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# Soil Fertility Status and Disorders in Arecanut (*Areca Catechu* L.) Grown on Clay and Laterite Soils of India

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*In arecanut, disorders like crown choking and crown bending lead to death of palms within a short span. Spatial and temporal variability in soil and leaf nutrient status was used as a tool to find out the causes for disorders in clay and laterite soils. Availability of nutrients in soils was sufficient to excess. Deviation from optimum percentage index was negative for nitrogen (N), phosphorus (P), and zinc (Zn) in both soils. Zinc deficits of –26 to –63 in higher number of palms (84–97%) indicate the reduction in Zn uptake. Regression between leaf Zn and soil fertility parameters indicated negative relation with soil Zn and calcium (Ca) in clay and soil organic carbon, soil P, and soil boron (B) in laterite soils. Multiple regression indicated negative relation of diethylenetriaminepentaacetic acid (DTPA)-extractable Zn with nutrients like Ca, magnesium (Mg), potassium (K), and iron (Fe) in soil in different years. The grouping of soil nutrients in opposite directions in first two components of principal component analysis supports negative nutrient interactions in both soil types. The results reveal that nutrient interactions in soil affect the uptake of nutrients despite sufficient nutrient availability. Zinc deficiency in arecanut may be the result of complex interactions between DTPA-extractable Zn and other nutrients in soil.*

**Keywords** Arecanut, clay soil, disorders, laterite soil, soil fertility, zinc deficiency



## Introduction

Arecanut (*Areca catechu* L.), which belongs to family Palmae, is one of the economically important plantation crops grown in India. India ranks first in area and production of arecanut in the world. It is cultivated in an area of 0.397 million hectares with a production of 0.559 million tonnes (GOI 2008). The productivity remained stagnant at 1200 kg $ha^{-1}$ during the last decade. The palm grows to a height of about 10–15 m with production of 8–9 leaves per year. The palm has a shallow root system, and the trunk biomass accounts for 74% of the total biomass in arecanut (Bhat, Sujatha, and Balasimha 2007; Bhat and Sujatha 2008). The average leaf area is 25 $m^2$ per palm, and net photosynthesis ranges

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between 2.4 and 8.2 μmol carbon dioxide ($CO_2$) $m^{-2}$ $s^{-1}$ (Balasimha 2004). Flowering starts four years after planting, and yield stabilizes by eighth year with economic life span of 25–30 years. The economic part of the palm is called "betel nut" and is mainly used for masticatory purpose in many parts of Asia. Arecanut is predominantly grown on laterite soils. Laterite soil belt in arecanut growing region is characterized by high rainfall, undulating topography, leaching of potassium ($K^+$) and calcium ($Ca^{2+}$,), phosphorus (P) fixation and high zinc (Zn) fixing capacity. The cultivation of arecanut was extended to clay soil belt in nontraditional areas during 1980s. Clay soils pose a problem to monocot palm due to water stagnation and poor soil aeration and drainage.

The influence of soil parameters is one of the main factors governing the phytoavailability of an element (Kabata-Pendias 2004). Nutrient uptake by plants is affected by nutrient concentrations in soils, soil pH, cation exchange capacity (CEC), soil organic carbon (SOC), types and varieties of plants, and plant age. Adequate nutrition of plants depends on many factors such as ability of the soil to supply the nutrients, rate of absorption of nutrients by the plants, distribution of nutrients to functional sites, and nutrient mobility within the plant. Hartemink (2005) stated that large quantities of nutrients are immobilized in the above and below ground biomass of perennial crops. The serious concerns in arecanut cultivation are huge yield gap of 191% (Bhat, Sujatha, and Balasimha 2007), large nutrient requirement (Sujatha et al. 1999; Bhat and Sujatha 2009) and low nutrient use efficiency. Thus, maintaining appropriate levels of soil fertility is of paramount importance to sustain the growth and yield of arecanut.

In the recent past, disorders like crown choking (CC), crown bending (CB), shortened internodes and oblique nodes (SION) in arecanut are increasingly noticed in Karnataka and Kerala states of India. These two states together contribute to 56% of the total production of arecanut in India. The incidence of disorders was more in clay soil regions than traditional laterite soil belt. Earlier, incidence of disorders was reported from Konkan regions of Maharashtra (Salvi, Singh, and Deshpande 1985). Disorders are associated with symptoms like short and brittle leaves with dark green color, reduced internodal length, tapering of the stem, and failure of inflorescence production (Saraswathy 2004). Nutrient deficiencies are responsible for the most widespread crop nutrient disorders throughout the world (Fageria, Baligar, and Clark 2002; Alloway 2008). Earlier studies have ruled out the association of biotic agents, nematodes, and pests with disorders (Saraswathy 2004). Poor soil aeration and continuous application of nutrients without soil testing are also some of the contributing factors for disorder development. However, the exact causes for development of disorders in arecanut are not clear.

There are several methods of establishing a nutritional diagnosis using various analytical techniques. Soil and plant analysis has been used as a powerful tool for diagnosing crop nutrient deficiencies and solving the nutrient problems all over the world (Mengel and Kirkby 2001; Yin and Vyn 2004; Srivastava and Singh 2006). Walworth, Letzsch, and Sumner (1986) stated that the realistic strategy would be to maintain nutrient levels at or very close to the optimal levels, although the optimum nutritional ranges may be used as guidelines. Leaf nutrient status gives an indication of the current soil fertility and eventually of the need for fertilizers (Walworth and Sumner 1988). In perennial palms, tissue analysis to identify deficiencies/toxicities at an early stage is very important as it may be too late to reverse the situation effectively by the time visual symptoms appear on palms. With this background, an attempt was made to identify the causes for disorders based on the assessment of nutrient status of disorder affected arecanut plantations in clay and laterite soils.

