range of the nutrients and fertilizer rates proposed vary with the variety (Table 8.28).

A critical level of 0.12% P in leaf 14 as suggested by Fremond (1966) and Magat (1978) was considered satisfactory for a long time. Magat et al. (1981a) showed a relationship between leaf P and coconut yield. However, Limbaga (1986) showed that yield increases were obtained by increasing frond P up to 0.15% indicating this

Table 8.28 Optimum range of concentration of nutrient elements in frond 14 in mature bearing palms

Nutrient element (as per cent dry matter)	Variety		
	Local Tall	Dwarf	Hybrid
N	1.80–2.00	1.80–2.00	1.80–2.00
P	0.12–0.14	0.12	0.12–0.30
K	0.80–1.00	0.60–0.80	0.90–1.40
Mg	0.20–0.30	0.25	0.25–0.35
Ca	0.30–0.50	0.2–0.5.0	0.32–0.35
S	0.13–0.17	–	0.15–0.16
Na	0.10–0.20	–	0.15–0.17
Cl	0.30–0.60	–	0.45–0.50
Mn (ppm)	60–115	60	–
B(ppm)	9–11	8	–

Source: Tall palms: Magat (1979); Magat (1992); Dwarf palms: Chew (1982); Hybrid varieties: Magat (1988)

to be the optimal level. It was suggested that yield is related to the ratios between foliar N and K, but that the K level should in turn be interpreted in the light of a balance between the monovalent and divalent cations (Smith 1969).The critical K levels are higher for young than for old palms. It should be higher if the pool of available K is low or vice versa.

According to Fairhurst (2003), the optimum requirement for individual nutrients can vary over a considerable range, depending upon factors such as the age of the palms, soil moisture regime, ratio to other nutrient concentrations, type of planting material, etc. Hence, the optimum leaf nutrient concentration must be determined for each agroecological environment taking local soil and climate conditions into consideration.

Discrepancies in the critical nutrient levels are expected as the yield is modified by several other extraneous factors and critical levels established for one region may not hold good for another. Kamala Devi et al. (1983) from a fertilizer experiment also opined that the critical level of nitrogen under the coastal condition of India must be less than the value recommended by IRHO. The critical level obtained for Ca and Mg (0.36 and 0.24–0.25%, respectively) was in the range more or less similar to the concentration reported by Chew (1982) and Ravi Savery et al. (1994).The critical level for S was almost similar to the figure of 0.15–0.20% suggested by Manciot et al. (1980). Foale and Ashburner (2005) summarized the critical nutrient concentrations proposed in the literature with their comments on behaviour of nutrients in the plant system (Table 8.29).

Manciot et al. (1980) working on the critical level of trace elements opined that it was not possible to define critical levels for Fe, Mn and Cu in coconut. The critical values of Cu-5-7 ppm, Zn-15 ppm, Fe-50 ppm and Mn-60 ppm in the 14th leaf suggested by Manciot et al. (1979c) are only proposed values, and critical levels have so far not been established experimentally (Manikandan et al. 1986).

Table 8.29 Critical values of concentration of mineral elements in the leaf tissue (14th frond) of adult tall coconut

Major elements	% Dry matter	Comments
N	1.8–2.0	In tall × dwarf hybrid −2.2
P	0.12	–
K	0.8–1.0	In tall × dwarf hybrid −1.4
Mg	0.20–0.24	Strong inverse sensitivity to extremes of K
Ca	0.30–0.40	Strong inverse sensitivity to extremes of K
Na	Not essential	Substitutes K in case of deficiency
Cl	0.5–0.6	–
S	0.15–0.20	–
Trace elements	**Parts per million**	**Comments**
B	10	–
Mn	>30	Difficult to fix value as very interactive with Fe in strongly alkaline soil; potentially toxic in extreme acid soils
Fe	50	Deficient only in strong alkaline soils
Cu	5–7	Deficiency very rare, not very certain
Mo	0.15	Common value-no response observed yet
Zn	20	Common value-no response observed yet
Al	>38	Nonessential element but always present; potentially toxic at values well in excess of this common level

Source: Manciot et al. (1979b, c); Manciot et al. (1980); de Taffin (1993); Foale and Ashburner (2005)

Acharya and Dash (2006) employing Cate Jr and Nelson (1965) technique and relative yield on random selection of palms observed critical level of major, secondary and micronutrients for palms growing on coastal sandy tract of Odisha (India) which can be considered as sufficiency levels only.

8.9.3 The Soil–Plant Integrated Approach

The third important approach is the soil-plant integration models in which the soil nutrients, the plant nutrient composition and the yield would be viewed as a relationship where soil nutrient contents influence plant (leaf) nutrients and yield, leaf nutrient content is related to yield. Among them, the Mitscherlich-Bray model is being popularly used in most of the field crops. This principle was employed to evaluate the nutrient requirement of three high-yielding genotypes of coconut by Khan et al. (1986b) (Table 8.30). They indicated that the nutrient requirement of D × T hybrid was relatively lower than that of talls to produce the same quantity of yield. Tall × dwarf hybrid was intermediate between D × T and WCT. They further evaluated the efficiency of soil and fertilizer nutrients with respect to productivity. It is also possible to forecast coconut productivity for a given quantity of nutrient inputs.

Table 8.30 Fertilizer recommendation based on Mitscherlich-Bray equation

Cultivar	Nutrients	Baule units fertilizer to be applied palm^{-1} year^{-1} (g)			
		1 (50%)	2 (75%)	3 (87.5%)	4 (93.75%)
WCT	N	370	851	1332	1813
	P_2O_5	370	851	1332	1813
	K_2O	741	1703	2665	3626
COD × WCT	N	75	214	352	490
	P_2O_5	75	214	352	490
	K_2O	150	427	704	980
WCT × COD	N	144	333	521	710
	P_2O_5	144	333	521	710
	K_2O	288	666	1043	1420

WCT: West Coast Tall, *COD:* Chowghat Orange Dwarf

Although leaf analysis may indicate that one or more elements are abnormally low or high in the leaves, it will not necessarily tell which of the yield-limiting factor (e.g. inadequate or excess water, pests and diseases, improper nutrition, improper fertilizer placement, very low or very high pH, over grazing) is the cause. Magat (1976) opined that when leaf analysis is supplemented by soil analysis, a much better insight on the nutritional status of the crop may be obtained. It appears that foliar diagnosis is an efficient method of detecting nutrient deficiencies if they occur singly. If, however, several deficiencies occur simultaneously, greater interpretative caution is required, and other agricultural factors have to be considered. In most cases, field trial or experiment is advisable, especially if the results of soil and leaf analyses, respectively, are inconsistent.

Magat (2000) provided a complete guide for fertilizer recommendation for coconut in the Philippines based on soil and leaf analysis. The guide classified the nutrient content in soils as low/deficient, medium/adequate and high/excessive and provided information on the quantity of nutrients to be applied for a given set of soil test values. A similar guidance was also given for nutrient application based on leaf analysis. He also suggested the fertilizers N, P, K, Cl, Mg and S to be applied to different age group of palms.

For coconut, the advantage of leaf analysis over soil analysis as a basis of fertilizer recommendation is now largely accepted. This has been so, as leaf analysis reveals amounts (concentrations) of nutrients absorbed by the crop and diagnosis is not highly dependent on varying concepts of soil nutrient “availability” or exchange reactions (highly dynamic in behaviour). Thus, with the strong consideration that nutrient levels or concentration in a plant part like the leaf is directly related to its (coconut) growth and / or yield, leaf analysis has been successfully developed as a diagnostic tool to predict the fertilizer needs of the crop.

Magat (1978) revealed the usefulness of leaf analysis as an effective and rapid tool in determining the qualitative needs and estimating the fertilizer rates of coconut based on results of several fertilizer trials. Results obtained by Magat (1978) were reviewed by Manciot et al. (1979b, c) with the conclusion that leaf analysis or foliar diagnosis is undoubtedly a very effective tool in predicting fertilizer needs of existing stands. Moreover, further analysis done on soil, leaf and yield data of the Philippine Coconut Authority (PCA) survey (1975–1980) collected from 1131 sampling areas (57 coconut provinces) with diverse agroclimatic conditions showed that leaf analysis could give a better predictive value of the nutrient needs of the coconut and that leaf nutrients (N, P, K, Ca, Cl and S) are more closely associated with coconut yields (nuts, copra) compared to soil properties and yields (Cosico and Fernandez 1983; Limbaga 1986). It is now well recognized that plant and soil analysis techniques used in complementary roles are indispensable tools for assessing the nutrient status of soils and determining correct fertilizer practice (Nathanael 1967).

Magat (1991) summarized the experience gained on use of leaf analysis in coconut nutrition as follows:

1. Both the soil analysis and leaf analysis can be used as basis of fertilizer recommendations for coconut and these complement each other.
2. As leaf analysis is not affected by soil nutrient “availability” and exchange reactions, it is a more reliable method.
3. For macronutrients as Cl, S and N, leaf analysis is a more accurate tool as these elements are highly mobile in the soil.
4. In both the methods, availability of guides on critical or satisfactory values (soil analysis), critical and optimum levels (leaf analysis) and average nutrient and fertilizer needs, under different stages/ ages of the coconut, should improve reliability of recommendations.
5. Reference critical levels (soil and leaf) should be evaluated under local conditions before wider use.

8.9.4 Use of Nut Water for Nutrient Analysis

In Sri Lanka, Salgado (1951, 1954) suggested usefulness of nut water analysis in the diagnosis of nutrient deficiency of palms, and found it to be a better guide in interpreting the response of K fertilizers in terms of nut yield besides its usefulness as an additional tool in the interpretation of experimental yield data on K, Na, Mg and Cl.

According to Salgado (1955), while soil analysis attempts to measure the nutrient supply of a limited stratum of the soil (“intensity factor”), the nut water technique measures the “capacity factor” and takes into account not only the nutrient status of the soil but also the volume of soil from which the palm is drawing its nutrients. It was generally concluded that coconut water is analogous to plant sap and accordingly would indicate the physiological status of the palm and also the soil conditions in which it grows. The dominant requirement of the coconut is K, which is concentrated in the pericarp and water of the nut. K_2O in the nut water can be determined by the gravimetric cobaltinitrite method. It was shown that drought

Table 8.31 Changes in nut water composition during development of coconut (West Coast Tall)

Age of nut (month)	Volume of water (ml)	pH	Total sugars (%)	N	P	K
				———mg^{-1}———		
4	75	3.5	0.8	32	48	1113
6	310	4.7	3.3	195	118	5320
8	230	5.5	5.6	432	186	7300
10	145	5.9	3.4	336	140	3260
12	100	6.1	1.8	299	108	3181

markedly affected nut size and the volume of nut water, as well as its potash content. The K_2O content of nut water increased with potash applications and can provide an index of the K_2O status of the soil and of the expected yields.

In Sri Lanka, chemical analysis of nut water has been successfully used in the study of P and K nutrition of coconut (Salgado and Abeyawardena 1964). In other countries this approach has also been used with some measure of success (Southern 1956; Lockard et al. 1969). Jeganathan (1990) suggested the possibility of using nut water analysis as an additional tool in the interpretation of field experiment data for Na, K, Mg and CI. Both Ca and Mg have functionally limited roles to perform, both in the liquid and in the solid endosperm, and, therefore, their concentration will be low and so too the changes.

