Communications in Soil Science and Plant Analysis, 43:2400–2412, 2012

ISSN: 0010-3624 print / 1532-2416 online
DOI: 10.1080/00103624.2012.708074

Impacts of Vermicompost and Nitrogen, Phosphorus, and Potassium Application on Soil Fertility Status in Arecanut Grown on a Laterite Soil

S. SUJATHA AND RAVI BHAT

Central Plantation Crops Research Institute, Regional Station, Vittal, India

A field experiment (1998 to 2010) investigated the effects of vermicompost (VC) and chemical fertilizer (CF) application alone or in combination on soil fertility status in arecanut. Vermicompost significantly increased the soil pH (6.3) over CF and integrated treatments (5.7–5.8). Greater soil organic carbon was noticed with VC (2.85–3.00%) than with CF (1.72–1.89%) and VC + CF (1.89–2.55%) in 2009. Soil test phosphorus (P) (mg kg^{-1}) significantly increased with VC 200% nitrogen (N) equivalency (35.3) compared to other treatments (8.5–23.3) at the 0- to 30-cm depth in 2009. In 2003, soil test potassium (K) (mg kg^{-1}) was significantly greater with CF at depths of both 0–30 cm (162–187) and 30–60 cm (172–214) than VC and control. Soil test K depleted with VC application in 2009. Application of VC significantly improved soil test calcium (Ca) and magnesium (Mg) compared to CF, CF + VC, and control at 0–30 cm deep. Soil test values for micronutrients increased in 2009 compared to initial status.

Keywords Arecanut, laterite soil, organic waste recycling, soil fertility, vermicompost

Introduction

Arecanut (*Areca catechu* L.), which belongs to family Palmae, is a tall commercial plantation crop grown in humid tropics of India. It is cultivated in an area of 0.397 million ha with a production of 0.559 million tons and productivity of 1200 kg ha^{-1} (GOI 2008). The economic part of the palm is called *betel nut* and is mainly used for masticatory purposes in many parts of Asia. India ranks first in area and production of arecanut in the world. Imbalanced and insufficient nutrition is one of the reasons for poor yields of arecanut in India. The ultimate aim of any management practice is not only to increase productivity and profitability but also to improve the soil fertility status in the long run. Under perennial ecosystems, larger amounts of nutrients are removed from soil and hence an adequate supply of nutrients is required for sustainable crop production. The soil fertility status holds paramount importance in influencing the production pattern of arecanut (Bhat and Sujatha 2004, 2009) and in determining the production-related constraints. A vast majority of arecanut is predominantly grown in acidic laterite soils in India. Soils in the Western Ghat region are mainly derived from granite, gneisses, and schists (Babu 1981). The soils

Received 2 December 2010; accepted 29 November 2011.
Address correspondence to S. Sujatha, Division of Crop Production, Central Plantation Crops Research Institute, Regional Station, Vittal 574243, India. E-mail: s_sujatha68@rediffmail.com

are poor in native soil fertility with abundant sesquioxides and low bases. Kaolinite is the dominant clay mineral low in potassium (K) fixation. Further, excessive rainfall aggravated the problem by leaching of nutrients such as nitrogen (N), K, and calcium (Ca). In these soils, N and K are highly mobile and labile, whereas phosphorus (P) is highly immobile. Deficiency of N, K, and zinc (Zn) was reported in laterite soils of this region (Badrinath, Gajendragad, and Balakrishna Rao 1998). The cation exchange capacity (CEC) of the soils is quite low (3–15 c mol kg^{-1}), resulting in poor nutrient-retention capacity. The perennial palm requires a large quantity of nutrients to support its growth and yield.

In present-day agriculture, organics increasingly plays supplementary and complementary roles for sustainable productivity and to keep soil healthy. Organic farming has expanded rapidly in recent years and is seen as a sustainable alternative to chemical-based agricultural systems (Stockdale et al. 2001). However, limited availability and greater cost of organic manures necessitates the need for recycling organic wastes. The arecanut ecosystem generates considerable organic wastes, which otherwise find no use and requires efficient on-farm waste recycling. One hectare of arecanut garden can produce about 9.0 t of recyclable biomass. In arecanut plantation, the nonmarketed produce such as shed leaves, leaf sheath, husk, and arecanut bunch waste supplies approximately 95 g N, 10 g phosphorus pentoxide (P_2O_5), and 110 g dipotassium oxide (K_2O) per palm per year (Bhat and Mohapatra 1989). Recycling of plantation wastes directly would not meet the crop nutrient demand immediately because of the high carbon (C)/N ratio. It is also important to avoid N immobilization, which occurs when plantation wastes with high C/N ratio (37–62), lignin, and polyphenol contents are directly added to the soil. The low-cost vermicomposting technology enhances the decomposition process and provides ecofriendly organic manure having a smaller C/N ratio with greater nutrient content (Biddappa et al. 1996; Chowdappa, Biddappa, and Sujatha 1999). Bhat and Sujatha (2007) opined that there is enormous scope to increase nutrient recycling in arecanut. The beneficial effects of vermicompost utilization in the management of other horticultural crops have been reported (Saciragic and Dzelilovie 1986; Tomorti, Gropelli, and Galli 1987). Several reports indicated mining of soil P and K in organic systems (Gosling and Shepherd 2005; Andrist-Rangel et al. 2007).