## Materials and Methods

### *Details of Sampling and Locations*

The study area covered 14 different arecanut-growing locations in southern parts of India. Soils are predominantly clayey in Shimoga district of Karnataka and lateritic in South Kanara district of Karnataka and Kasaragod district of Kerala. The altitude of different locations ranges from 24 to 664 m. The annual average rainfall is 1000 and 3600 mm in clay and laterite soil belts, respectively. The age of arecanut plantations varied from 12 to 25 years. The disorder-affected palms were classified as palms showing symptoms of CC with shortened leaves, CB, SION, and SION and CB. Apparently healthy (AH) palms were also included for comparison. Overall, the incidence of CC, CB, and SION was noticed to the extent of 9%, 13%, and 19%, respectively, during the survey in 2006 prior to sampling. Different management practices followed by farmers were documented. Organic manures [press mud, farmyard manure, and neem cake], fertilizers, magnesium sulfate, lime, and borax were applied without soil testing. Flood irrigation and earthing up with soil or tank silt were adopted in clayey soil region. Micronutrient mixture containing 3% Zn, 1% manganese (Mn), 0.5% boron (B), and 2% iron (Fe) was applied by arecanut farmers in Shimoga district.

### *Collection of Soil and Leaf Samples*

In 2006, soil and leaf samples were collected from 10 different arecanut plantations in Shimoga district. During 2007–2009, samples were collected from representative arecanut plantations covering both clay and laterite soils. Overall, 850 soil and 600 leaf samples were collected during the study period. The soil and leaf sampling was done from the same palm in all the years. The number of samples was reduced during the study period from 2006 to 2009 in clay soil belt due to death of palms affected by CC. Samples were collected separately from 4th and 6th leaf, and the average nutrient concentration of two leaves was considered for interpretation of the results as negligible differences were noticed between 4th and 6th leaf. Soil samples were collected from 0 to 30 and 30 to 60 cm depths in arecanut root zone at 60 cm distance from the trunk.

### *Preparation and Analysis of Plant and Soil Samples*

Leaf samples were cleaned with tap water followed by distilled water, air-dried, packed in brown paper bags, oven-dried at 60 °C to a constant weight and ground. The ground samples were kept in labeled butter paper bags for further analysis. The air-dried soil samples were ground to pass through a 2.0 mm sieve and kept in labeled plastic bags for further analysis. The leaf samples were analyzed for total nitrogen (N) using micro-Kjeldahl digestion method (Jackson 1973). The powdered plant samples were digested in a 3:1 nitric-perchloric acid mixture for total P, K, and micronutrient estimation. Total P was determined by vanadomolybdate method (Piper 1966). Estimation of K, Ca, magnesium (Mg), and micronutrients like copper (Cu), Zn, Fe, and Mn was done in atomic absorption spectrophotometer (AAS). Boron in plant samples was estimated in ultraviolet (UV) spectrophotometer using azomethine-H (Gupta 1979). Deviation from optimum percentage (DOP) index was expressed as the percentage deviation of a plant nutrient concentration from the optimum (Montanes et al. 1993).

Soil samples were analyzed for pH, organic carbon (OC), CEC, available P and K using standard procedures (Jackson 1973). Soil pH was measured in 1:2 soil water suspension. SOC was measured by Walkley and Black method. Available P was estimated by ascorbic acid reductant method (Watanabe and Olsen 1965) for color development after extraction with Bray's/Olsen's reagent as per the soil pH values. Available K, Ca, and Mg were estimated in AAS using ammonium acetate extract. The concentration of micronutrients was estimated in AAS using diethylenetriaminepentaacetic acid (DTPA) extract (Lindsay and Norvell 1978). Boron in soil was estimated by hot water method using azomethine-H in UV-spectrophotometer (Gupta 1979).

### *Statistical Analysis*

*t*-Test and multiple regression analysis were employed to analyze soil and leaf nutrient data using MSTATC (Michigan State University, East Lansing, MI, USA) and Microsoft Excel (Microsoft Corp., Redmond, WA). The principal component analysis (PCA) using PRINCOMP procedure of SAS was employed to illustrate how the different variables were associated in the multivariate analysis for explaining the disorders. The soil fertility data set was standardized with mean equal to 0 and variance equal to 1 for PCA.



## Results

### *Soil Fertility Status in Disorder-Affected Plantations*

Temporal variation in soil nutrient status of disorder affected arecanut plantations at both soil depths is presented in Table 1. The CEC ranged between 11.4 and 12.3 $cmol_c\ kg^{-1}$ in laterite soils and 43–79 $cmol_c\ kg^{-1}$ in clay soils. The soil pH was near to neutral in clay soil region (6.77) and slightly acidic in laterite soil tract (6.11). The SOC was high in laterite soil (3.48–3.61%) compared to clay soil (1.62–2.21%). In clay soil, temporal variation in availability of Ca, Mg, Mn, and Zn was significant. The DTPA-available Fe was significant between 2006 and 2007. The availability of K, Ca, Mg, and Mn showed significant temporal variation in laterite soil. The soil P availability was high both in clay (85–126 mg $kg^{-1}$) and laterite soils (73–99 mg $kg^{-1}$). The availability of K, Ca, Mg, Fe, Mn, Zn, Cu, and B was sufficient to excess at 0–30 cm soil depth. Similarly, the nutrient availability at 30–60 cm soil depth was in sufficiency range.