Nagarajan and Pandalai (1965) opined that coconut water furnishes, by and large, a good material to study the nutrient needs of the palms, based on the studies on enzymatic activity during various stages of development of the nut. They found that the enzymes such as catalase, peroxidase and polyphenol oxidase are to be correlated with potash content of nut water. According to them, a higher enzymatic activity of the nut water indicates that the palms required to be supplied with potash.

Coconut water and its relationship with potassium were reported by many workers. An account of increase in the K content of nut water with K application to palms at different rates was given by Jeganathan (1990) in Sri Lanka and Silva et al. (2006) and Riberio et al. (2011) in Brazil. The difference in composition with age of the palms and among cultivars in India has been reported by Kamala Devi and Velayutham (1978). The quality of tender nut water of *anão verde* coconut, grown in Brazil, in relation to doses of N and K through fertigation was evaluated by Neto et al. (2007). An increase in dose of K (258–4872 g plant^{-1} year^{-1}) decreased the salinity and increased °Brix of coconut water.

An account of nutrient content of tender coconut water at different stages of the development of the nuts indicated abundance of K at maturity stage of 8th month (Table 8.31).

Total sugars and potash content indicate that tender coconut water can be considered as a health drink in the 8th month. Kamala Devi and Velayutham (1978) observed least difference among cultivars. Nitrogen and potassium affected the volume of coconut water of a dwarf variety with maximum volume of 417.75 ml found when 818 g of N and 1487 g of K palm^{-1} year^{-1} were applied (Silva et al. 2006).

Holanda et al. (2007) observed that in green dwarf coconut, the critical levels of N and K on frond 14 are between 18.7 and 19.3 g kg^{-1} and between 9 and 10 g kg^{-1}, respectively. The critical level of K is larger than the range of 6 to 8 g kg^{-1} proposed by Magat (2005) for leaf 14 of the dwarf coconut without irrigation.

Nitrogen and potassium levels had a linear effect on the soluble solids content of coconut water, where N had a negative and K exhibited a positive effect. In accordance with published reports elsewhere, Riberio et al. (2011) in Brazil observed that application of KCl increased the concentration and content of K in nut water and kernel of green dwarf coconut and there was no influence of K fertilization on the mass, the volume, the pH, the C.E. and the TSS of the coconut water. Irrigated plantations of dwarf coconut for the production of tender coconut water have expanded considerably in Brazil. Higher yields obtained under irrigation affect the amount of N and K required by dwarf coconut, influencing the relationships between yield and soil and leaf contents of these nutrients. The highest fruit weight and coconut water volume were obtained with the lowest N level (Sobral and Nogueira 2008). Nitrogen and K combinations did not influence the coconut water pH but increased coconut water brix. The K content in the coconut water increased along the K doses. Teixeira et al. (2005a) found that application of N decreased the volume of the coconut water and the fruit weight, while K had the opposite effect. Silva et al. (2006) and Ferreira et al. (2007) observed that N decreased solid content and K increased the same.

Though experimental evidences show the possibility of use of nut water as a diagnostic tool, this technique did not gain wider acceptability in nutrient diagnostic studies on coconut.

8.10 Nutrient Management

8.10.1 Nutrient Management in the Nursery

The haustorium absorbs food materials from the nut water as well as kernel and supplies to the growing plant. The role of haustorium in seedling growth has been discussed by Child (1974). Foale (1968) reported that haustorium decreases from the fourth month after germination suggesting that the young seedlings are in short supply of nutrients for a major part of their 1-year growth. Harries (1970) opined that though food reserves were adequate as far as carbon compounds and nitrogen are concerned, potash application is needed considering its uptake. Based on the studies in India, Nelliat (1973) suggested application of fertilizers to the nursery in December, February and April to supply 40 kg N, 20 kg P_2O_5 and 40 kg K_2O ha^{-1} under west coast conditions to produce good-quality seedlings. For nursery seedlings fertilizer recommendation with emphasis on chloride nutrition as needed for the Philippines' conditions is prescribed by Magat (2000).

8.10.2 Nutrient Management of Young Palms

Young transplanted seedlings require adequate nutrients for better growth on all soils. Fertilizer application to the seedling is very important to guarantee good development of bole, which is important for the productivity of the tree, as it increases the rooting surface. Given a good nutrition, the stem will also attain its maximum width (Ohler 1999). With a very active root system, the young plants respond well to manuring, grow better and start bearing early. An enhanced rate of leaf production with larger number of leaves on the crown results in larger total leaf area leading to increased/required photosynthetic activity which may probably increase building up of adequate carbohydrate reserves in the system. There is a correlation between chlorophyll content in the leaves, rate of apparent photosynthesis and annual yield (Narayanan Kutty and Gopalakrishnan 1991). Ramadasan and Mathew (1977) observed that adequate nutrition to the palms in the juvenile phase leads to build-up of required carbohydrate reserves in the trunk with commencement of flowering, a question of partition of assimilates towards reproductive phase once the vegetative phase is satisfied. The above statement implies that in an intelligent nutrition management programme, importance of fertilizing young palms with adult palm dosage should be resorted to well in advance before they come to flowering. Studies indicate that the recommended adult palm dosage is given from the fourth year onwards. The damage caused by K deficiency in the early stages cannot be fully repaired by later K dressings (Fremond and Ouvrier 1971). Although later applications of K enabled re-establishment of good physiological functioning, the palms which suffered from K deficiency during pre-bearing age remained on an average 15% less productive than those which never suffered from K deficiency. In Sri Lanka, fertilizer recommendation for young palms is based on a 3-year fertilizer application conducted earlier (Jeganathan 1993). The results gave good indications on the importance of fertilizing the palms and unequivocally established that neglect at the seedling stage can have very damaging effect on future production (Loganathan 1977).

8.10.3 Nutrient Management of Adult Palms

The economic importance of nutrition of adult palm has drawn attention of many researchers in all the coconut growing countries, as a sustainable yield only will satisfy the requirement of the grower and increasing need of the industry. A basic understanding of management of the plantation is discussed here. Annually, the palm removes large quantities of nutrients from the soil (Nathanael 1961; von Uexkull 1971; Ouvrier and Ochs 1978). The most rapid growth occurs between the second and fifth year in the life of the coconut palm. The crown grows 30–50 cm year^{-1}, up to about 50–60 years. Dry matter production is around 50–80 kg year^{-1}. In its prime, a coconut palm normally produces 12–15 leaves and about 80–100 nuts year^{-1} (Chan and Elevitch 2006). A balanced application of nutrients is essential to obtain high and sustainable yield, and it is the key to increased plant use efficiency of applied nutrients. It replaces the amount of nutrients removed by the crop besides ensuring that fertilizers are applied in adequate quantities and correct ratios for optimum growth and ensures sustenance of soil and crop productivity. Several field experiments to assess the nutrient need have been carried out under different environmental conditions on adult palms, and some of the earlier reports are available from India (Thampan 1970; Muliyar and Nelliat 1971), in Sri Lanka (Balakrishna 1975), Jamaica (Smith 1964, 1969), the Philippines (Prudente and Mendoza 1976) and Malaysia (Soon and Wat 1972) and on young palms in Côte d''Ivoire (Fremond and Ouvrier 1971). Preliminary results of fertilizer experiment carried out at Tanganyika (east Africa) indicated the necessity of fertilization for increasing the yields (Anderson 1967).

Over years of gathering research information, Magat (2000) published a guide on soil fertility levels in coconut production in which he categorized the soils of the Philippine coconut growing areas into low/deficient, medium/adequate and high/excessive classes for major, secondary and micronutrients assigning values for each nutrient. Corresponding to this, fertilizer is prescribed for different age groups from field planting to palms of 5 years and above. The rates of fertilizers are the ones recommended under moderate level of nutrients, that is, those above the critical levels. When the level of nutrients are above equal or lower than the critical level, rates of nutrient and fertilizer application should be increased to at least 20–50% of values in the reference tables, while when levels of nutrients are higher than critical, the rates of nutrients and corresponding fertilizers should be lower by at least 20–50% of reference values. Under high levels of soil fertility, fertilization is not usually required except for periodic maintenance. Similar recommendation is made taking into account plant nutrient levels. Straight fertilizers, fertilizer mixtures and dolomite- and chloride-bearing fertilizers are recommended for different groups of palms.

In the Philippines, studies have shown the beneficial effects of fertilization (Mendoza and Prudente 1972; Magat et al. 1975; Prudente and Mendoza 1976; Magat et al. 1981a) in increasing copra yields as high as 3 tons ha^{-1} year^{-1}.

Menon and Pandalai (1960), in a review of nutritional studies on coconut palm in India, observed that a minimum of 3 years is required to obtain the full response to fertilizer application to coconut. Muliyar and Nelliat (1971) registered that response to N was obtained from third year onwards and for phosphorus from ninth year onwards at Kasaragod, India. Their studies indicated that for palms yielding less than 60 nuts annually, optimum nitrogen dose ranged between 400 and 650 g palm^{-1} year^{-1}. Nitrogen affected all the nut characteristics studied, viz. weight of whole nut, and that of husked nut, volume of husked nut and copra weight nut^{-1}. These characters were much improved by potassium manuring, while phosphorus had negligible effect. Although nitrogen application increased the yield by 16.9%, copra yield was increased only 6%. With potassium, increase in nut production was 12%, while copra yield was 22%. Large-scale fertilizer demonstration trials conducted all over the west coast of India (John and Jacob 1959) showed that application of 340 g N, 340 g P_2O_5 and 680 g K_2O palm^{-1} year^{-1} had resulted in an increase of 35% in yield of nuts and 44% in copra outturn over the farmer's practice. In certain locations where the above fertilizer dose is not producing expected response, significant increase in yield was obtained when the K_2O level was raised to 900 g palm^{-1} year^{-1}. These trials demonstrated the need for fertilizer inputs to increase yields and the importance of a specific nutrient for correcting the deficiency to further increase the yield.

However, the general fertilizer recommendation for palms in India by ICAR-CPCRI is 500 g N, 320 g P_2O_5 and 1200 g K_2O palm^{-1} year^{-1}, which was arrived based on the agronomy trials. Nelliat (1973) recommended an increased quantity of 1000 g N, 500 g P_2O_5 and 2000 g K_2O palm^{-1} year^{-1} for palms with higher yield potential. Based on long term multilocation trials in different soil and agroclimatic conditions, fertilizer recommendation has been prescribed for different coconut growing regions in India (Table 8.32).

In addition to the recommended fertilizer application for Kerala, 50–60 kg organic manure is also usually applied. Mostly fertilizers are applied in two or three splits according to the rainfall pattern and soil type. Fertigation is also recommended for economizing the quantity of fertilizers being applied. Please refer to Chap. 7 for details.