The annual nutrient mining by the arecanut is estimated as 79 kg N, 28 kg P_2O_5, and 79 kg K_2O per hectare (Rethinam 1990). The nutrient-use efficiency of the crop is very low, that is, 10–15% for N, 25–30% for P, and 20–25% for K. Though nutrition schedule for major nutrients was standardized for arecanut, there is complete lack of studies on secondary and micronutrient requirements of arecanut. Thus, it is necessary to study the recycling potential of vermicompost produced from arecanut wastes in maintaining the soil fertility status. With this background, the present study was contemplated to monitor the changes in soil fertility status due to organic waste recycling as vermicompost in arecanut plantation in laterite soil.

Materials and Methods

Description of Study Site

The study was conducted at the Central Plantation Crops Research Institute, Regional Station, Vittal, Karnataka, India (12° 15′ N latitude and 75° 25′ E longitude, 91 m above mean sea level). The climate of the experimental site is humid tropical with mean annual rainfall of 3670 mm and 120 rainy days. Monthly rainfall during the experimental period is depicted in Figure 1. The annual rainfall during 1997–2009 varied from 2869 mm in 2002 to 4325 mm in 1998. Mean temperature ranges from 21 °C (minimum) to 36 °C

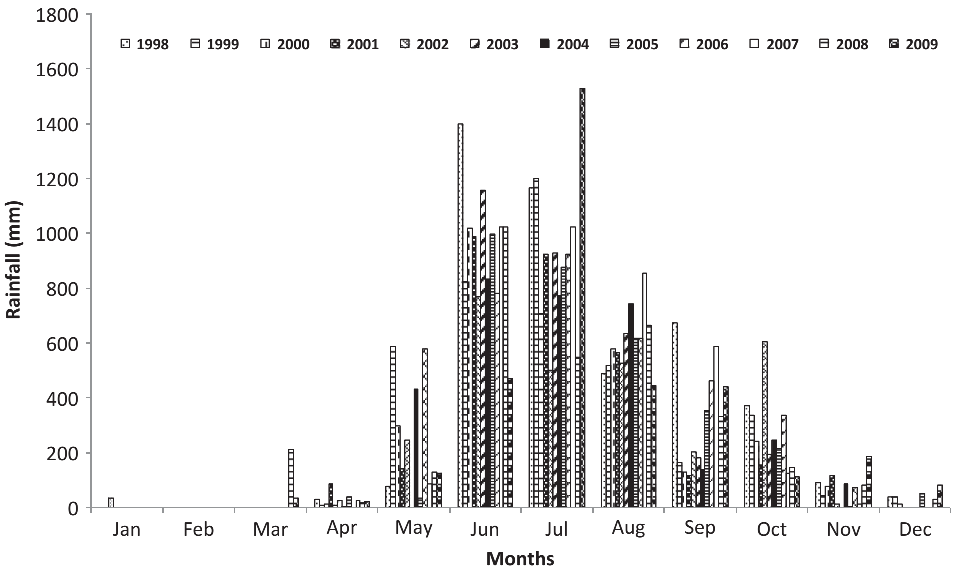


Figure 1. Monthly rainfall in different years during experimental period.

(maximum). The average relative humidity varies between 61 and 94%. The soil of the experimental site is sandy clay loam (laterite) comprising 49.6% sand, 14.4% silt, and 36% clay at 0- to 60-cm soil depth. The bulk density of soil is 1.61 g cm^{-3} and field capacity 18–22%. The cation exchange capacity (CEC) of the soil is 11.4 cmol$_c$ kg^{-1}. The soil is acidic with a pH of 5.6, 1.52% organic C, 10 mg kg^{-1} P, 53 mg kg^{-1} K, 542 mg kg^{-1} Ca, 141 mg kg^{-1} Mg, 1.3 mg kg^{-1} Zn, 12.1 mg kg^{-1} copper (Cu), 13 mg kg^{-1} iron (Fe), and 21 mg kg^{-1} manganese (Mn) at 0–30 cm deep.

Experimental Details

The arecanut plantation was established in 1997 by planting 1-year old seedlings (cv. Mohitnagar) in 60-cm^3 pits at a spacing of 2.7 m × 2.7 m. A field plot size of 2930 m^2 was selected for the study. Each treatment included eight palms as net plot, which accounted to 58.32 m^2. The experiment was laid out in September 1998 following a randomized block design (RBD) with nine treatments and three replications. The treatments included (1) 100% vermicompost (VC) on N equivalent basis, (2) 200% VC on N equivalent basis, (3) 100% NPK through chemical fertilizers (CF), (4) 200% CF, (5) 50% VC + 50% CF, (6) 100% VC + 100% CF, (7) 150% VC + 50% CF, (8) 50% VC + 150% CF, and (9) control (no fertilizer). Recommended fertilizer dose for arecanut is 100:18:117 g N/P/K per palm per year. Fertilizers were applied around the base of the palm at a distance of 60–75 cm from the trunk of the palm after opening the basin to a depth of 15 cm followed by application of VC as per treatment schedule. Then the soil was forked to mix fertilizers and compost with soil. In the first and second years of planting, one-third and two-thirds of recommended fertilizer levels were applied, respectively. The sources of fertilizers used were urea, rock phosphate, and muriate of potash. The crop was irrigated through the basin method at IW/CPE ratio of one during postmonsoon season (December–May). Bordeaux mixture (1%) was sprayed on bunches twice at 45-day intervals during monsoon season (June–September) to prevent fruit rot incidence caused by *Phytopthora palmivora*.

Nutrient Composition of Vermicompost

The fallen arecanut leaves were collected from the plantation regularly and made in to VC using *Eudrilus euginae* as per standard technology (Chowdappa, Biddappa, and Sujatha 1999). Total leaf biomass collected from the plantation was quantified per year and amounted to 5 to 8.5 tons in different years. Recovery of VC from these wastes was quantified as 80%. The nutrient composition of VC was estimated in different years and is presented in Table 1.