### *PCA of Soil Fertility Variables*

In 2008, PCA of eight soil nutrient variables revealed that most of the soil nutrient variables loaded in component 1 and 2 with variance of 58% in clay soil and 64% in laterite soil at 0–30 cm depth (Figure 1). Similar trend was noticed in second depth. In 2009, PCA of 10 soil fertility variables explained about 78.7% of total variance from four components in clay soil, and 74.8% of total variance from three components in laterite soil at first depth. In clay soils, PC1 contrasted the positive effects of Fe, K, Cu, P, Mn, and Zn and negative effects of Mg and Ca explaining 32.6% of the total variance (Figure 2). In laterite soil, component 1 was dominated by positive loading of OC, Zn, Ca, P, Fe, Cu, and Mg at 0–30 cm soil depth. At 30–60 cm soil depth, all the soil fertility variables were loaded in PC1 and PC2 explaining 64.0% and 71.7% variation in clay and laterite soils, respectively.

**Table 1**
Soil fertility status in disorder-affected arecanut plantations at different soil depths

| Nutrients | Clay soil | | | Laterite soil | |
|---|---|---|---|---|---|
| (mg $kg^{-1}$) | 2006 (n = 63) | 2007 (n = 54) | 2009 (n = 56) | 2008 (n = 37) | 2009 (n = 41) |
| | | | 0–30 cm soil depth | | |
| pH | 6.75 ± 0.1 | 6.77 ± 0.08 | — | 6.11 ± 0.07 | — |
| OC (%) | 1.64 ± 0.07 | 1.58 ± 0.06 | 2.21 ± 0.06* | 3.61 ± 0.30* | 3.48 ± 0.25 |
| P | 126 ± 9.9 | 85 ± 7.8 | 88 ± 8.3 | 73 ± 12.5 | 99 ± 17.5 |
| K | 267 ± 26.8 | 261 ± 24 | 259 ± 23.9 | 309* ± 20.7 | 207 ± 17.1 |
| Ca | 1456 ± 93.8 | 1862† ± 146 | 2988* ± 184 | 2641* ± 202 | 1476 ± 129.7 |
| Mg | 280 ± 12.9 | 358† ± 32.5 | 506* ± 34 | 335* ± 22.4 | 234 ± 23.7 |
| Fe | 90† ± 5.7 | 46 ± 3.9 | 43.6 ± 3.4 | 68 ± 5.6 | 72.2 ± 6.5 |
| Mn | 60† ± 4.5 | 24 ± 1.1 | 41* ± 2.8 | 82* ± 10.8 | 36 ± 4.5 |
| Zn | 20† ± 3.4 | 5.2 ± 0.5 | 25.3* ± 3.0 | 16 ± 2.2 | 8.5 ± 1.0 |
| Cu | 8.8 ± 0.84 | 5.3 ± 0.4 | 4.3 ± 0.28 | 12.2 ± 1.6 | 12.2 ± 1.5 |
| B | — | — | 0.72 ± 0.05 | 0.60 ± 0.11 | 0.67 ± 0.06 |
| | | | 30–60 cm soil depth | | |
| pH | 6.83 ± 0.09 | 6.84 ± 0.08 | — | 5.86 ± 0.07 | — |
| OC% | 0.86 ± 0.06 | 0.85 ± 0.05 | 1.05 ± 0.04 | 1.80* ± 0.13 | 1.62 ± 0.12 |
| P | 54 ± 5.3 | 39.6* ± 8.4 | 22.9 ± 3 | 13.1 ± 4.0 | 11.4 ± 3.1 |
| K | 204† ± 23.8 | 138.5 ± 17.4 | 143 ± 21.5 | 204* ± 20.6 | 122.6 ± 10.4 |
| Ca | 1696 ± 155 | 1652 ± 160.4 | 2931* ± 250 | 1323* ± 154 | 661 ± 47.1 |
| Mg | 363 ± 36.7 | 353 ± 38.9 | 517* ± 41 | 192 ± 19.3 | 121 ± 11.6 |
| Fe | 58† ± 4.9 | 28.4* ± 4.1 | 16.6 ± 1.5 | 34.9* ± 3.5 | 26.8 ± 3.0 |
| Mn | 48† ± 3.7 | 20.3 ± 1.1 | 22 ± 1.4 | 47.4* ± 8.1 | 13.1 ± 2.7 |
| Zn | 7.3† ± 0.97 | 1.9 ± 0.2 | 2.7 ± 0.6 | 5.0* ± 1.2 | 1.6 ± 0.25 |
| Cu | 4.9 ± 0.6 | 2.8* ± 0.2 | 2.1 ± 0.14 | 3.7* ± 0.6 | 3.1 ± 0.8 |
| B | — | — | 0.63 ± 0.06 | 0.43 ± 0.05 | 0.24 ± 0.03 |

†Indicates significant difference between two-year (2006 and 2007 in clay soil) means by *t*-test at $P < 0.05$; *Indicates significant difference between two year (2007 and 2009 in clay soil and 2008 and 2009 in laterite soil) means by *t*-test at $P < 0.05$.

### *Leaf Nutrient Status of Arecanut in Disorder-Affected Plantations*

The variation in leaf nutrient status of disorder-affected arecanut plantations in clay and laterite soils was assessed during 2006 to 2009 (Table 2). Leaf nutrient concentration of disorder-affected arecanut palms was compared with the optimum (Bhat and Sujatha 2013). Temporal variation in leaf nutrient concentration of N, P, Ca, Mg, Zn, Cu, and B was significant between 2007 and 2009 in clay soil. Though leaf Zn and B concentrations increased significantly during the two-year period, leaf Zn still remained below optimum in clay soil. The concentration of other nutrients decreased during the same time.