Table 8.32 Fertilizer recommendation for coconut in different regions of India

	Fertilizer recommendation for adult palms (g palm^{-1} year^{-1})					
State	N	P_2O_5	K_2O	Variety	Soil type	References
Tamil Nadu	560	320	1200	Tall	Red sandy loam/ alluvial soil	
	1000	250	2000	Hybrid	Red sandy loam/ alluvial soil	Venkitasamy (2004)
Karnataka	560	320	1200	Tall	Red sandy loam	Khan et al. (1986a, b)
	1000	250	1000	Hybrid	Red sandy loam/light black soil	
Andhra Pradesh	500	250	1000	Tall	Coastal alluvial type	
Odisha	560	320	1200	Tall	Coastal alluvial type	
	1500	750	1250	Tall	Coastal littoral sand (150 g each Ca and Mg)	
Maharashtra	1000	500	1000	Tall and hybrid	Konkan coastal area	Nagewekar et al. (2004)
Assam	500	500	2000	Tall and hybrid	Alluvial clay loam soil	Nath et al. (2012)
West Bengal	500	250	750	Tall	Alluvial sandy loam soil	
	1000	500	1000	Hybrid	Alluvial sandy loam soil	Ghosh and Maheswarappa (2016)
Kerala	500	320	1200	Tall/ hybrids	Sandy loam, laterite and littoral sandy soil	Khan et al. (1986a, b)

While application of chemical fertilizers over years alone makes the soil fertile and increases productivity of crops, it brings adverse effects on soil and environment. It is essential that fertility and productivity of the soil be restored through integrated nutrient management (INM) approach (Khan et al. 2000). A review of the results of fertilizer experiments carried out in different agroclimatic regions of Sri Lanka (Loganathan 1978) has shown that coconut responds to fertilizer application. Striking responses have been obtained in the poorer soils of the wet zone compared to the relatively richer soils of the intermediate zone. Though the per cent increase in yield was very much higher for the poorer soils, the absolute increase in yield was nearly the same for all soils (about 3–4 kg palm^{-1} year^{-1}). Chew (1978) observed that fertilization increased the number of female flowers by bunch. However, continued applications of fertilizers decreased the size of the fruit to a certain extent, and the amount of copra per fruit though increased the number of nuts.

From the long-term experiment on a lateritic gravelly soil in Sri Lanka, where the rates of fertilizers were progressively increased up to the 16th year, Loganathan and Balakrishnamurti (1975) obtained the optimum yield by applying 1.818 kg sulphate of ammonia, 1.136 kg *saphos* phosphate and 2.043 kg muriate of potash palm^{-1} year^{-1} from the 16th year onwards. Application of 1.362 kg each of sulphate of ammonia, *saphos* phosphate and muriate of potash between the 9th and the 16th years produced a yield of 20.7 kg copra palm^{-1} year^{-1} from the 13th to the 16th years, which is about 150% higher than the plots which received no fertilizer from the seedling stage. Based on the results, they suggested that in the current fertilizer recommendations, for both young and adult palms, the rate of N could be reduced and that of K be increased. Their subsequent studies (Loganathan and Balakrishnamurti 1975) highlighted the importance of balanced fertilizer application. The combination of the highest dosage of N and without P gave the lowest yield, the yield being even lower than the control plots. This has shown that an increase of N without a corresponding increase of P would be detrimental. The positive NP interaction indicates that the benefit from an increase of N could be obtained only if P also is increased and vice versa.

Results of an experiment with adult coconut on a lateritic gravelly soil showed that application of muriate of potash up to 1.8 kg palm^{-1} year^{-1} linearly increased nut and copra yield and copra weight nut^{-1} (Loganathan and Balakrishnamurti 1979), while sulphate of ammonia, up to 4.4 kg palm^{-1} year^{-1}, decreased copra weight nut^{-1}. The optimum rates of fertilizers were 1.1 kg sulphate of ammonia, 0–0.83 kg *saphos* phosphate and 1.8 kg muriate of potash palm^{-1} year^{-1} giving a yield of 12 kg copra palm^{-1} year^{-1}. Prudente and Mendoza (1976), based on the first 25 months yield data of young coconut in the Philippines, also reported that application of N without P would give yield even less than the plots which received no fertilizer.

Use of fertilizer increased yield in the range of 30–200% for palms grown in moderate to virtually poor soil types in Sri Lanka. Palms grown in poor soils or those receiving little or no field care have shown 100% improvement in the yield over a period of 3 to 5 years when they received fertilizer annually at the rate of 1.58–2.26 kg palm^{-1} (de Silva 1973). In the coastal quaternary sands of the Côte d'Ivoire, Pomier and de Taffini (1982) noticed a drop in fertility especially that of N, where the soil has become very poor due to prolonged monocropping of coconut. They suggested adopting regular application of nitrogen fertilizers or raising leguminous cover crops. At the adult stage, an annual manuring of 1.5 kg of sulphate of ammonia tree^{-1} (besides the usual application of 2–3 kg of KCI and 1 kg of Kieserite) was also recommended. de Silva (1981) estimated the aggregate response of coconut production to quantity of fertilizer applied in each year and the weather (rainfall) by analysing aggregate data for 26-year period from 1956 to 1981 and suggested that the aggregative approach appears to be a useful alternative in modelling fertilizer response under non-experimental conditions.

Results of leaf analysis revealed significant widespread N deficiencies at most of the sampled sites and geographic variations in K deficiency. Chlorine deficiency varied with geographic sites and was closely related to the prevailing wind pattern. Preliminary results on nut set and flowering in the trial at Stewart Research Station, Papua New Guinea (Ollivier et al. 1999), revealed a positive response to N- and Cl-based fertilizer applications. This suggests that appropriate fertilizer applications would be beneficial to future coconut production on this particular site. Potassium-chlorine interaction was found significant in the result and most probably related to the K-Na antagonism. This was also observed at Gunung Batin in Indonesia (Bonneaux et al. 1997). Chlorine is the dominant element, and potassium only reveals its effect if the Cl effect is resolved.

The nutrients exported from the soil at highest quantities by palms are mostly N and K (Pillai and Davis 1963; Ouvrier and Ochs 1978). In the commercial coconut plantations in Papua New Guinea, N and K are the most yield-limiting elements (Ollivier et al. 1999). In coconut plantations, harvested nuts, as well as fronds and much of the other residues, are removed, resulting in gradual depletion of plant nutrients from the soil (Somasiri 1987). Furthermore, the nutrients stored in the trunk are not returned to the soil system. Application of fertilizers containing N, P, K and Mg at the recommended rates only partially compensates for this depletion. Studies indicated that nuts remove a considerable quantity of major nutrients (Jeganathan et al. 1977; Ohler 1984; Jayasekara et al. 1991). Though increasing N, P and K rates were tested, there was no yield response to the increased levels of P application (Sobral and Leal 1999).

In Sri Lanka, adult palm mixture containing 800 g of urea, 600 g of rock phosphate and 1600 g of muriate of potash with 1 kg of dolomite palm^{-1} year^{-1} is recommended to meet the demand of nutrients of plantations yielding 7500 nuts ha^{-1} year^{-1}. The recommendation for high-yielding plantations is 1.5 times the above rates (Mahindapala and Pinto 1991). It would be sufficient for plantations yielding up to 11,250 nuts ha^{-1} year^{-1}. Nevertheless, since plantations yielding 12,500–19,000 nuts ha^{-1} year^{-1} (shown by land suitability studies) remove higher quantities of nutrients than the above inputs, they require additional fertilizer nutrients (Somasiri et al. 1994, 2000, 2001). To sustain productivity of such high-yielding plantations, the nutrient-supplying power of the soil is to be maintained with large supplements of organic manures. Details of inorganic fertilizer recommendation for coconut in Sri Lanka (Anon 2016) are given in Table 8.33.

Table 8.33 Inorganic fertilizer recommendation for coconut in Sri Lanka

	Age of palms							
Fertilizer (g)	6 months	1 year	1.5 years	2 years	2.5 years	3 years	3.5 years	4 years up to bearing
Wet and intermediate zone								
Urea	190	235	235	305	305	375	375	470
Eppawela rock phosphate	420	530	530	690	690	850	850	1060
Muriate of potash	190	235	235	305	305	375	375	470
Dolomite	500	500	500	500	500	500	500	500
Dry zone								
Urea	190	235	235	305	305	375	375	470
Eppawela rock phosphate	270	330	330	490	490	600	600	660
Muriate of potash	190	235	235	305	305	375	375	470
Dolomite	500	500	500	500	500	500	500	500

For adult palms

Wet and intermediate zones		Dry zone	
Fertilizer	Amount (g)	Fertilizer	Amount (g)
Urea	800	Urea	800
Eppawela rock phosphate	900	Eppawela rock phosphate	–
Imported rock phosphate	–		600
Muriate of potash	1600	Muriate of potash	1600
Dolomite	1000	Dolomite	1000

Adult palm mixture for the wet and the intermediate zones-APM-W	
Urea	8 parts by weight
Eppawela rock phosphate	9 parts by weight
Muriate of potash	16 parts by weight
NPK composition of the mixture	
11% N, 8% P_2O_5, 29% K_2O (11-8-29)	
Adult palm mixture for the dry zone-APM-D	
Urea	8 parts by weight
Muriate of potash	16 parts by weight
NPK composition of the mixture	
12% N, 6% P_2O_5, 32% K_2O (12-6-32)	

Broadcast method of fertilizer application is recommended best for flat lands. However, on sloping lands where soil erosion or run-off is possible, fertilizer may be applied in full circle trenches cut around the palm or half circle trench on the upper side of the palm. The trench should be 0.9 m away from the base, 0.9 m wide and 10 cm deep.

Based on studies on mineral nutrition of coconut palms, Gunathilake et al. (2008) emphasized that coconut palms responded well to mineral fertilizers. The highest average response to mineral fertilizers was observed in the wet and intermediate zones of Sri Lanka (41%) followed by the dry zone (32%). The fertilizer response was associated with favourable climate (sunshine hours and rainfall). The contents of micronutrients in fronds, nuts and inflorescences are governed by the soil characteristics, and accordingly application of micronutrients to specific soil sites is suggested to improve the soil reserves of various nutrients (Nadheesha and Tennakoon 2008).

Several studies suggest that the nutrients exported through harvested nuts and other usufructs be returned to soil in chemical and organic forms to maintain the productivity of soil. According to Somasiri et al. (2003), nutrients exported by the coconut plant components were 116.79 kg N, 14.02 kg P, 245.43 kg K, 40.47 kg Ca and 33.66 kg Mg and additionally 55.79 kg Na ha^{-1}. Inputs at the recommended rate (4.5 kg of APM and 1.5 kg of dolomite palm^{-1} year^{-1}) supplied 87.21 kg N, 17.07 kg P, 188.90 kg K, 104.80 kg Ca and 28.59 kg Mg ha^{-1} year^{-1} indicating a negative budget for exchangeable K (363 kg ha^{-1}), whereas the other macronutrients were present in reasonably high quantities in the experimental site. As the K reserves in the soil were low and fertilizer inputs supplied only about 77% of the requirement of high-yielding coconut, soil K will deplete rapidly, and it is necessary to compensate for either by increasing the quantity of chemical fertilizer or recycling organic products of the palm itself or both.