Soil Sample Preparation and Analysis

Soil samples were collected at depths of 0–30 and 30–60 cm in arecanut root zone at 60 cm from the tree trunk. The air-dried soil samples were ground to pass through a 2.0-mm sieve and kept in labeled plastic bags for further analysis. Soil samples were analyzed for pH, organic C, and soil test P and K using standard procedures (Jackson 1973). Soil pH was measured in 1:2 soil/water suspension. Soil organic C was measured by the Walkley and Black method. Soil test P was estimated by the ascorbic acid reductant method (Watanabe and Olsen 1965) for color development after extraction with Bray's reagent. Soil test K, Ca, and Mg (magnesium) were estimated in atomic absorption spectrophotometer (AAS) using ammonium acetate extract. The concentration of micronutrients was estimated in AAS using diethylenetriaminepentaacetic acid (DTPA) extract (Lindsay and Norvell 1978). The irrigation water contained 10–25 mg kg^{-1} nitrate (NO_3) N, 0.2 mg kg^{-1} P, 3–9 mg kg^{-1} K, 30–40 mg kg^{-1} Ca, 4.0–7.5 mg kg^{-1} Mg, 1.7 mg kg^{-1} of Zn, and 0.16 mg kg^{-1} of Fe with a pH of 6.9.

Statistical Analysis

The data were statistically analyzed using MSTATC (East Lansing, Mich.). Statistical analysis was done using standard analysis of variance (ANOVA) technique. Correlations were done between yield and other parameters for better understanding of results.

Table 1
Nutrient composition of vermicompost

	Nutrient content		
Nutrient	1998[a]	2004	2006
N (%)	1.38	2.18	2.64
P (%)	0.35	0.52	0.6
K (%)	0.98	0.9	0.9
Ca (%)	1.6	1.68	1.9
Mg (%)	0.45	0.60	0.66
Fe (mg kg^{-1})	2561	2883	4412
Mn (mg kg^{-1})	242	306	502
Zn (mg kg^{-1})	396	382	351
Cu (mg kg^{-1})	120	105	70

[a]Source: Chowdappa et al. (1999).

Results and Discussion

Soil pH

Significant variation in soil pH was noticed as a result of application of VC and CFs alone or in combination in arecanut basin in 2009 (Figure 2). In general, the pre-experimental soil pH in 1997 was 5.6, and it increased to 5.9 at 0–30 cm deep in 2009. Application of VC at 100% and 200% N equivalency significantly increased the soil pH (6.3) over CF and integrated treatments (5.7–5.8). Application of VC 150% + CF 50% (6.1) and control (6.0) maintained pH levels at par with VC at 100% and 200%. It has been stated that manuring tends to move soil pH toward neutrality (Whalen et al. 2000). There are contrasting reports of greater soil pH as a result of organic management (Clark et al. 1998; Liebig and Doran 1999) as well as lower pH in organic systems (Haraldsen et al. 2000). However, in the present study pH increased by 0.7 units with VC application alone and by 0.1–0.5 units with CF application alone or in combination with VC at the end of experimentation. The greater Ca and Mg contents in arecanut basin due to application of VC substantiate these results. The use of non-acid-forming fertilizers and the quality of irrigation water, which had a pH of 6.9–7.0 and naturally occurring Ca and Mg ions, might have contributed to the increase in soil pH irrespective of treatments. Because the laterite soils have low CEC and buffering capacity, the pH may fluctuate with application of irrigation water containing high Ca and Mg contents.

Soil Organic Carbon

Soil organic matter is the key for the productive capacity of many tropical soils (Woomer et al. 1994). Application of VC improved the soil organic C (SOC) content in arecanut basin significantly between 2003 and 2009 (Figure 3). At 0–30 cm soil deep, the SOC content enriched from 2.1% in 2003 to 2.3% in 2009. The increase in SOC was 51% in 2009 (2.3%) over pre-experimental status (1.52%). The SOC content reduced from 1.3 to 1.1% during the same period at 30–60 cm soil deep. Greater SOC content was recorded with VC application at 100% N (2.85%) and 200% N (3.00%) than chemical fertilizer alone or conjunctive use of VC and chemical fertilizers. Increases in soil organic matter under organic management are widely reported (Clark et al. 1998; Liebig and Doran 1999;