Leaf N in clay (1.93–2.36%) and laterite soil regions (2.36–2.56%) was less than optimum (2.70%). Leaf P was optimum to above optimum in clay soil region (0.23–0.30%) and below optimum in laterite soil region (020–0.22%). The K concentration was consistently below optimum in clay soil region (0.87–1.05%) and above optimum in laterite soil belt (1.14–1.41%). Similarly, there was wide variation in concentration of Ca, Mg,

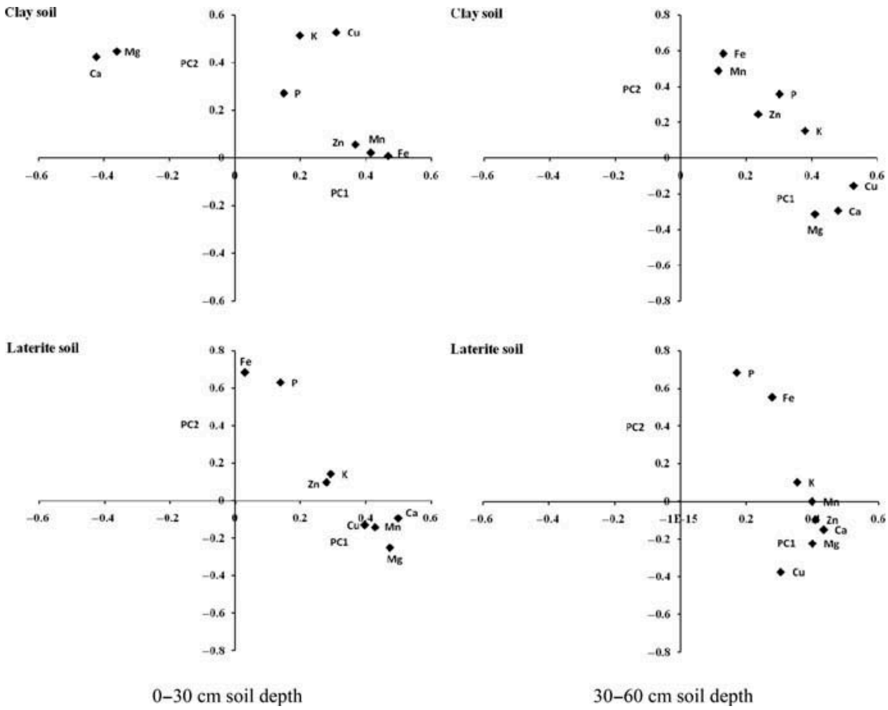


**Figure 1.** Values of eigenvector loadings for soil nutrient variables in component 1 and 2 at two soil depths in clay and laterite soils in 2008.

and micronutrients in leaf tissue during study period. Leaf Zn (mg $kg^{-1}$) was consistently below optimum in clay soil belt (22.1–34.1), but fluctuated widely in laterite soil tract (16.9 and 69.0). The concentration of leaf nutrients among different disorder symptoms like CC, CB and SION, and AH was not significant in clay soil type, but was significant for P and micronutrients in laterite soil type (Figure 3).

The comparison of leaf nutrient status of arecanut in disorder-affected areas with the optimum values indicated considerable differences in N, P, Ca, Mg, Zn, Mn, and B (Table 3). The concentrations of leaf nutrients, except for Mn and B, were low in disorder-affected palms compared to optimum. The concentrations of N, Ca, Mg, and Zn were lower than optimum by 18%, 21%, 35%, and 43%, respectively, in affected plantations. Leaf B was higher in affected gardens (58 mg $kg^{-1}$) than optimum (39.5 mg $kg^{-1}$). The ratios of P:Zn (149.8), K:Mg (9.4), Fe:Zn (13.2), and Mn:Zn (7.7) were higher in disorder-affected palms than the optimum.

### *DOP Index*

DOP index of different leaf nutrients in disorder-affected arecanut palms is depicted in Figure 4. Overall, deficiency of N, P, and Zn was noticed in both clay and laterite soils. Nutrients like K, Ca, Mg, Fe, and Mn showed negative deviation in clay soil and positive deviation in laterite soil. Nitrogen deficiency in arecanut leaf was higher in clay soil (29%) than in laterite soil (5%). The DOP index was negative only for Zn in both clay (–25) and laterite soils (–63) with a variation of –14 to –90 among different symptoms. Leaf P showed

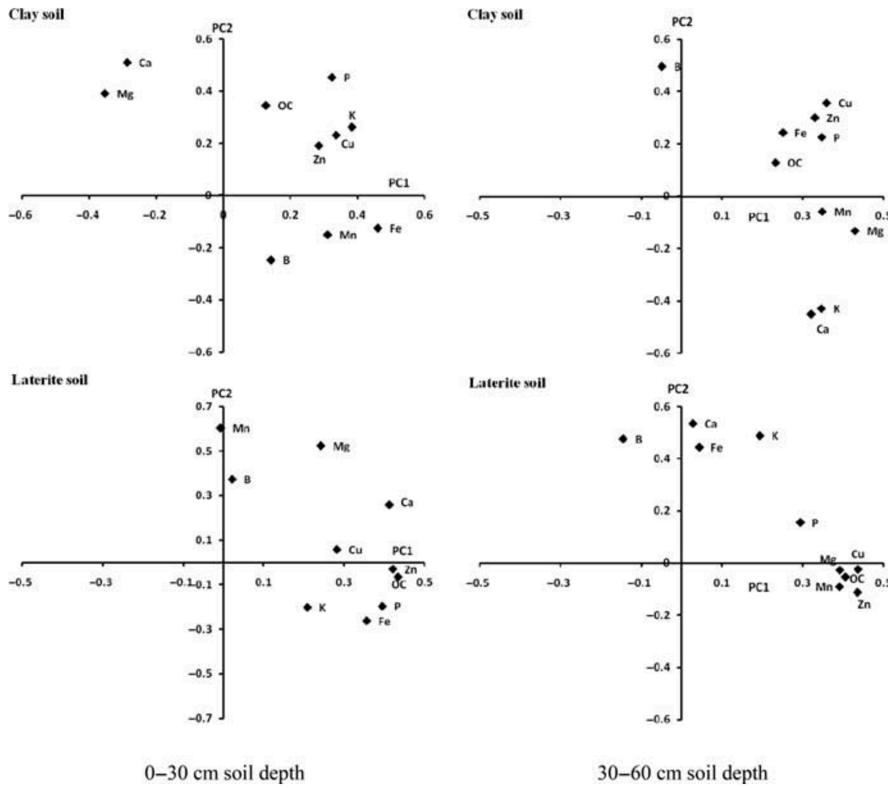


**Figure 2.** Values of eigenvector loadings for soil nutrient variables in component 1 and 2 at two soil depths in clay and laterite soils in 2009.