Studying the nutrient removal by all plant parts of coconut through leaf and soil analysis (164, 53, 37, 22, 19 and 9.85 kg ha^{-1} year^{-1} for K, N, Na, Ca, Mg and P, respectively) and comparing with that of the amount of N, P, K, Ca and Mg applied annually as fertilizers (58, 11.5, 125.9, 69.9 and 19 kg ha^{-1}). Wijebandara et al. (2015) observed that K and Mg, input by application of fertilizer, slightly exceed the nutrient removal. The N, P, Ca and Mg reserves of soil were high and would not deplete rapidly. The K input by application of 3.3 kg of APM fertilizer mixture was about 76.7% of the K removal. It is inferred that if the harvested nuts and fallen plant components are all removed from the plantation, depletion of exchangeable K pool will occur rapidly and should be compensated for either by adding extra 80 kg ha^{-1} of muriate of potash or recycling of fallen fronds and residues of the inflorescences or mulching the manure circle using fresh coconut husks or addition of organic manure. Their specific studies in Boralu soil series also indicated high reserves of available Fe, Mn, Cu and Zn, and micronutrient application would not be required.

The apparent result of reduction in N content with higher yields has to be viewed in the context of N/Mg and N/S ratios (Mathewkutty et al. 1995, 1997). Higher productivity calls for an increase of Mg and S in relation to N suggesting that yield-limiting influences come from a real and apparent deficiency of Mg and S. This indicates that Mg and S have to be applied even at the expense of N. This calls for recommendation of Mg and S for coconut cultivation in Kerala, India. The yield-limiting influences of coconut are not the limitation in major nutrients that are regularly applied but the deficiency of some non-applied elements like Mg and S and excesses of Ca, Fe, Mn, etc.

Micronutrient status of coconut palms receiving 500:250:1200 g N/P_2O_5/K_2O palm^{-1} year^{-1} for 10 years was studied by soil and leaf analysis (Venkitaswamy et al. 2006). They observed that leaf analysis showed sufficiency levels of Fe, Mn, Zn, Cu, whereas soil critical levels established in Tamil Nadu, India (Krishnasamy et al. 1994), indicated deficiency for Fe and Cu suggesting a relook into the soil critical levels for coconut growing regions.

In COD × WCT palms, significant difference in yield was observed with N and K, influencing bunches harvested, female flower-produced inflorescence^{-1}, while P did not influence any of the characters. When N was a major limiting nutrient, influence of P and K was not much expressed (Venkitaswamy et al. 2011). A trivariate extension of the quadratic model without higher-order interaction terms fitted to the yield accounted for 98.3% of the variation. The physical optimum rate of fertilizer requirement worked out to 818, 130 and 1362 g palm^{-1} year^{-1} of N, P and K, respectively, with a yield of 159 nuts palm^{-1} year^{-1}. Application of NPK at 500:108:830 g palm^{-1} year^{-1} recorded 178 g copra nut^{-1} and 26.0 kg copra palm^{-1}.

Upadhyay et al. (2002) worked out response function for coconut taking into account recommended dose as one (500 N: 320, P_2O_5 and 1200 K_2O g palm^{-1} year^{-1}) and transforming other treatments accordingly (Fig. 8.5).

The quadratic response led to optimum fertilizer requirement as 359 N: 229 P_2O_5 and 860 K_2O which gave a nut yield of 151.77 nuts palm^{-1}.

Magat (2009) in the Philippines compared application of multi-nutrient fertilizer 14:0:20:15:4.5:0.2 (N/P_2O_5/K_2O/Cl/S/B) and NaCl and found that the former increased coconut yield during the first, second and ensuing years by 50%, 100% and 150%, respectively. The increase in copra yield was 20%, 33% and 66%, respectively, over the latter during the same period. Magat et al. (2009) further reported that the multi-nutrient coconut-specific fertilizer formulation (14–5-20 NPK) with adequate content of other nutrients at 1 kg palm^{-1} is highly suitable, nutritionally balanced and practical for long-term productive coconut farming.

A dosage of 120 kg N ha^{-1} year^{-1} was enough to maintain sufficiency range on leaves, for "dwarf green" coconut cultivated in the State of São Paulo, Brazil (Teixeira et al. 2005a). Application of muriate of potash at 120 kg ha^{-1} was sufficient to maintain soil exchangeable K at the same concentration as found prior to the experiment and influence the leaf K levels above sufficiency range. Foliar P contents were always higher than sufficiency range despite of P fertilization, indi-

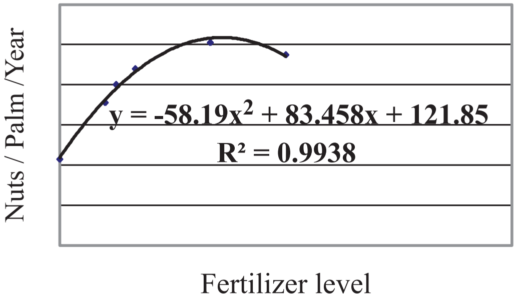

Fig. 8.5 Fertilizer response function for coconut

cating that soil of the experiment site has adequate reserve of phosphorus to support the plantation. In Pakistan, maximum nut yield was obtained with the application of 700 g urea +270 g diammonium phosphate +1600 g muriate of potash palm^{-1} year^{-1} for tall variety of coconut (Baloch et al. 2004).

The fertilizer recommendation for coconut in Malaysia (Table 8.34) and Indonesia (Table 8.35) is given below.

In Trinidad and Tobago, data obtained from soil tests in coconut growing areas, along with the nutrients required to produce 100 nuts year^{-1}, formed the basis to formulate a fertilizer recommendation (Ramkhelawan 2013). The fertilizer formulation recommended was 15-5-20 NPK, and the fertilizer rates palm^{-1} at different age group of palms are shown in Table 8.36.

Alternatively to 15-5-20 coconut palm mixture, straight fertilizers, viz. urea, triple superphosphate (TSP) and MOP, could be procured and blended by weight in the ratio of 3:1:3 (urea/TSP/MOP) and applied at the rate shown in the above table. In addition to the above recommendations, where soils are acidic, 2 kg of finely ground dolomite limestone application is suggested for each adult palm^{-1} year^{-1}.

A programme was developed for establishing “Malayan dwarf” coconut palms in Florida using foliar and granular fertilizer (Malayan dwarf coconut palm granular fertilizer) for the initial 6 months and subsequently with granular fertilizer alone at

Table 8.34 Recommended fertilizer rates for coconut on mineral soils in Malaysia

Fertilizer rate (kg ha^{-1})				
N	P_2O_5	K_2O	Plant population (ha^{-1})	Recommending agency
71.7	93.21	107.55	239	Peninsular Malaysia’s Department of Agriculture

Anon (2004)

Table 8.35 Fertilizer rates recommended for coconut in Indonesia

		Fertilizer rate (kg ha^{-1})			
Crop	Growth stage	N	P_2O_5	K_2O	Kieserite
Hybrid coconut	Mature	150	100	105	190
	Immature	65	70	155	125
Tall variety	Mature	75	50	00	95

Anon (2005)

Table 8.36 Rate of fertilizer application of 15-5-20 NPK formulation palm^{-1} year^{-1} followed in Trinidad and Tobago

Age of palm	Application (kg palm^{-1} year^{-1})	Period of application
Adult >4 years	2.00	June and December
1 year and less	0.20	At planting and 6 months later
2 years	0.60	June and December
3 years	1.20	June and December

3 to 4 months intervals to maintain soil fertility (Donselman 1980). The granular fertilizer contained primary plant nutrient sources such as potassium magnesium sulphate, ammonium sulphate, granular sludge, urea form, potassium sulphate and diammonium phosphate and secondary plant nutrient sources such as magnesium sulphate, manganese oxide, borate, iron sulphate and zinc sulphate. The micronutrient foliar spray FER-A-GRO consisted of 17.46 g l^{-1}, tribasic copper of 1.19 g l^{-1}, urea of 5.82 g l^{-1} and a spreader-sticker.

Rosa et al. (2011) developed a new concept for recommendation of fertilizers for coconut in Brazil by considering the expected productivity and plant nutrient use efficiency to estimate nutrient demand and effective rooting layer, soil nutrient availability, as well as any other nutrient input to estimate the nutrient supply and developed a "lime and fertilizer recommendation system" for coconut crop based on the nutritional balance.

Diagnosis and Recommendation Integrated System (DRIS) provides a means of simultaneous identifying imbalances, deficiencies and excesses in crop nutrients and ranking them in order of importance in which leaf analysis values are interpreted on the basis of interrelationship among nutrients, rather than nutrient concentration themselves (Beaufils 1973). The DRIS is based on the comparison of crop nutrient ratios with optimum values from a high–yielding group (DRIS norms). The major advantage of this approach lies in its ability to minimize the effect of tissue age on diagnosis, thus enabling one to sample over a wider range of tissue age than permissible under the conventional critical value approach.

Khan et al. (1988) proposed preliminary N, P and K foliar DRIS norms for coconuts growing in sandy loam soil following the general procedure outlined by Sumner (1982). They indicated that based on the norms developed, nutrient application can be tailored to the optimum needs of production. Mathewkutty et al. (1998) developed DRIS norms for N, P, K, Ca, Mg, S, Cl, Fe, Mn and Zn in middle–aged (30–40 years old) coconut West Coast Tall palms in Kerala based on their ratios in the diagnostic 14th leaf. DRIS successfully diagnosed the deficiency of K in the palms, and accordingly, response in terms of nut yield was obtained when palms with low K index were fertilized with K. But the method failed to diagnose N and P deficiencies. There is ample scope to use DRIS as a diagnostic tool for coconut fertilizer application and refine and adopt Differential Fertilizer Recommendation (DFR).

In Sri Lanka, Jayasekara (1993) developed DFR programme. DFR is based on the leaf and soil analysis nutrient levels, present/potential/target yield and resources of the plantation. The DFR computer model is capable to adjust "sufficiency" ranges and nutrient removal factors for a range of plant, soil, agroclimate and management conditions. The model provides with the required fertilizer for individual field/estate to achieve sustainable high productivity with increased profits.

Biddappa et al. (1984) have developed system models for the integrated nutrient management in coconut-based cropping systems. The basic principle in employing such a model is that the systems are being enriched and depleted of nutrients simultaneously through different processes. This model has been used to evaluate the nutrient budget and balance in different systems, viz. the coconut-based high-density multispecies cropping system, the coconut-cacao mixed cropping system and the coconut-grass mixed farming system. The studies indicated that the nutrient budget and balance of nitrogen and magnesium progressively decreased, while those of P and K increased, indicating the build-up of P and K in the system, while N and Mg got depleted. Such studies help to rationalize the application of fertilizers to coconut and coconut-based cropping systems.

Saldanha et al. (2017) evaluated the nutritional status and established nutritional standards for cultivation of hybrid coconut in Brazil with 134 observations which formed the basis and analysed the nutritional status of the palms. They found most common deficiency as K and possibly excess of Mg. The order of limitations was K > P > Ca > Fe > N > B > Zn > Cu > Mn and Mg. Interpretation of the data with DRIS indicated large divergence for nutrients, viz. Ca, Mg, Cu, Fe, Mn and Zn, when compared to those adopted as regional reference by means of critical levels showing the need for revalidation through experimental work.