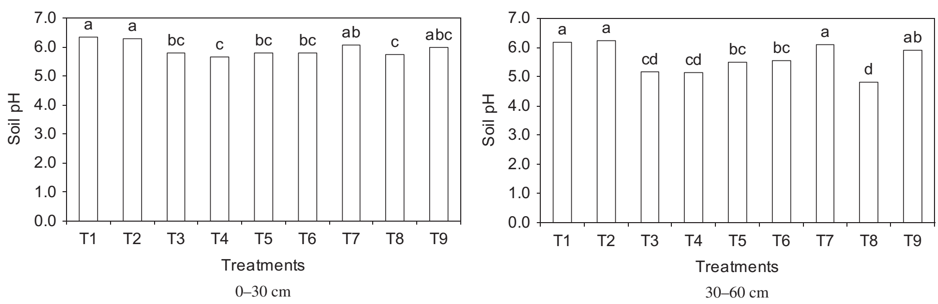
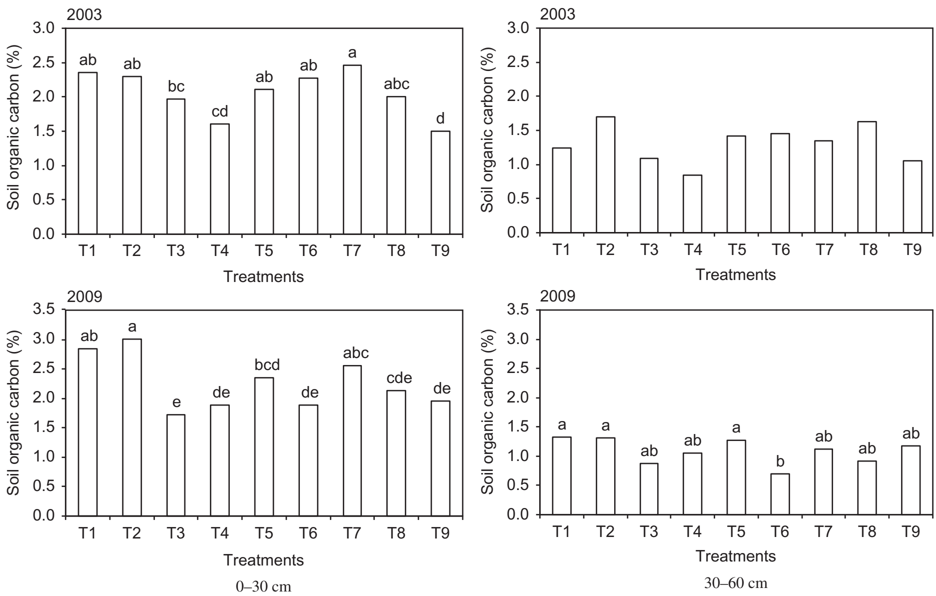


Figure 2. Variation in soil pH due to different treatments in 2009, LSD 0.37 for 0–30 cm; 0.41 for 30–60 cm. T1, 100% vermicompost on N equivalent basis (VC); T2, 200% VC; T3, 100% NPK through chemical fertilizers (CF); T4, 200% CF; T5, 50% VC + 50% CF; T6, 100% VC + 100% CF; T7, 150% VC + 50% CF; T8, 50% VC + 150% CF; and T9, control. *Note.* LSD indicates significant differences between two means at 5%. Bars with same letters do not differ significantly.



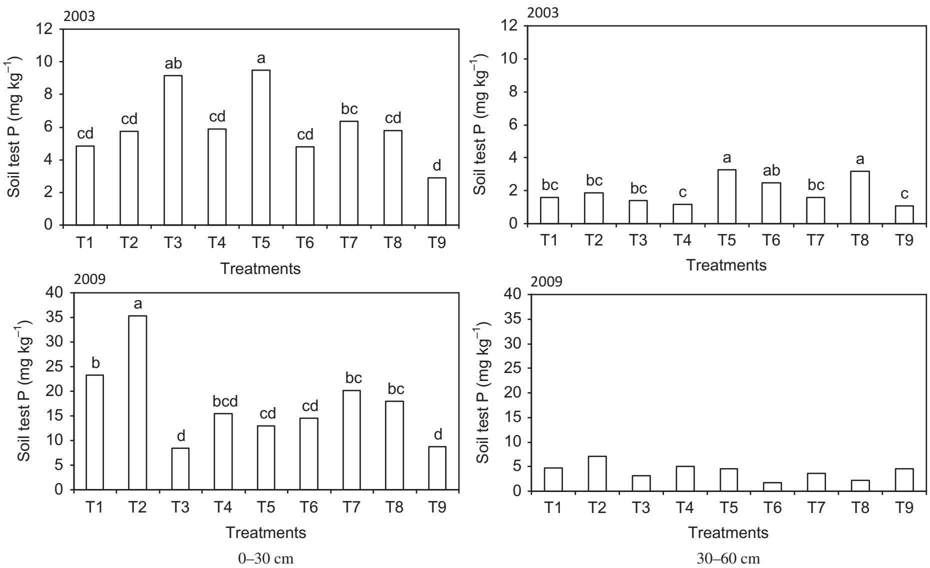
Soil depth	LSD	
	2003	2009
0–30 cm	0.46	0.56
30–60 cm	NS	0.49

Figure 3. Temporal and spatial variation in soil organic carbon at different soil depths. T1, 100% vermicompost on N equivalent basis (VC); T2, 200% VC; T3, 100% NPK through chemical fertilizers (CF); T4, 200% CF; T5, 50% VC + 50% CF; T6, 100% VC + 100% CF; T7, 150% VC + 50% CF; T8, 50% VC + 150% CF; and T9, control. *Note.* LSD indicates significant differences between two means at 5%. Bars with same letters do not differ significantly.

Stockdale et al. 2001; Pulleman et al. 2003). Arecanut wastes have high cellulose and lignin content with wide C/N ratio and the recycling of these wastes as VC might have increased the SOC content. A similar opinion was expressed by Campbell and Zentner (1993).