**Table 2**
Temporal variation in leaf nutrient status in disorder-affected arecanut plantations

| Nutrient content | Clay | | | Laterite | |
|---|---|---|---|---|---|
| | 2006 (n = 69) | 2007 (n = 76) | 2009 (n = 44) | 2008 (n = 71) | 2009 (n = 38) |
| N | — | 2.36[*] ± 0.03 | 1.93 ± 0.04 | 2.36 ± 0.04 | 2.56 ± 0.07 |
| P | 0.30[†] ± 0.01 | 0.24[*] ± 0.004 | 0.23 ± 0.006 | 0.22[*] ± 0.006 | 0.20 ± 0.004 |
| K | 0.87 ± 0.038 | 1.05[†] ± 0.03 | 1.01 ± 0.04 | 1.41[*] ± 0.04 | 1.14 ± 0.04 |
| Ca | 1.44[†] ± 0.09 | 0.99[*] ± 0.05 | 0.36 ± 0.03 | 0.98[*] ± 0.02 | 0.62 ± 0.03 |
| Mg | 0.05 ± 0.005 | 0.41[†*] ± 0.02 | 0.11 ± 0.006 | 0.27[*] ± 0.008 | 0.14 ± 0.005 |
| Fe | 445[†] ± 22.9 | 315[*] ± 13.5 | 108 ± 6.2 | 1391[*] ± 44.3 | 188 ± 14.6 |
| Mn | 74 ± 6.0 | 81[*] ± 6.1 | 38 ± 2.4 | 194[*] ± 10.9 | 108 ± 11.0 |
| Zn | 22.1 ± 3.0 | 24.0 ± 0.9 | 34.1[*] ± 2.0 | 69.0[*] ± 4.2 | 16.9 ± 2.0 |
| Cu | 4.6 ± 0.4 | 4.7[*] ± 0.2 | 1.8 ± 0.74 | 9.1[*] ± 0.4 | 3.1 ± 0.63 |
| B | 34 ± 2.8 | 46 ± 3.8 | 70[*] ± 3.9 | 25 ± 2.4 | 42.9 ± 3.9 |

[*]Indicates significant difference between two-year means by *t*-test at $P < 0.05$.

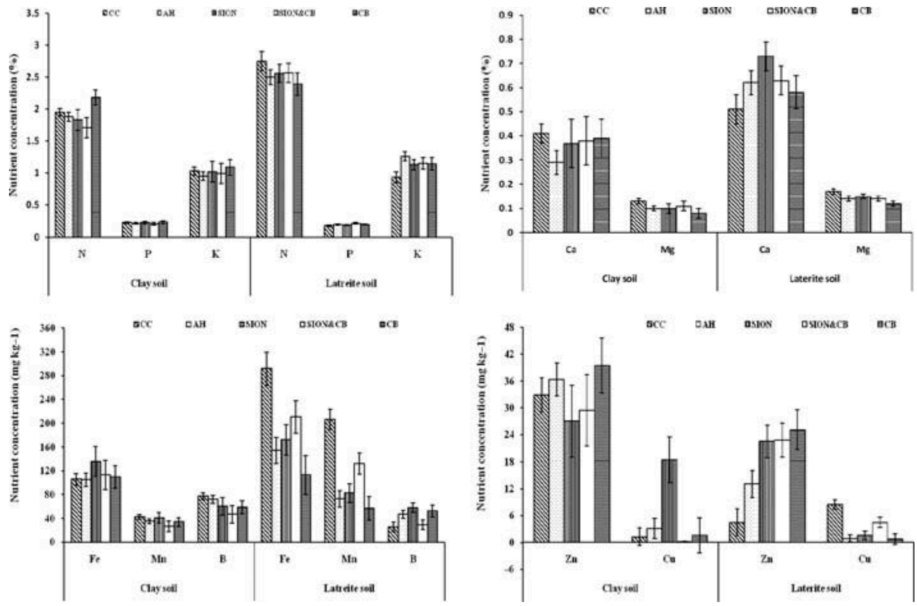


**Figure 3.** Leaf nutrient variability in different disorder-affected arecanut palms in 2009.CC, Crown choking; AH, Apparently healthy; SION, Shortened internodes and oblique nodes; CB, Crown bending.

**Table 3**
Comparison of leaf nutrient status of arecanut in disorder-affected areas with optimum values

| Nutrients | Affected | Optimum[a] |
|---|---|---|
| N (%) | 2.22 | 2.70 |
| P (%) | 0.22 | 0.23 |
| K (%) | 1.07 | 1.12 |
| Ca (%) | 0.48 | 0.61 |
| Mg (%) | 0.13 | 0.20 |
| Zn (mg $kg^{-1}$) | 26.1 | 45.8 |
| Cu (mg $kg^{-1}$) | 2.4 | 2.6 |
| Fe (mg $kg^{-1}$) | 145 | 146 |
| Mn (mg $kg^{-1}$) | 70.6 | 56.5 |
| B (mg $kg^{-1}$) | 57.6 | 39.5 |
| P:Zn | 149.8 | 45.8 |
| K:Ca | 3.0 | 2.6 |
| K:Mg | 9.4 | 5.7 |
| Ca:Mg | 4.0 | 3.6 |
| Fe:Zn | 13.2 | 4.0 |
| Mn:Zn | 7.7 | 2.3 |

[a]Source: Bhat and Sujatha (2013).