8.10.4 *Period of Fertilizer Application*

Chemical fertilizer should be applied either after heavy rains have passed, or early in the rainy season, preferably some months before the heavy rains will fall (Ohler 1999). Studies conducted in the coconut growing countries under varying soil and climate proposed time/period and frequency of application of fertilizers taking into account better utilization of nutrients by the crop, prevent loss of applied fertilizer to a great extent by leaching and gaseous means. The growth demand for the nutrient and water exists continuously especially with adult palms, and nutrient availability should be ensured adequately for desirable productivity. By virtue of the inherent characteristics of fertilizer and its interaction in the soil environment, availability in the nutrient pool varies with time. Period of fertilizer application in India is linked with the south west monsoon in the west coast and north east monsoon and local irrigation facilities on the east coast and inland areas.

Studies carried out in India and Sri Lanka reported that the increased availability of N and K due to fertilizer application to coconut do not last long under the prevailing agroclimatic conditions and to ensure continuous availability of these nutrients and their use efficiency, N and K fertilizers should be applied in small doses frequently rather than in larger doses (Markose and Nelliat 1975). The inherent characteristics of some of the coconut growing soils in Sri Lanka suggest that the most efficient method of fertilizer application would be to apply small quantities frequently (Sathirasegaram et al. 1966; Kamala Devi et al. 1973). It was also indicated the need to apply slow release nitrogenous fertilizers for efficient utilization by the crop under the heavy rainfall conditions of Kerala, India.

Better growth as well as greener foliage with split application of N and Mg was observed for coconut palms growing in sandy soils, during the first 2 years (Coomans 1977). At an early age of palms, such practice makes it possible to limit losses through leaching by rain in soils with a low power of fixation and in the presence of a root system yet undeveloped. In the conditions of the lower Côte d'Ivoire, the

Table 8.37 Fertilizer recommendation for coconut palms in India (g palm^{-1})

	May–June			September –October		
Age of palm	N	P_2O_5	K_2O	N	P_2O_5	K_2O
1st year	Planting in May–June			50	40	120
2nd year	50	40	125	110	80	275
3rd year	110	80	250	220	160	550
4th year onwards	170	120	400	330	200	800

period from July to September is the most appropriate period as it makes it possible to avoid the excessive leaching in the long duration of the rainy season (May to June), at the same time profiting from the short rainy season for better availability in the nutrient pool. For effective assimilation, fertilizer application is advised during a humid period and avoiding heavy rain, to limit element losses through leaching. When the young palms are in their first and second years, the annual manuring may be given in 2 instalments; and afterwards, there is only one time application, every year. In India and Sri Lanka, the adult palm dosage is partitioned and applied according to the age and growth demand of seedlings as discussed earlier in this chapter (Table 8.37).

Frequency of fertilizer application recommended in Sri Lanka is as follows:

(a) *Young palms*: At least half yearly application is recommended. Wherever possible, split application may be adopted particularly in areas with sandy soils to minimize leaching of fertilizer due to heavy rainfall during monsoon months.
(b) *Bearing palms*: Fertilizer application should be made annually. In areas where heavy rainfall is likely during both the monsoons, and for sandy soils, half yearly application with each monsoon may be adopted to minimize leaching losses.

In West Africa, where there are two rainy seasons (April and August), young coconuts are fertilized just before or at the very beginning of each rainy season. Older palms are only manured in August before the short rainy season (Ouvrier and de Taffin 1985).

The application of K fertilizer decreased the quantity of exchangeable Mg and vice versa (Giritharan et al. 2002). Instead of using 15-5-20 fertilizer formulation, urea, triple superphosphate (TSP) and muriate of potash can be blended in the ratio (by weight) 3:1:3 (urea/TSP/MOP). The Jamaica Coconut Industry Board (Anon 2017) recommends that fertilizer should not be placed in the planting hole because the planted seedling is still receiving its nutrition from the endosperm. The first application of fertilizer should be made 3–6 months after planting by which time active feeding roots will have developed. Subsequent applications should be made at 6-monthly intervals. The fertilizer must be spread over the zone where the active root tips occur. This zone stretches from the base of the palm to the limit of the leaf spread. During the first year, fertilizer should be applied in a circle 15–20 cm from the seedling stem. Subsequent applications should be made in wider circles as the roots grow outwards. For bearing trees, fertilizer should be spread about 2 m from the base of the trunk. On sloping lands, the fertilizer should be incorporated to a depth of 15 cm at various points at the same radius as described previously.

The frequent application of small amounts of N and K, keeping the nutrients within reach of the roots, is one of the benefits of fertigation. Teixeira et al. (2005b) concluded that higher doses 240 kg ha^{-1} of N as ammonium nitrate caused acidification of the soil, reducing saturation.

Ohler (1999) summarized the effect of fertilizer application and the transformation that takes place in the physiology of palms leading improvement in yield. The time required for a yield response to fertilizer application is considerable. Fertilizer application results in a slight increase in yield in the second year followed by a higher yield in the third year, and full response to fertilizer will be obtained from the fourth year onwards.

8.10.5 Organic Manuring in Coconut

Organic manures serve not only as a source of plant nutrients but also in restoring soil fertility by increasing chemical, physical and biological properties of soil through soil aggregation. The mineral composition depends on the type of organic manure and has been discussed in detail (Mantiquilla et al. 1994). Where the usufructs of coconut palms are added to the soil as organic manure, considerable amounts of nutrients of the palms are returned to the soil. In newly planted coconut gardens, the fertility status of interspaces can be improved by sowing green manures like *Crotalaria juncea* (sun hemp) and ploughing in situ at its flowering and developing a base in organic farming system.

According to the 2009 statistics report by IFOAM on world organic agriculture, coconut has been listed among the key crops organically cultivated worldwide and suggests that the importance of understanding the prospects of organic coconut cultivation. At least 28,000 hectares of coconuts are grown organically (including conversion areas). However, for some of the world's leading coconut producers (Indonesia, India and Sri Lanka), no details are available, and it can therefore be assumed that the actual coconut area is higher (Willer and Kilcher 2009).

Nirukshan et al. (2016a) compared the soil and plant nutritional status between organically and conventionally cultivated coconut in Sri Lanka. The organically cultivated system had a better soil nutrient status than those receiving inorganic nutrition. Information on the yield of palms was not indicated.

8.10.5.1 Effect on Soil Physico–Chemical and Microbial Properties

The physical and chemical properties of soils depend upon the nature of their formation, and the biological properties are largely governed by the environment which contributes to organic matter status of soil. Coconut is also governed by the physical and chemical properties and the biological environment which influence the mineral nutrition. Generally the organic matter is subject to mineralization and immobilization turnover (MIT) under the influence of microbial population of the soil before release of the nutrients and mostly governed by the complexity of the organic matter available/added to the soil.

Large areas of sandy soils are cultivated to coconut that are poor in basic nutrients, and the nutrient-supplying capacity of these soils is improved by addition of tank silt once a year to improve the soil texture and CEC and enhance water-holding capacity. The organic matter content of these soils can be further improved by addition of around 50 kg green leaf manure palm^{-1}.

Coconut husk piled at the base of the coconut palm as mulch or chopped and composted is found to improve the water-holding capacity of soil by its physical presence and improve the organic matter content on degradation, besides being a rich source of chlorine (40.7%) and potassium (66.9%) (Eroy 1991). Joshi et al. (1982) recorded increase in water-holding capacity of sandy soil and decrease in the bulk density due to continuous application of organic sources mostly coconut usufructs blended with inorganic fertilizers.

Considering the characteristics of husk, it is a practice to bury the husk with convex face upwards around 2 m away from the base to improve water retention characteristics of soil and reduce weed growth. Such a practice in the sandy loam soil improved the yield of East Coast Tall (ECT) palms by 49% over control treatment. As moisture conservation measures for the palm roots to retain and utilize the moisture, it can also be buried in trenches of 3 m × 1.2 m and 50 cm deep and covered with soil (Grimwood 1975).

Burying husk in the surface soil is also found to lower the bulk density of soil (Cadigal and Magat 1977). Husk was found to be beneficial to increase the yield of ECT palms maintained under inorganic fertilizer. Mulching coconut husk around the base of the palm at 2 m distance improved the yield by 49.6% over control. Coconut husk can conserve moisture and store water nearly three times its weight, and a thousand husks can yield 7–8 kg potash, and this practice raised yield by 44.6% over the control (Balasubramanian et al. (1985).

The use of green manures like *Eucheuma spinosum* (a seaweed) and *Leucaena leucocephala* contributed soil organic matter and improved physical properties, besides functioning as source of K and N, and improved the growth and functioning of seedlings especially that of MAWA hybrid (Cadigal and Prudente 1983; Cadigal et al. 1983).

Mahindapala (1989) obtained 100% survival rate of 2-month-old poly bag seedlings transplanted in sandy soil amended with *Gliricidia sepium.* A sandy soil environment responded well on receiving goat dung and inorganic fertilizers when applied together, supporting adult coconut palm with 42% increase in yield and 45% in copra outturn when continuously applied for 5 years.

In coralline soils of Lakshadweep Islands, fertility status of coconut groves was improved with the incorporation of coir dust, coconut sheddings, available forest leaves and cattle manure along with inorganic fertilizers carrying N, P and K continuously over 10 years, reduced the mortality of transplanted seedlings from 50 to 17% and improved the organic matter status from 0.06 to 0.17% (Bavappa 1986).

Table 8.38 Organic manuring schedule for bearing adult coconut palms in India

Mixture	Manures	Quantity (kg)
Mixture 1	F Y M (or) compost	35–70
Mixture 2	Fish guano	5–7
	Wood ash (or)	18–20
	Coconut husk ash	2.5
Mixture 3	Prawn dust	5–7
	Wood ash (or)	18–20
	Coconut husk ash	2.5
Mixture 4	Ground oil cake	5–7
	Wood ash (or)	18–20
	Coconut husk ash	2.5
	Bone meal	1–2

For these coral soils, Krishnamoorthy (1985) advised incorporation of green manures or compost 1.2 m away around the base of the adult palms for conservation of moisture and favourable utilization by the palm roots.

In India, organic manure mixture which is exclusively made up of organic sources is recommended for tall variety palms in coarse-textured soils which are deficient in organic matter (Thampan 1982) (Table 8.38).

Long-term applications of inorganic fertilizers were found to be detrimental to the beneficial soil microorganisms such as *Pseudomonas*, *Azotobacter* and *Bacillus* as well as soil physical parameters (Pushpakumari et al. 2008). They, however, observed significant improvement in parameters like available nutrients in soil and improved nutrient levels in the palm with the application of either goat dung (25 kg) and MOP (800 g) palm^{-1} or poultry manure (30 kg) and MOP (250 g) palm^{-1}. The microbial biomass was much influenced by application of poultry manure (Kondagama et al. 2009). Silva et al. (2008) also reported higher levels of macronutrients, favourable soil physical properties and higher microbial biomass with the addition of soil amendments than the inorganic fertilizer application.