Soil Test P

The soil test P increased from 6.1 mg kg^{-1} in 2003 to 17.4 mg kg^{-1} in 2009. Though soil test P was significantly different among treatments in 2003, no definite trend was noticed (Figure 4). Control treatment registered lower soil test P (2.9 mg kg^{-1}) than nutrition treatments (4.8–9.1 mg kg^{-1}). In 2009, VC 200% N equivalency significantly increased the soil test P content in soil (35.3 mg kg^{-1}) over VC 100% N equivalency (23.3 mg kg^{-1}), CFs (8.5–15.4 mg kg^{-1}), and integrated treatments (13–20.2 mg kg^{-1}) at 0–30 cm deep. At 30–60 cm deep, different treatments had no significant impact on soil test P. The findings by Motavalli and Miles (2002) and Laboski and Lamb (2003) support these results. Nelson and Mikkelsen (2008) opined that long-term use of manures and compost as the primary N source leads to an accumulation of P in the soil. The greater availability of soil test P with VC application can also be attributed to lower adsorption of P with organic source compared to inorganic P application through CF, which will be readily adsorbed in



Soil depth	LSD	
	2003	2009
0–30 cm	3.04	8.09
30–60 cm	1.18	NS

Figure 4. Temporal and spatial variation in soil test P at different soil depths. T1, 100% vermicompost on N equivalent basis (VC); T2, 200% VC; T3, 100% NPK through chemical fertilizers (CF); T4, 200% CF; T5, 50% VC + 50% CF; T6, 100% VC + 100% CF; T7, 150% VC + 50% CF; T8, 50% VC + 150% CF; and T9, control. *Note.* LSD indicates significant differences between two means at 5%. Bars with same letters do not differ significantly.

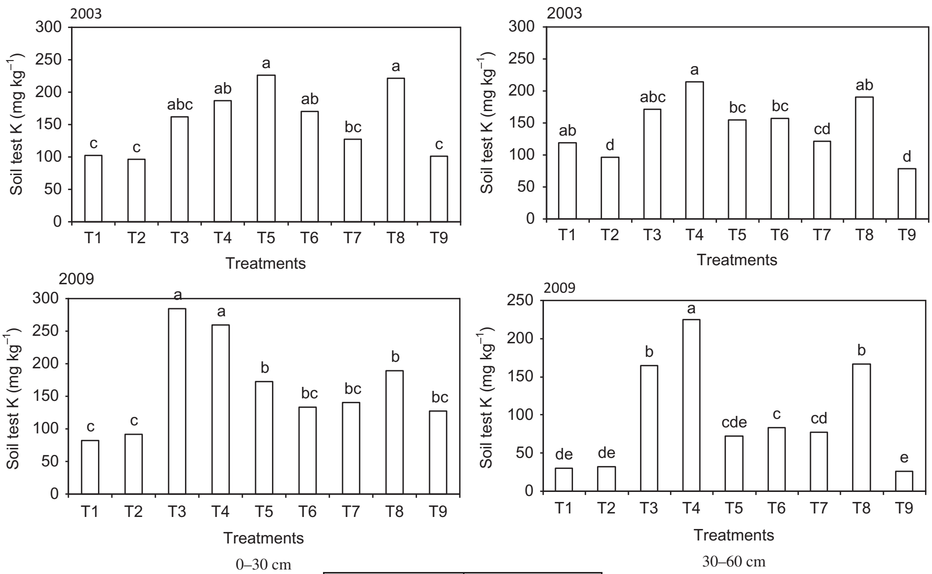
Table 2
Correlation between different nutrients in soil

Parameter	Correlation	Probability
SOC vs. soil test P	0.868	0.002
SOC vs. soil test K	−0.739	0.02
SOC vs. soil test Ca	0.898	0.001
SOC vs. soil test Mg	0.838	0.004
Soil test K vs. soil test Ca	−0.779	0.011
Soil test K vs. soil test Mg	−0.770	0.013
Soil test Ca vs. soil test Mg	0.932	0.000

laterite soils (Perur 1996). Significant correlation between SOC content and soil test P ($r = 0.868$) substantiates the increase in P content due to VC application (Table 2).

Soil Test K

Temporal and spatial variation in soil test K content at 0–30 cm and 30–60 cm deep is illustrated in Figure 5. In general, soil test K content decreased with VC application



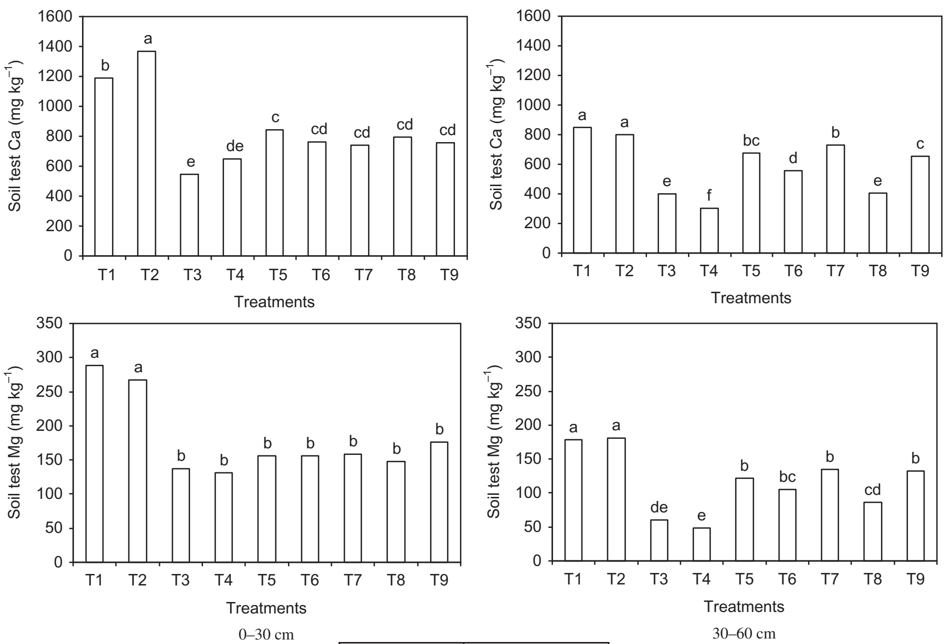
Soil depth	LSD	
	2003	2009
0–30 cm	66.9	70.6
30–60 cm	55.1	47.8