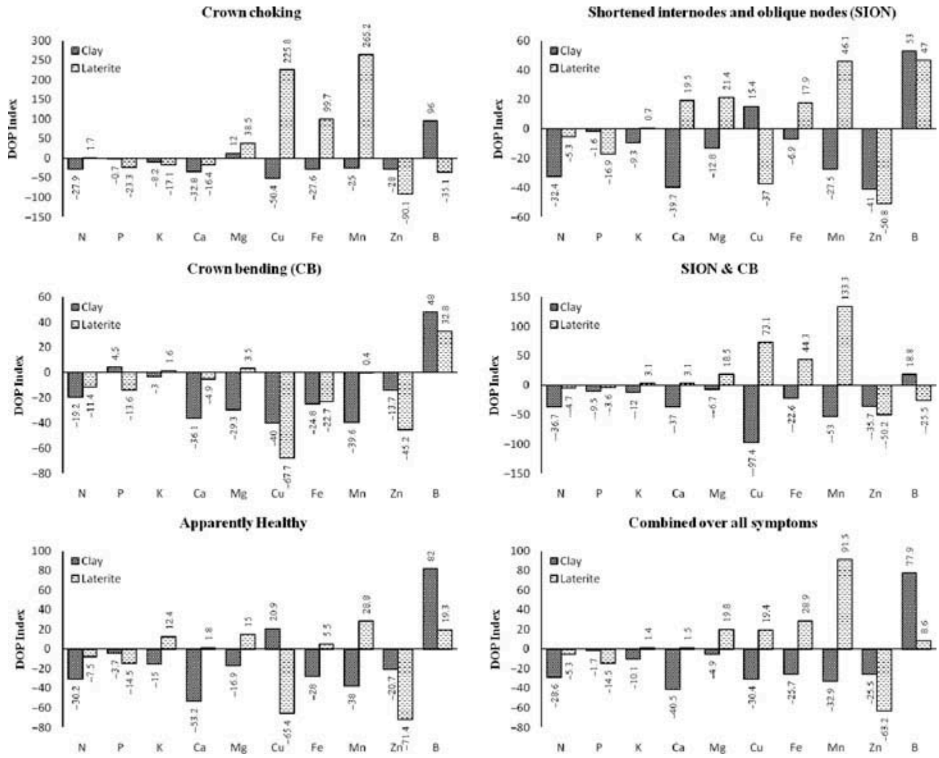


**Figure 4.** DOP index for leaf nutrients in different disorder-affected arecanut palms combined over locations in 2009.

negative deviation of –2 to –14 in both soils. Cu and B showed positive deviation in both soil types.

The yearwise variation in percentage of palms with below and above optimum level of leaf nutrients is depicted in Figure 5. In 2008, leaf Zn was below optimum in 100% and 22% of the palms in clay and laterite soil regions, respectively. In 2009, concentration of leaf nutrients was below optimum in more than 75% of the palms in disorder-affected areas for N, Ca, Mg, Cu, Fe, and Zn in clay soil region and for P, Mg, and Zn in laterite soil region. In 2009, higher number of palms (84–97%) registered below optimum level of leaf Zn in affected plantations.

### *Relation Between Soil Zn and Other Soil Nutrients*

When soil fertility parameters were regressed with soil Zn as dependent variable, negative relation with Ca, K, and Fe in clay soils and Ca, Mg, K, B, and Cu in laterite soils was observed in different years (Table 4 , Eqs. 1–5). Stepwise multiple regression analysis between leaf Zn and soil fertility parameters indicated negative relation with soil Zn and Ca in clay soils in 2009 (Table 4, Eq. 6). In laterite soils, SOC, Bray's P and soil B showed negative relation with leaf Zn (Table 4, Eq. 7).