Intercropping coconut with *Gliricidia sepium* is an effective strategy to improve soil chemical, physical and biological properties, viz. soil microbial activity, bulk density, organic matter, total nitrogen, available phosphorus and exchangeable potassium and magnesium dynamics of coconut growing, reaffirming the quality of *G. sepium* for replenishing soil fertility of degraded coconut growing soils in intermediate and dry zone of Sri Lanka (Secretaria and Maravilla 1997).

Long-term nutrient application studies in coconut palms (red-yellow podzolic soil classified as Andigama series; moderately acidic, rich in organic carbon) with cattle manure were found to increase the Fe and Mn levels, while poultry manure increased the Cu and Zn level in soil as evidenced in the contents of coconut diagnostic leaf (Chathurangani et al. 2010). The content of micronutrients in leaf was similar to the reports of the sufficiency for Mn, Cu and B. However, Zn levels in 14th leaf in all the treatments were below the sufficiency levels reported elsewhere.

Udayangani et al. (2013) reported that only goat manure and poultry manure contributed to sufficient level of P, while sufficient level of K residuals was recorded in cattle manure treatment. Addition of organic manure increased soil organic carbon and improved the microbial population and activity. However, the sulphate content added with sulphate of potash (SOP) had an inhibitory effect more on microbial activity than on microbial population (Nirukshan et al. 2016b).

In a *Trichoderma*-activated compost study, the application of city garbage plus swine manure produced significantly taller seedlings with wider girth, higher leaf count and dry matter accumulation and significantly higher N uptake at the rate of 606 g seedling^{-1}. The compost could also be mixed with ammonium sulphate at 75:25 ratio and capable of substituting the latter wholly for coconut seedlings (Ebuna and Cagmat 1992).

Green manure like *G. sepium* helped the establishment of 2-month-old poly bag seedlings at 100% survival rate. Palms grown in sandy soils with application of inorganic fertilizer and extra goat dung increased production of nuts by 42%, while copra production increased by 45% at the end of the fifth year (Mahindapala 1989).

Application of organic manure (either 18 or 24 kg goat dung) supplemented with inorganic fertilizers (NPK or K alone) in the gravel soils commonly found in coconut lands of the low country wet zone of Sri Lanka, increased the microbial counts and microbiologically mediated processes in the soil compared with the control resulting in increased yield and yield attributes (Tennakoon et al. 1995). Mantiquilla et al. (1994) reported consistent positive response in terms of growth and yield of coconut when organic fertilizers were combined with inorganic fertilizer high in chloride.

8.11 Soil and Nutritional Aspects Associated with Certain Disorders

The soil and other environmental factors exert considerable influence in the development, spread as well as intensity of plant diseases. The coconut palm is a very adaptable crop and has been grown under extreme conditions of soils. It is often difficult to specify the influence of a specific soil or nutritional factor associated with different diseases of the palm, mainly because of its perennial nature, the high heterogeneity among the field populations and also the highly heterogeneous soil environment under which it is distributed, particularly the subsoil environment. The influence of the extensive root system is still another factor as it is beyond the control of the experimenter to explore the root functions in the subsoil layers and also in places far beyond the basal region.

The different diseases of the palm, their causes and control have been described in greater detail in Chap. 10. Under ideal soil/ nutritional and other environmental conditions, the palm may be in a better position to offer resistance to pathogenic infections.

Most of the important diseases of the palm are generally found to occur on all soil types under which it is grown (Menon and Nair 1951). However, the diseases appear in a more acute form in areas with unfavourable soil such as poor aeration, waterlogging, poor moisture retentive capacity, high water table/shallow soil depth, poor drainage, etc. Menon (1961) suggested that many of the diseases cannot be primarily caused by unfavourable soil conditions or nutrient deficiencies, but they provide an environment conducive to infection by biological factors. If deficiency of one or more elements in the soil is responsible for the diseases, the incorporation of the deficient element(s) in an available form shall help to restore the palm into normal health or prevent fresh incidence of the disease. Menon and Pandalai (1960) have stated that certain diseases like bud rot and leaf rot are known to be purely parasitic; some like the bronze leaf wilt and "tapering stem" or "pencil point" condition are due to unsuitable soil conditions, while others like stem bleeding and fungal root rot are known to be associated with parasitic infection predisposed by soil conditions. Yet another set of disorders are caused by nutritional deficiencies/imbalances. Some of these problems are enumerated in the following sections.

8.11.1 Bronze Leaf Wilt

The term "bronze leaf wilt" described by Briton-Jones (1940) covered more than one diseased condition including lethal yellowing. However, when critically examined, a state of unhealthy condition of the palm without any abnormality in inflorescence, nuts and roots indicated to be purely of physiological origin (Child 1974). Potassium deficiency is reported to be associated with the disease. Briton-Jones (1940) from observations in Trinidad and St. Lucia suggested very strongly that the disease to be caused by a combination of adverse soil conditions, which include waterlogging, drought or/and impermeable soil strata, leads to shallow root system resulting into a condition of physiological drought. Analysis of the various physical and chemical factors of the soil throughout Trinidad suggested that unbalanced nutrition coupled with the physical conditions of the soil and its water relationship constitutes the primary cause of the disease (Bain 1937). Maramorosch (1964) concluded that the cause of bronze leaf wilt was purely physiological and related to soil and water conditions. Correction of deficiencies and adequate soil and nutritional management restore the palm to normal health (Briton-Jones 1940).

8.11.2 Crown Choke Disease

The occurrence of "crown choke" (crown rot) disease of coconut was reported in 1964 from Kahikuchi (Assam-India) by Chakrabarthy et al. (1970), and later studies were conducted by Brunin and Coomans (1973) in Côte d'Ivoire. Cecil and Pillai (1978) and Baranwal et al. (1989) in India have confirmed the possible role of boron deficiency in the development of the disorder. The "little leaf disease of coconut" described by Ashby (1917) and the "frond choke" disease reported by Dwyer (1937) seem to be similar to the "crown rot" disease reported. Fremond (1965) reported that a form of bud rot of coconut palms in the New Hebrides might be due to boron deficiency. A survey conducted in Assam, India (Anon 1990), showed that about 10.8% of the palms were affected by the disease and the total annual loss in yield due to the malady was then estimated at 6.38 million nuts.

Dufour and Quencez (1979) observed boron deficiency symptoms in 1-year-old coconut seedlings in solution culture. Only the first sign of deficiency was noticed which was the development of small chlorotic spots symmetrically oriented in relation to the main veins of the young leaves. The symptoms of the disease in 3–10-year-old palms have been described by Cecil and Pillai (1978) and Baranwal et al. (1989) and 18–20-month-old palms in Côte d'Ivoire by Brunin and Coomans (1973) which are more or less identical. The conspicuous symptoms of the disease are the fusion of terminal pinnae of young fronds, emergence of shorter fronds that crowd around the apex; development of deformed and crinkled pinnae; development of "hook" at the frond tips and also other parts of the frond; development of fronds with very short unfolded pinnae either on one or both the sides of the rachis with zigzag folding, necrosis on rachis and frond tips; and development of black necrotic stumpy frond without any pinnae in the advanced stage. Finally the growth of the bud is arrested, and the palm succumbs to deformity. The unaffected outer whorls of leaves remain normal throughout and even quite some time after the death of the growing point. Laminal expansion is very much restricted, and the affected pinnae become brittle and thicker than normal. The crowding of young abnormal fronds around the bud gives a choked appearance to the palm which might be the reason for the terming of the disorder as "frond choke". In some cases, the young affected fronds show "witch's broom" appearance. In other cases, the petiole of the new frond becomes very thick and forms a tubular structure enclosing the entire space of the apex.

Brunin and Coomans (1973) could prevent the occurrence of the symptoms on young palms in Côte d'Ivoire by application of borax pentahydrate ($Na_2B_4O_7{\cdot}5H_2O$) at 15 g palm^{-1} at planting and again once after 6 months. For the affected palms, IRHO has recommended the above dose of borax pentahydrate in April and October for 1–3-year-old palms and application of 30–80 g borax pentahydrate as a single dose for 4-year-old palms depending on the symptoms.

Chakrabarthy et al. (1970) made 9 applications of borax (sodium tetraborate), 20 g palm^{-1} in each application through soil. In each set, 3 consecutive applications of boron were given at an interval of 15 days, followed by the rest in 3 months. The field was irrigated after each application of boron. After the first set of application was over, treated plants showed signs of recovery, whereas in the control plants, the conditions remained unchanged. In all the treated plants, healthy leaves emerged after the application of third set of boron. Cecil and Pillai (1978) reported that soil application of borax as decahydrate at 250 g and 500 g palm^{-1} as a single dose followed by irrigation to 5-year-old palms was effective in curing the disease and the recovery was faster in palms treated with 500 g borax. The newly emerged leaves after treatment were normal in appearance.

In West Bengal, India, where the soil pH ranged from 4.9 to 5.0, highly deficient gardens showing symptoms of crown choking recorded 0.19 ppm B, and in healthy gardens the boron level was 0.22 ppm (Baranwal et al. 1989). They recommended soil application of borax at 50 g palm^{-1} just after the appearance of the symptoms. In slightly advanced stages, two applications of borax, 50 g each, at an interval of 3–4 months were found necessary for the redemption of the disorder. They reported a lower content of B in the leaf tissues of diseased palms compared to disease-free palms, both in Assam and West Bengal. Comparison of leaf B levels of samples collected from diseased areas with those of healthy area indicated that leaf B concentration is much less in diseased areas than in palms from healthy area. The Ca/B ratio (expressed in equivalent basis) is significantly lower for healthy palms when compared with diseased palms. It is interesting to note that the Ca/B ratio of palms in healthy area is much lower as compared to that of healthy palms in the affected area.

Cecil and Pillai (1978) reported 5.7 ppm B in affected palms and 9.2 ppm B in healthy palms. Margate et al. (1979a) suggested that the critical level of boron in hybrid coconut seedlings (frond 3) was likely to fall within the range of 13 to 14 ppm. They recommended the application of 1–1.5 g of borax seedling^{-1} in the nursery to prevent the occurrence of B deficiency symptoms. The dose of borax, however, suggested by them is extremely low. Rosenquist (1980) reported a mean foliar content of 10.5 ppm B, and he suggested that 9.5 ppm B in frond 14 was critical. The boron contents of coconut palms (frond 14) growing on different soil types of Kerala reported by Pillai et al. (1975) ranged from 10.9 to 14.6 ppm. They also reported that the available soil boron levels were low. Studies carried out in Kerala showed that boron deficiency causes reduction in coconut productivity and the deficiency could be cured by the application of 300 g and 500 g borax palm^{-1} year^{-1} in 2 split doses for seedlings and adult palms, respectively. The deficiency symptoms associated with B were completely recovered by borax application (Kamalakshiamma and Shanavas 2002).