Figure 5. Temporal and spatial variation in soil test K at different soil depths. T1, 100% vermicompost on N equivalent basis (VC); T2, 200% VC; T3, 100% NPK through chemical fertilizers (CF); T4, 200% CF; T5, 50% VC + 50% CF; T6, 100% VC + 100% CF; T7, 150% VC + 50% CF; T8, 50% VC + 150% CF; and T9, control. *Note.* LSD indicates significant differences between two means at 5%. Bars with same letters do not differ significantly.

alone both in 2003 and 2009 compared to chemical fertilizer application. This decline was less pronounced in integrated treatments in both years. In 2003, soil test K was significantly greater with CF application alone (162–187 mg kg^{-1}) or in combination with VC (127–226 mg kg^{-1}) than only VC application (97–102 mg kg^{-1}) and control (101 mg kg^{-1}) at 0–30 cm deep. At 30–60 cm soil deep, the soil test K was significantly greater with application of CF fertilizers (172–214 mg kg^{-1}) than with VC application and control.

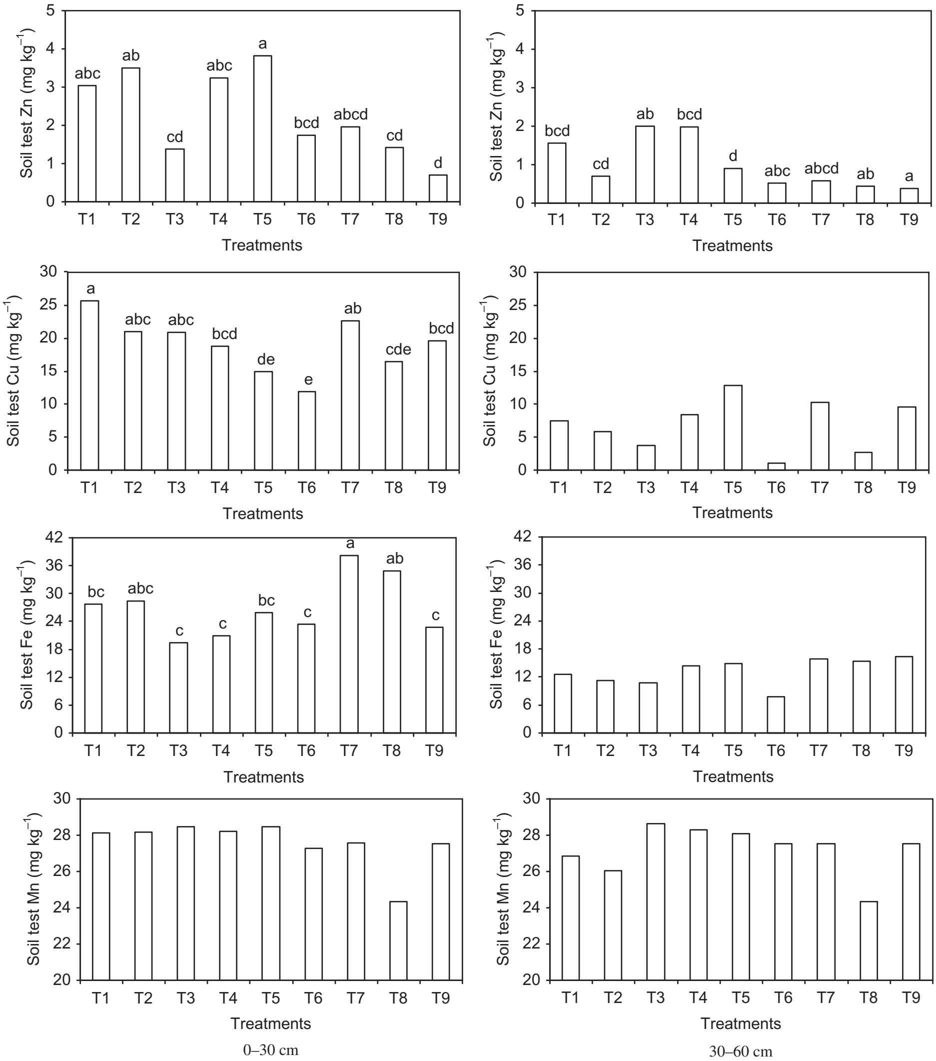
In 2009, CF application maintained significantly greater soil test K (260–285 mg kg^{-1}) than VC application alone (82–92 mg kg^{-1}), integrated treatments (133–189 mg kg^{-1}), and control (127 mg kg^{-1}) at 0–30 cm soil deep. Similarly at 30–60 cm deep also, soil test K (mg kg^{-1}) was significantly greater with CF application (165–225 mg kg^{-1}) than VC application alone (30–32 mg kg^{-1}), integrated treatments (72–83 mg kg^{-1}), and control (26 mg kg^{-1}). The reduction in soil test K was drastic between 2003 (97–119 mg kg^{-1}) and 2009 (30–32 mg kg^{-1}) with VC application alone at 30–60 cm deep. The results indicate the K depletes once the bearing stage starts in arecanut. Lower concentrations of extractable K are noticed in soils managed organically (Gosling and Shepherd 2005). Increased application of N through conjunctive use of VC + CF and other sources such as irrigation water, atmosphere, and native soil fertility would also contribute to K depletion. Oenema et al. (2006) reported that application of single-element fertilizers (mostly N) has contributed to accelerated exhaustion of other nutrient elements.