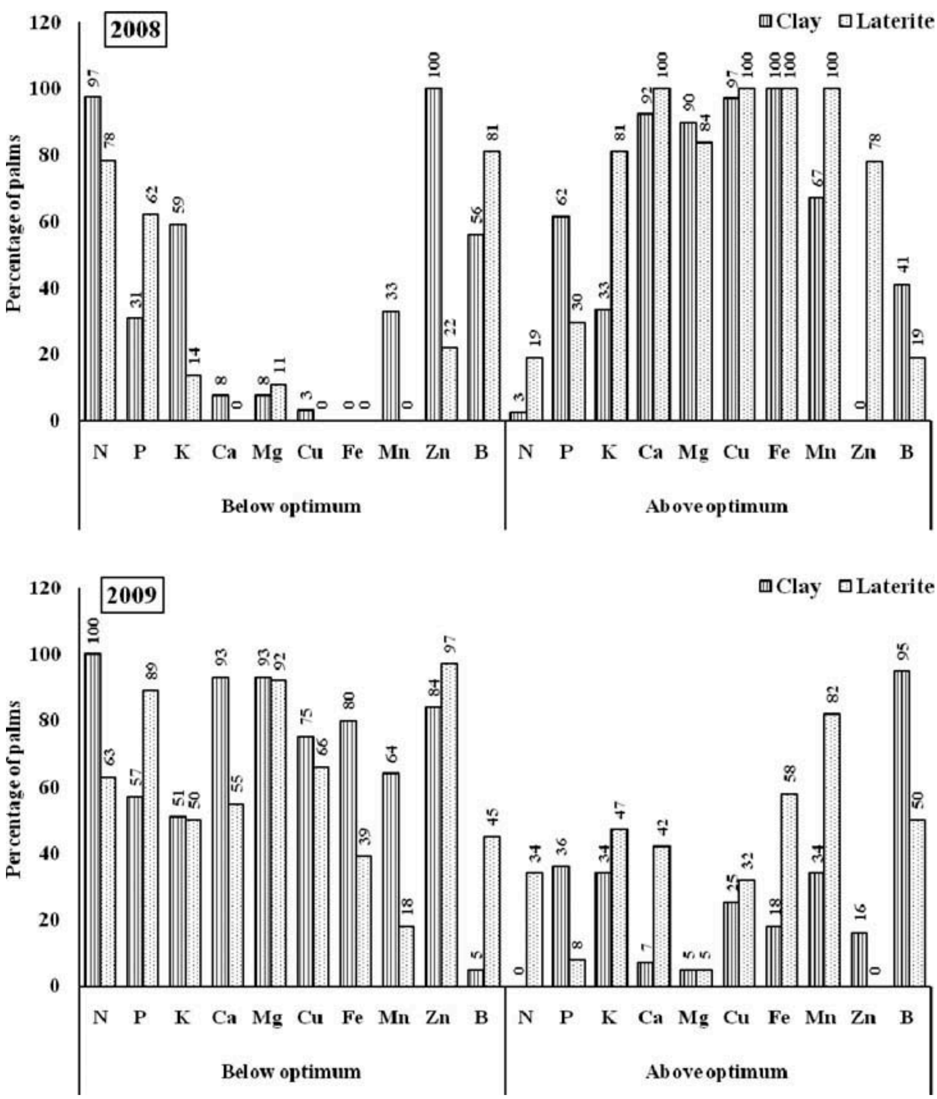


**Figure 5.** Percentage of palms with nutrient status below and above optimum level in two soil types of arecanut tract in 2009.



### *Relation Between Soil and Leaf Nutrients*

Application of stepwise regression to identify the soil/leaf nutrient variables with a significant influence on leaf Zn resulted in significant equations, which showed different trends in different years (Table 5). Leaf Mg, SOC, and leaf Ca showed negative relation with leaf Zn in clay soils in 2006 (Table 4, Eq. 8). Analysis of soil and leaf nutrients in 2008 (Table 4, Eq. 9) revealed that leaf Mg, soil Cu, soil P, soil K, and leaf K had negative impacts on leaf Zn status. In 2009, leaf N and Fe showed negative relation with leaf Zn when soil and leaf nutrients of both soils were regressed together (Eq. 10). Regression analysis was also done separately for clay and laterite soils in 2009 to identify the soil and

**Table 4**
Stepwise linear multiple regression equations showing relationship between leaf/soil Zn and soil fertility parameters at 0–30 cm depth in 2009

| Soil | Multiple regression equation* | $R^2$ | Equation no. |
|---|---|---|---|
| 2006 | | | |
| Clay | Zn (S) = –2.648 + 0.710 Cu – 0.003 Ca – 0.035 Fe + 0.013 P + 1.437 pH – 0.008 Mg | 0.630 | 1 |
| 2008 | | | |
| Clay | Zn (S) = –5.946 + 0.742 Cu – 0.007 K – 0.0399 Fe – 0.0016 Ca + 1.367 pH | 0.510 | 2 |
| Laterite | Zn (S) = –3.689 – 0.1107 Fe + 0.742 Cu – 0.007 K – 0.0016 Ca + 1.367 pH | 0.466 | 3 |
| 2009 | | | |
| Clay | Zn (S) = 35.207 + 0.218 P + 3.511 Cu – 0.431 Fe | 0.490 | 4 |
| Laterite | Zn (S) = –7.454 + 0.006 Ca – 3.585 B + 0.068 Mn + 0.048 Fe – 0.013 Mg + 0.013 P – 0.089 Cu | 0.850 | 5 |
| Clay | Zn (L) = 10.575 – 0.232 Zn – 0.005 Ca + 0.356 CEC + 0.063 P + 7.539 SOC | 0.260 | 6 |
| Laterite | Zn (L) = –222.6 + 21.01 CEC + 0.011 Ca – 4.797 SOC – 0.048 P – 7.226 B | 0.424 | 7 |

*$P < 0.0001$.

**Table 5**
Stepwise linear multiple regression equations showing relationship between soil (S) at 0–30 cm depth and leaf (L) nutrients

| Year | Multiple regression equation* | $R^2$ | Equation no. |
|---|---|---|---|
| 2006 (Clay) | Zn (L) = 148.898 – 316.14 Mg (L) – 25.12 SOC + 0.223 Fe (S) – 18.246 Ca (L) + 114.63 P (L) | 0.534 | 8 |
| 2008 (Combined over soils) | Zn (L) = 56.91 + 0.0113 Ca (S) – 82.25 Mg (L) – 1.453 Cu (S) + 0.696 Zn (S) – 0.10 P (S) – 0.213 B (L) + 0.016 Fe (L) + 0.072 Mn (L) – 0.032 K (S) – 16.16 K (L) + 109.67 P (L) | 0.593 | 9 |
| 2009 (Combined over soils) | Zn (L) = 19.16 + 136.01 P (L) – 11.36 N (L) + 22.74 Ca (L) – 0.04 Fe (L)+ 0.014 K (S) | 0.480 | 10 |
| 2009 (Clay) | Zn (L) = –25.85 + 0.104 P (S) + 0.323 Mn (L) – 0.170 Zn (S) + 79.03 P (L) + 8.494 N (L) | 0.450 | 11 |
| 2009 (Laterite) | Zn (L) = 30.16 + 41.57 Ca (L) – 12.91 N (L) – 0.056 Fe (L) + 0.436 Cu (S) – 15.51 K (L) + 122.14 P (L) – 0.038 P (S) – 7.125 B (S) | 0.770 | 12 |

*$P < 0.0001$.

leaf nutrients affecting the Zn concentration in leaf and soil. Soil Zn was negatively correlated with leaf Zn in clay soil (Table 4, Eq. 11), while leaf N, leaf Fe, leaf K, soil P, and soil B were negatively related in laterite soils (Table 4, Eq. 12).