Apart from N, P, K and Mg deficiencies in coconut so far observed in Sri Lanka, boron (B) deficiency was observed in 12 young coconut palms of age 1–3 years at Poojapitiya in Kandy District. The third leaf of the affected palms had 3.4–7.5 ppm B as compared to 7.6–10.0 ppm B for healthy palms in the same vicinity (Jayasekara and Loganathan 1988). The presence of healthy palms in the same vicinity is not uncommon. Ohler (1999) suggested that this may be due to local differences in soil, individual differences in sensitivity to boron deficiency or individual differences in the root system development, the palms with a more extensive root system being able to obtain a sufficient supply, while those with a smaller root system suffer from the deficiency.

8.11.3 Stem Tapering Disease

The “pencil point” or “tapering stem” disease is generally considered to be due to deficiency of nutrients/water and unfavourable soil conditions, and the malady has been referred to as “starvation of palm” (Briton-Jones 1940; Menon and Pandalai

1960). Ohler (1984) stated that stem tapering is not a disease by itself, but it is the result of various unfavourable growing conditions. The leaves become pale and diminished in size, photosynthetically inefficient, the trunk diameter becomes reduced, the inflorescence production is very much reduced and the inflorescences have very few female flowers which rarely develop into nuts. In course of time, the palm becomes barren, the crown size is progressively reduced and the trunk diameter is gradually reduced to a condition of pencil point until the palm finally dies. The malady is more prevalent in waterlogged and other infertile areas and also in areas with very hard substratum of laterite, coral or other formations which are basically unsuitable for coconut culture. Intensive manuring and management may provide reasonable growth and productivity in the early period which eventually exhausts the limited soil of its nutrient reserves. Multiple deficiencies including those of secondary and micronutrients are often associated with the malady (Menon and Pandalai 1960). In Kerala, the disease is commonly found in swampy or shallow soil situations which are ordinarily not suitable for coconut cultivation. In such areas planting is usually done on mounds, and the land is periodically raised with transported sand or soil which is an expensive practice in most of the areas. As long as the land reclamation process is continued along with generous manuring, the palms grow normal and yield satisfactorily. Subsequent neglect leads to tapering stem problems. Park and Fernando (1941) and Menon and Pandalai (1960) have suggested factors leading to tapering stem disease. The palms do recover when deficiencies are corrected through intensive manuring and soil conditions are improved. Savy (1962) reported that in severe cases the palms do not bear to their full capacity even after recovery. Recovery is possible with intensive soil and nutritional management for sustaining the palms to normal bearing.

8.11.4 Rubbery Copra

The problem of “rubbery copra” in coconut was reported to be due to acute deficiency of sulphur (Southern 1969). Extensive occurrence of sulphur deficiency was reported from Papua New Guinea (Southern 1969) and Madagascar (Ollagnier and Ochs 1972). Sumbak (1975, 1976) reported sulphur deficiency in Madang, which according to him was associated with poor drainage conditions. The main sulphur deficiency symptoms reported are orange-yellow leaves (both young and old) and weakening and arching of the rachis followed by necrosis of leaflets. Chlorosis and necrosis increase with the age of the fronds, and in severe cases, second or even the first leaf may show yellowing. Colouration may vary from greenish yellow to bright yellow and in some cases vivid orange. The number of live fronds becomes fewer. In the advanced stages, the crown loses most of the leaves, and severe necrosis is found on the older leaves. A sulphur-deficient palm may be distinguished from nitrogen-deficient palm in that the young leaves as well as old leaves are discoloured (Southern 1967).

The nuts are usually small with normal kernel thickness, but on drying, the kernel collapses into soft, flexible and leathery copra, often brown in colour, which is usually referred to as "rubbery copra" possessing very poor physical and chemical characteristics. The rubbery copra is characterized by low oil content (as low as 36% on dry basis) and high nitrogen, ash and sugar contents. The oil from rubbery copra has high iodine value and low saponification value compared to the oil from normal copra.

According to Southern (1969), deficiency symptoms on the foliage and incidence of rubbery copra were more associated with the sulphur content of nut water. The nut water of sulphur-deficient palms contained less than 10 ppm sulphate sulphur, while 20 ppm was suggested as critical even though values up to 100 ppm were observed. According to him, with 20 ppm sulphate sulphur in nut water and 150 ppm sulphate, sulphur deficiency is likely to occur in the palm. The deficiency condition can be corrected by the application of sulphur or sulphur-bearing fertilizers. He recommended sulphur-containing fertilizers equivalent to 900 g sulphur palm^{-1} once in 2 years. There was spectacular response on the foliage within 6 months, and the copra quality had become normal in 18 months after sulphur application.

The total sulphur content in frond 14 reported by Pillai et al. (1975) ranged from 0.113 to 0.152%, while Margate et al. (1979b) reported a mean value of 0.162%. The results presented by Manciot et al. (1980) showed that the values varied from 0.163 to 0.238% for talls and 0.175–0.445% for hybrids. They suggested a critical level of 0.15–0.20% sulphur in frond 14, while Magat (1979) suggested a critical level of 0.15%. While discussing the sulphur nutrition of coconut, Cecil and Pillai (1976) reported that S deficiency did not seem to be an immediate problem for coconut in the west coast of India, but continued application of sulphate-free fertilizers could eventually lead to S deficiency conditions. They recommended the inclusion of any one of the S-bearing fertilizers like ammonium sulphate, single superphosphate, ammophos, magnesium sulphate or sulphate of potash in the fertilizer schedule for coconut.

8.11.5 The Coconut Root (Wilt) Disease

The coconut root (wilt) had been considered as a disease of uncertain aetiology until Solomon et al. (1983) observed constant occurrence of phytoplasma in sieve tubes of roots, tender stem, petiole and developing leaf bases of root (wilt)-diseased palm as against their total absence in healthy palms from disease-free areas. The survey carried out by Pillai et al. (1973) indicated that the disease has been found to occur on all soil types of Kerala. However, the spread of the disease has been faster on light-textured sandy, sandy loam and alluvial soils, particularly in low-lying areas and also on heavy textured clays compared to laterite soils. The incidence has been higher in waterlogged low-lying areas adjacent to rivers and canals. Investigations on soil conditions and nutritional factors associated with the disease were initiated in 1939 by Menon and Nair (1949) and Menon et al. (1950,1952) suggested that in addition to biotic agents, the disease might also be associated with nutritional deficiencies. They reported that the soils of disease-affected areas were generally deficient in major nutrients, particularly K, and had a lower content of exchangeable cations and a low pH and cation exchange capacity. The silica/sesquioxide ratio was higher.

Soil sickness characterized by low pH, inadequate drainage, poor aeration, low microbial activity in the rhizosphere and nutrient imbalances together with mineral deficiencies, probably those of K, Ca and Mg were reported to have a predisposing decisive role on the incidence of the disease (Menon et al. 1952; Pandalai et al. 1958a, b; Menon 1961; Verghese 1961; Lal 1964; Cecil 1969). An intensive study of the major soil groups of erstwhile Travancore-Cochin State, India, representing healthy and diseased pockets was conducted by Sankarasubramoney et al. (1954, 1955, 1956) and Pandalai et al. (1958a, b, 1959a, 1959b). Their studies showed, in general, that soils in disease-affected areas were low in available K, total Ca and Fe, exchangeable Ca and Mg, total exchangeable cations, CEC, pH and percentage base saturation. Waterlogging was found to favour disease incidence in the tract, and majority of the diseased areas had a high water table. Cecil and Verghese (1959) observed that the reduction products formed in soils under waterlogged conditions were not responsible for disease incidence. Verghese (1966) indicated the association of faulty nutrient ratios in soils, particularly K/Mg, K/Ca and N/K with disease incidence. Pillai and Pushpadas (1965) observed that coconuts growing on *Kari* tracts (peat soil) having high acidity, often in the pH range of 3–4, had less incidence of disease.

Menon and Nair (1952) were the first to examine the major nutrient status of leaves in relation to the disease. Subsequent studies by Sankarasubramoney et al. (1952), Verghese et al. (1959a), Pillai (1959) and Pandalai (1959) showed that there was a tendency for N, P and K to get accumulated in the leaf tissues of diseased palms and the accumulation increased with the advancement of the disease. Verghese (1959) suggested that probably the mineralogical composition of rocks and some toxic products of weathering could be responsible for the disease and the possibility of water acting as their carrier. Compared to healthy, the diseased palms contained more of N, P, K and silica to the extent of 5.0–13.0, 0.0–13.0, 5.0–39.0 and 59.0–134.0%, respectively (Verghese et al. 1959b). Similar accumulation of nutrients in the leaves of Cadang-Cadang-affected palms was reported by Yualves et al. (1958). Biddappa and Khan (1985) studied the heavy metal status of coconut growing soils of Kerala and found that the contents of DTPA extractable barium, chromium, cadmium, lead, sulphur and vanadium were significantly high in diseased soils compared to healthy.

Further studies showed that there was no significant accumulation of nutrients in the palms in the early stage, while the concentration of N, P and K was significantly higher in the middle and advanced stages of the disease (Cecil 1981). The nutrient exhaust values reported by Pillai and Davis (1963) showed that about 50% of N and P and 78% of K are exhausted through the harvest of bunches with nuts which indicates that when the yield of nuts is restricted basically due to the disease, the excess nutrients are liable to get concentrated in the foliage of the diseased palms. So the accumulation of nutrients, particularly in the advanced stage of the disease, is partly due to the reduced rate of dry matter content of the foliage and partly due to the reduced rate of nut yield with increased rate of disease intensity.

Verghese et al. (1957, 1959b) ruled out the possibility of Cd and Sr toxicity in the disease complex. Cecil (1975) found that the N, P and K contents did not differ between healthy and diseased palms in the early stage of infection; but Ca and Mg contents of healthy palms in disease-free areas were significantly higher than those of apparently healthy or diseased palms in the diseased tracts. He also reported that the palms in the diseased area were in a state of imbalanced nutrition with wide ratios of N/Mg, P/Mg, K/Mg and Ca/Mg indicating a lower content of Mg in proportion to other major nutrients. Imbalance in cationic ratios like K/Na, K/Mg, K/(Ca + Mg) and K/(Ca + Mg + Na) and anionic ratios like P/S and N/S were also reported to be associated with the diseased conditions of the palm (Pillai et al. 1975). A critical evaluation of the earlier studies on the quality of nutrition in relation to the disease suggested that the palms in the disease-affected areas, whether apparently healthy or visibly diseased, are in a state of an unbalanced nutrition, possibly the result of a relatively higher content of N, P and K on the one hand and a lower content of Ca, Mg and S on the other.

Biddappa and Cecil (1984) and Biddappa (1985) studied the deposition of heavy metals in the root and cabbage tissues, respectively, of diseased palms by employing scanning electron X-ray microprobe analyser. High deposition of Al, Mn, Cu and Co in the diseased roots and Cr, Ti, Pb, Bi and Ga in the cabbage tissues of diseased palms was also observed compared to healthy tissues. This was also confirmed by the chemical analysis of a large number of soil and tissue samples under identical conditions. Wahid et al. (1983) studied the non-nutrient elemental composition of soil (0–30 cm) and plant tissues of healthy and root (wilt)-diseased palms from a few selected locations employing energy dispersive X-ray fluorescence technique and found that Ni and Sr were present at a higher concentration in the root of diseased palms compared to healthy.