The optimum range of soil test K in laterite soil was estimated at 122–262 mg kg^{-1} through boundary line approach (CPCRI 2011). In the present study, soil test K levels were lower than optimum range with long-term application of VC alone. Singh et al. (2002) stressed that more attempts are needed to quantify temporal changes in the K-supplying capacity of soil over time under different crop and soil management practices. Both soil K and plant K (1.0%) declined with VC application alone, suggesting that more emphasis on K management at field scale would be beneficial. The significant negative correlation (Table 2) between SOC and soil test K (r = –0.74), soil test K and Ca (r = –0.78), and soil test K and Mg (r = –0.77) clearly indicate that soil test K depletion was closely related to increase in SOC (Figure 3) and that Ca and Mg accumulation in arecanut basin is due to long-term VC application (Figure 4). As K is not organically bound and also because of absence of K fixation sites in laterite soils, the K content might have reduced in arecanut basin applied with VC. To minimize the risk of decline in long-term soil fertility and K depletion, it is important to analyze K concentrations in leaf, in addition to soil tests, and adjust the K application rates and timings. The increased crop yields increase the rate of depletion of nutrients. In the longer term, laterite soils run the risk of increased soil exhaustion, unless the soils are supplied with targeted amounts of P, K, and other essential nutrients.



Soil depth	LSD	
	Ca	Mg
0–30 cm	66.9	70.6
30–60 cm	55.1	47.8

Figure 6. Temporal and spatial variation in soil test Ca and Mg at different soil depths. T1, 100% vermicompost on N equivalent basis (VC); T2, 200% VC; T3, 100% NPK through chemical fertilizers (CF); T4, 200% CF; T5, 50% VC + 50% CF; T6, 100% VC + 100% CF; T7, 150% VC + 50% CF; T8, 50% VC + 150% CF; and T9, control. *Note.* LSD indicates significant differences between two means at 5%. Bars with same letters do not differ significantly.



Soil depth	LSD			
	Zn	Cu	Fe	Mn
0–30 cm	1.81	5.56	10.1	NS
30–60 cm	0.91	NS	NS	NS

Figure 7. Variation in micronutrient content due to different treatments and soil depths in 2009. T1, 100% vermicompost on N equivalent basis (VC); T2, 200% VC; T3, 100% NPK through chemical fertilizers (CF); T4, 200% CF; T5, 50% VC + 50% CF; T6, 100% VC + 100% CF; T7, 150% VC + 50% CF; T8, 50% VC + 150% CF; and T9, control. *Note.* LSD indicates significant differences between two means at 5%. Bars with same letters do not differ significantly.

Soil Test Ca and Mg

Soil test Ca and Mg varied significantly because of different treatments at both depths in 2009 (Figure 6). Application of VC at 100% and 200% N equivalent basis significantly improved the soil test Ca (1191–1365 mg kg^{-1}) and Mg (267–289 mg kg^{-1}) content compared to CF application alone or in combination with VC and control at 0–30 cm deep. Similar trend was noticed at 30–60 cm deep. Lower Ca and Mg contents were noticed with application of CF alone at both soil depths than combined application of VC and CF. This trend of lower accumulation of Ca and Mg in soil can be attributed to greater K content in soil with CF application.

Soil Test Values of Micronutrients

The DTPA-extractable Cu, Zn, and Fe contents in soil were significantly influenced by different treatments (Figure 7). Soil Mn content was not significantly influenced by application of VC and CF alone or in combination. In general, micronutrient content was greater with VC application, and soil test values increased compared to initial status in 1997. This suggests that VC application, native soil fertility, and irrigation water would have contributed to accumulation of micronutrients in soil. It was reported that the soil OM exerts a significant and direct impact on the availability of Zn, Fe, and Mn but has little influence on the availability of soil Cu (Zhang, Wang, and Jin 2001). Application of appropriate rates of N, P, and K fertilizers can increase soil Cu, Zn, and Mn availability (Zhang, Guo, and Nan 2004). Shortage of K also increases Cu, Zn, Fe, and Mn concentrations (Cheng 1995).

Conclusions

The study indicates that VC application maintained SOC and soil test levels of P, Ca, and Mg at high rates compared to CF application. However, K depletion was noticed with VC application alone. The results do offer support to the argument that organic farming is mining reserves of K built up by conventional management. If long-term declines in soil K leading eventually to declining yields are to be avoided, increased use of K supplementary fertilizers is required.

References

Andrist-Rangel, Y., A. C. Edwards, S. Hillier, and I. Oborn. 2007. Long-term K dynamics in organic and conventional mixed cropping systems as related to management and soil properties. *Agriculture Ecosystem and Environment* 122:413–426.

Babu, P. V. L. P. 1981. *Laterite as an unconformity plane in the evolution of the Indian Peninsula: A synthesis*. New Delhi: Oxord & IBH.

Badrinath, M., R. Gajendragad, and K. Balakrishna Rao. 1998. Distribution of micronutrients in laterite soils of Puttur in relation to some soil properties. In *Red and Lateritic soils*, eds. J. Sehgal, W. E. Blum, and K. S. Gajbhiye, vol. 1, 271–274. New Delhi: Oxford & IBH Publishing Co.

Bhat, N. T., and A. R. Mohapatra. 1989. Supplying nutrients through organic manures, inorganic fertilizers, and their combination on arecanut. *Journal of Plantation Crops* 16 (Suppl): 443–447.

Bhat, R., and S. Sujatha. 2004. Crop management. In *Arecanut*, ed. D. Balasimha and V. Rajagopal, 76–102. Kasaragod, India: CPCRI.

Bhat, R., and S. Sujatha. 2007. Soil fertility status as influenced by arecanut-based cropping system and nutrient management. *Journal of Plantation Crops* 35 (3): 158–165.