## Discussion

Initiation of disorders in arecanut affects the reproductive growth and reduces the yield drastically. Incidence of disorders to the tune of 14% would reduce the total production substantially in India as CC and CB would lead to death of palms within a short span of 2–3 years. Spatial and temporal variability in soil and leaf nutrient status is used as a tool to assess the causes for disorders in arecanut. Initial trends in 2006 indicated sufficient to excess soil fertility status (Table 1) with wide imbalance in leaf nutrient status of arecanut in clay soil region (Table 2). Positive deviation of P (+30), Fe (+205), Mn (+33), Cu (+77), Ca (+136), and negative deviation of Zn (–52), K (–22), and Mg (–75) in leaf nutrient concentration of arecanut suggest the disturbance in nutrient uptake pattern. Further, negative relation of soil Zn with Ca, Fe, and Mg in soil (Table 4, Eq. 1) and leaf Zn with leaf Mg, SOC, and leaf Ca (Table 4, Eq. 8) was noticed. From these results, it is obvious that the uptake of Zn was disturbed due to competition from other nutrients for functional sites near root surface. Though leaf Mg showed huge negative deviation, the disorder symptoms were not comparable to previous reports on Mg deficiency in arecanut and other crops (Yadava, Vellaichami, and Mathai 1972; Mengel and Kirkby 2001).

It was observed that availability of soil nutrients was sufficient to excess in disorder-affected plantations in clay and laterite soils during 2006–2009. Kabata-Pendias (2004) stated that excess of trace metals in soils is a stronger stress to plants than their deficiency. Critical assessment of both soil and leaf nutrient status of disorder-affected plantations revealed that leaf Zn was consistently below optimum in clay soil region despite sufficient availability of DTPA-extractable Zn in the soil. In arecanut leaf, deviation was negative only for N, P, and Zn in both soils. In laterite soil region, total Zn was above optimum in disorder-affected palms in 2008 and reduced drastically in 2009. This might be due to initiation of disorders with less severity of symptoms in 2008. Optimum P:Zn ratio in arecanut was 45.8, and higher P:Zn ratio of 149.8 in disorder-affected palms substantiates the reduction in Zn uptake. Higher percentage of palms (84–97%) with below optimum level of Zn and Zn deficit of 26% in clay soil and 63% in laterite soil also gives an indication that Zn deficiency is responsible for development of disorders like CC, CB, and shortened internodes. It is reported that zinc deficiency is associated with symptoms like reduction in growth, leaf size, and internodal elongation in several crops (Brennan 1992; Durzan 1995; Mengel and Kirkby 2001), as zinc plays an important role in plant structure and function (Kabata-Pendias 2001).

Excessive availability of nutrients in soil leads to antagonistic nutrient interactions, which is evident from the negative relation of DTPA-extractable Zn with nutrients like Ca, Mg, K, and Fe in soil in different years (Table 4). The grouping of these soil nutrients in opposite directions in first two components of PCA (Figures 1 and 2) also supports negative nutrient interactions noticed in regression equations in both soil types (Tables 4 and 5). The review by Alloway (2008) clearly highlighted antagonistic nutrient interactions among Zn, Ca, Mg, and other trace elements in soil. Kabata-Pendias (2004) stated that Ca, P, and Mg are often the main antagonistic elements in the absorption of several microcations. Thus, the hindrance in the uptake of Zn by arecanut palm might be due to antagonistic soil nutrient interactions. Significant negative correlation of leaf Zn with Fe, Ca, Cu, and K in leaves in different years (0.25–0.42) confirms the role of antagonistic nutrient interactions leading to impaired Zn uptake. The reports of several investigators support the above findings (Tisdale, Nelson, and Beaton 1985; Gianquinto et al. 2000; Mengel and Kirkby 2001; Li et al. 2003; Shahriaripour and Tajabadipour 2010).

Alloway (2008) reported that a greater proportion of fine roots are required for Zn efficiency. It was noticed in this study that weight density of fine roots (mg $cm^{-3}$) in AH palm in disorder-affected plantations was 1.32 and 0.78 in clay and laterite soils, respectively, compared to 6.62 per palm in healthy areas (Bhat and Sujatha 2008). This factor also might have contributed to reduced nutrient uptake especially Zn by the palm as Zn is absorbed by diffusion. According to these results, zinc deficiency in arecanut may be the result of complex interactions between DTPA-extractable Zn and other nutrients in soil. Keeping in view the foregoing discussion, it can be inferred that Zn deficiency might be the major reason for development of symptoms like CC, CB, and SION in arecanut.

## Conclusions

The results reveal that imbalanced nutrition for longtime results in development of disorders like CC, CB, and SION due to antagonistic nutrient interactions in soil leading to hindrance in the uptake of Zn. This study also highlights that different nutrient interactions in soil may affect the uptake of nutrients though the soil has optimum nutrient availability. Application of zinc deserves attention; there is a need to include Zn in fertilizer recommendations for arecanut. Nutrient management strategies need to be planned for arecanut taking in to account the soil fertility status. It is advisable to consider nutrient deficiency/toxicity before the development of visual symptoms with the help of plant and soil analysis for improving the health and yield of arecanut.

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