The soil and nutritional aspects of the disease were reviewed by Cecil and Kamalakshi Amma (1991) who reported that neither the major nor micronutrients had any direct role on the incidence of the disease. While discussing the nutritional disturbances in relation to root (wilt) disease, Pandalai (1959) suggested that lack or unavailability of nutrients was not the cause of tissue abnormalities but was actually the inability of the palm to transact the normal processes at the appropriate site.

Reviewing the fertilizer demonstrations on coconut in the west coast of India, John and Jacob (1959) reported that in root (wilt)-affected areas, NPK applications along with the use of fungicides and insecticides markedly improved the health of the palms and increased the yield, possibly due to the improvement in the fertility levels of the neglected gardens. Sahasranaman et al. (1964) found that application of NPK at 227 g N and P_2O_5 and 454 g K_2O palm^{-1} year^{-1} gave economic yield and maintained general health of the palms, but higher doses of NPK, viz. 681–1362 N and P_2O_5 and 1362–2724 g K_2O palm^{-1} year^{-1}, aggravated the disease and reduced the yield. Cecil (1981) observed that increased levels of N, P and K had an adverse effect on the growth of young palms and on the yield of diseased palms. Application of lime and ash (Chettiar et al. 1959) and Chilean nitrate (John et al. 1959) showed no positive effect on the disease.

Davis and Pillai (1966) reported that the application of micronutrients and Mg did not prevent fresh incidence of disease. They observed that Mg had no significant influence on the yield of healthy palms, but it had decidedly a favourable response on moderately affected palms, while on severely affected palms, the effect was highly significant. Similar differential response of Mg on diseased palms was also reported by Varkey et al. (1979), Cecil (1981) and Anon (1981).

Khan et al. (1985b) did not observe any relationship between the micronutrient composition of diseased palms and the disease index compared to healthy palms. Zinc and molybdenum, both as soil application and foliar spray, had no effect on incidence or intensity of the disease, even though the tissue levels of Zn and Mo increased considerably (Mathew et al. 1986). A systematic micronutrient manurial experiment consisting of all combinations of two levels each of Fe, Mn, Cu, Zn, B and Mo since field planting had shown that the disease was not related to micronutrient nutrition of the palm (Anon 1986). Lal (1968) reported that the foliar yellowing associated with the disease might be largely due to Mg deficiency and the intensity of yellowing decreased markedly when diseased palms were sprayed with 2.0% solution of magnesium sulphate at quarterly intervals (Varkey et al. 1979; Anon 1966). Application of sulphur, calcium sulphate and magnesium sulphate along with NPK was found to increase the yield of affected palms (Lal 1964; Nair and Radha 1959). Lal (1964) reported reduction in foliar yellowing and increase in yield of diseased palms by applying NPK, lime and farmyard manure and spraying with Bordeaux mixture, micronutrients and magnesium sulphate. The results of a field fertility trial with three levels of NPK and two levels each of Ca and Mg on diseased palms showed that the lowest level of NPK tried, viz. 350 g N, 300 g P_2O_5 and 600 g K_2O along with 500 g MgO palm^{-1} year^{-1}, could be the economic dose for the management of the diseased palms (Anon 1981). The above observations suggest that the addition of NPK fertilizers without having a balance with the availability of secondary nutrients, particularly Mg and S, had an adverse effect on the diseased palms, while the inclusion of secondary nutrients showed beneficial effects. Based on the earlier observations, Cecil (1981) conducted a field study on the role of major nutrients in relation to disease incidence for a period of 12 years right from field planting in 1970. The following are the results emerged out of the study in relation to the disease.

1. The incidence of root (wilt) disease was not related to the major element nutrition of the palm. However, an imbalance between N and Ca, K and Ca and Mg was found to be associated with disease incidence. Heavy doses of NPK fertilizers had an adverse effect on growth as well as yield of diseased palms. A balanced supply of nutrients, particularly K, Ca and Mg, was found to be ideal for the management of root (wilt)-affected gardens.
2. The first level of N, P and K, viz. 500 g N, 300 g P_2O_5 and 1000 g K_2O palm^{-1} year^{-1}, was found to be adequate for the normal growth and productivity of WCT palms in the disease-affected areas. As the build-up of P and K in the

soils as well as in coconut palm tissues was high due to continued fertilization, their application has to be regulated based on foliar levels. The critical levels of 0.12% P and 0.8–1.0% K in frond 14 may be followed for regulating the P and K requirements of the palm.

3. Heavy liming is not necessary for the management of disease-affected plantations. Nevertheless, regulated additions of Ca through Ca-bearing fertilizers like rock phosphate/superphosphate or light additions of liming materials may be followed for supplying the Ca requirement of the palm. The concentration of 0.3% Ca in frond 14 may be considered as critical level for regulating the Ca requirement of the palm.
4. Regular Mg treatment since planting gave highly significant response on growth, onset of bearing and yield of young palms with simultaneous improvement in soil and foliar Mg levels. The pre-bearing age was reduced by 9.1 months, and the earliness of bearing was significantly correlated only with foliar Mg levels. Development of foliar yellowing was prevented in young palms, which was aggravated by higher levels of K, particularly in the absence of Mg. It increased the frond production rate and the number of functioning leaves of root (wilt)-affected palms at a highly significant level and improved the yield attributes and yield of affected palms more than those of healthy palms. When the increase in yield of nuts in healthy palms was 37%, the corresponding increase in root (wilt)-affected palms was 60%. Judicious manuring with Mg salts like magnesium sulphate from the time of field planting was highly essential for the successful growth and increased productivity of the palm in diseased area. An annual dose of 500 g MgO adult palm^{-1} was found to correct the Mg deficiency problems in the field. However, the dose may be regulated based on the foliar Mg levels as well as the Mg/K balance in the soil. The foliar content of 0.2% Mg in frond 14 and an exchangeable Mg/K ratio value of 2.0 in the soil may be considered as critical for regulating the Mg requirement of the palm.
5. The disease caused a heavy loss in the yield of nuts as well as copra outturn in the early bearing period. The general reduction in the yield of nuts was 60% and in the yield of copra was 64%. However, the reduction in the oil content of copra was not considerable. The mean values for the oil content of copra from healthy and root (wilt)-affected palms were 68.4 and 67.4%, respectively.
6. The application of P as ammophos (15% P) or that of magnesium sulphate (13% S) could effectively take care of the sulphur requirement of the palm.

The nutritional requirement of COD × WCT hybrids in the root (wilt)-affected area was investigated by Kamalakshiamma et al. (1982) who observed that the hybrid responded favourably to higher levels of NPK for its growth and early flowering. However, the dose of 500 g N, 300 g P_2O_5 and 1000 g K_2O along with 500 g MgO palm^{-1} year^{-1} was found to be ideal for optimum productivity under rainfed condition. A comparative study on the performance of WCT (Cecil 1981) and COD × WCT (Kamalakshiamma et al. 1982) under rainfed conditions and regular fertilization with N, P, K, Ca and Mg since field planting in the same locality showed that the hybrid was superior to WCT with respect to reduced disease incidence and increased nut yield.

Valiathan et al. (1992) reported the presence of high Ce and low Mg levels in the leaf may be responsible for the incidence of root (wilt) disease. They also reported a common geochemical basis for endomyocardial fibrosis in human beings and root (wilt) disease of coconut palms. Taking lead from these results, Wahid et al. (1998) studied the concentrations of major nutrients and micronutrients, rare earth elements (REEs) and Th and nutrient/REE ratios in the leaves of diseased, and apparently healthy coconut palms of the root (wilt) disease-affected tract and healthy palms of the disease-free tract, covering three major soil types of Kerala, viz. alluvial (entisols), laterite (ultisols), and sandy soils (entisols), were examined in relation to the disease. Accumulation of major nutrients, especially K, was generally observed in the leaves of diseased palms. Mg content of leaves of palms growing on laterite soil in disease-affected tract was lower than of palms in the disease-free tract. The leaf concentrations of La (lanthanum), Ce (cerium), Pr (praseodymium), Nd (neodymium), Sm (samarium), Gd (gadolinium) and Th (thorium) did not show significant differences between healthy and diseased palms. The only exception to this trend was Gd whose concentration was less in the diseased and apparently healthy palms growing on laterite soil of the disease endemic area than that in the healthy palms of the disease-free area. Some of the essential plant nutrients (EPN)/La and EPN/Ce ratios were significantly different in palms of the disease-affected tract compared to that in palms of the disease-free tract indicating imbalances in the relative concentrations of EPNs and REEs. These results call for more detailed study of the geochemical differences between the disease-affected and disease-free tracts for identification of the soil chemical factors associated with the incidence of the disease. Wahid et al. (2003) studied the pattern of uptake of 6 REEs from 3 types of soils varying widely in their chemical characteristics and monazite content through soil and tissue analysis and stated that Sm was the least accumulated lanthanide in coconut palm tissues and it was the most favoured element by palm on a comparable scale of substrate concentration.

Critical studies are needed to elaborate the beneficial role of Mg in the management of the disease, as the interaction between disease incidence and Mg deficiency on the productivity of the palm is negative. The root (wilt) disease is now known to be caused by phytoplasma (Solomon et al. 1983). However, a balanced and regulated supply of primary (NPK) and secondary nutrients (Ca, Mg and S) is necessary for the successful management of the disease. Further, the correction of unfavourable soil conditions like waterlogging, inadequate drainage and poor aeration shall help to check the deterioration of the palms.

8.12 Future Strategy

The coconut palm has emerged from the status of a back yard crop to that of a crop of commercial significance stressing the importance of mineral nutrition and sustainable productivity of coconut plantations. There is a need to revisit the agronomical interventions and modify them considering the site-soil-system as an entity. The following lines of investigations are suggested to ensure maximum coconut productivity on a sustainable basis.

1. A differential fertilizer system for fertiliser recommendations in an integrated manner involving plant and soil nutrient status.
2. Critical studies on boron and magnesium for inclusion as components of fertilizer recommendation to alleviate the ill effects of maladies associated with the deficiency of these nutrients.
3. Intensified research on INM involving organic recycling using the usufructs of coconut and component crops. Biochar initiatives in improving the carbon stock and reducing oxidation of organic matter for better nutrient use efficiency in coconut farming systems where sufficient biomass is generated from the plantations.
4. Developing an INM package for reducing the problems related to phytoplasmal diseases, in view of the absence of other control measures.
5. Developing desorption models for major coconut growing areas, to form a basis to prescribe potassium and phosphorus recommendation at a given soil test value.
6. A deeper understanding of the physiology of palms, especially on dry matter partitioning to design life-saving irrigation/fertigation in drought-affected areas.
7. Mandate to the national institutes for coconut palm nutrition survey, to prepare a status map in the major coconut growing tracts of respective countries to design a strategy for improving the yield levels and formulate yield prediction models.
8. Identification and study of the nutritional status of high-yielding palms in relation to soil nutritional status for designation of index gardens.
9. Further critical studies in nutrient budget and energy input-output analysis in high-density multiple cropping systems.
10. Refinement of precision farming technology in relation to coconut palms to ensure sustainable production.

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