Bhat, R., and S. Sujatha. 2009. Soil fertility and nutrient uptake by arecanut (*Areca catechu* L.) as affected by level and frequency of fertigation in a laterite soil. *Agricultural Water Management* 96 (3): 445–456.

Biddappa, C. C., A. K. Upadhyay, M. R. Hegde, and C. Palaniswami. 1996. Organic matter recycling in plantation crops. *Journal of Plantation Crops* 24 (2): 71–85.

Campbell, C. A., and R. P. Zentner. 1993. Soil organic matter as influenced by crop rotations and fertilization. *Soil Science Society of America Journal* 57:1034–1040.

Cheng, S. C. 1995. The effects of K supplement on the absorption and distribution of Zn, Mn, Fe, and Cu in wheat. *Journal of Anhui Agricultural University* 22:196–202.

Chowdappa, P., C. C. Biddappa, and S. Sujatha. 1999. Efficient recycling of organic wastes in arecanut (*Areca catechu* L.) and cocoa (*Theobroma cacao* L.) plantation through vermicomposting. *Indian Journal of Agricultural Sciences* 69:563–566.

Clark, M. S., W. R. Horwarth, C. Shennan, and K. M. Scow. 1998. Changes in soil chemical properties resulting from organic and low input farming practices. *Agronomy Journal* 90:662–671.

CPCRI. 2011. *Research highlights for 2010–2011*. Kasaragod, India: Central Plantation Crops Research Institute.

GOI. 2008. *Area and production statistics of arecanut and spices*. Calicut: Directorate of Arecanut and Spices Development, Ministry of Agriculture, Government of India.

Gosling, P., and M. Shepherd. 2005. Long-term changes in soil fertility in organic arable farming systems in England, with particular reference to phosphorus and potassium. *Agriculture Ecosystems and Environment* 105:425–432.

Haraldsen, T. K., A. Asdal, C. Grasdalen, L. Nesheim, and T. N. Ugland. 2000. Nutrient balances and yields during conversion to organic cropping systems on silt loam and clay soils in Norway. *Biological Agriculture and Horticulture* 17:229–246.

Jackson, M. L. 1973. *Soil chemical analysis*. New Delhi: Prentice Hall of India.

Laboski, C. A. M., and A. J. Lamb. 2003. Changes in soil test phosphorus concentration after application of manure or fertilizer. *Soil Science Society of America Journal* 67:544–554.

Liebig, M. A., and J. W. Doran. 1999. Impact of organic production practices on soil quality indicators. *Journal of Environmental Quality* 28:1601–1609.

Lindsay, W. L., and W. A. Norvell. 1978. Development of DTPA test for zinc, iron, manganese, and copper. *Soil Science Society of America Journal* 42:421–428.

Motavalli, P. P., and R. J. Miles. 2002. Soil phosphorus fractions after 111 years of animal manure and fertilizer fractions. *Biology and Fertility of Soil* 36:35–42.

Nelson, N., and R. Mikkelsen. 2008. Meeting the phosphorus requirement on organic farms. *Better Crops* 92:12–14.

Oenema, O., B. H. Janssen, E. Smaling, and E. Hoffland. 2006. Nutrient management in tropical agroecosystems. *Agriculture, Ecosystems and Environment* 116:1–3.

Perur, N. G. 1996. Acid soils of Karnataka. In *Acid soils of India*, ed. I. C. Mahapatra, S. C. Mandal, C. Misra, G. N. Mitra, and N. Panda, 165–173. New Delhi: Indian Council of Agricultural Research.

Pulleman, M., A. Jongmans, J. Marinissen, and J. Bouma. 2003. Effects of organic versus conventional arable farming on soil structure and organic matter dynamics in a marine loam in the Netherlands. *Soil Use and Management* 19:157–165.

Rethinam, P. 1990. Potassium in plantation crops. In *Potassium for plantation crops*, ed. M. Singh and M. K. Mishra, 7–15. Bangalore: Potash Research Institute of India.

Saciragic, B., and M. Dzelilovie. 1986. Effects of worm compost on soil fertility and yield of vegetable crops, cabbage, leeks, and sorghum hybrid yield. *Agrochimica* 3:343–351.

Singh, M., V. P. Singh, and D. D. Reddy. 2002. Potassium balance and release kinetics under continuous rice–wheat cropping system in Vertisol. *Field Crops Research* 77:81–91.

Stockdale, E. A., N. H. Lampkin, M. Hovi, R. Keatinge, E. K. M. Lennartsson, D. W. Macdonald, S. Padel, F. H. Tattersall, M. S. Wolfe, and C. A. Watson. 2001. Agronomic and environmental implications of organic farming systems. *Advances in Agronomy* 70:261–325.

Tomorti, U., A. Gropelli, and E. Galli. 1987. The hormone-like activity of earthworm casts on plant growth. *Biology and Fertility of Soil* 6:288–295.

Watanabe, F. S., and S. R. Olsen. 1965. Test of ascorbic acid method for determining phosphorus in water and sodium bicarbonate extracts of soil. *Soil Science Society of America Proceedings* 29:677–678.

Whalen, J. K., C. Chang, G. W. Clayton, and J. P. Carefoot. 2000. Cattle manure amendments can increase the pH of acid soils. *Soil Science Society of America Journal* 64:962–966.

Woomer, P. L., A. Martin, A. Albrecht, D. V. S. Resck, and H. W. Scharpenseel. 1994. The importance and management of soil organic matter in the tropics. In *The biological management of tropical soil fertility*, ed. P. L. Woomer and M. J. Swift, 47–80. Chichester: John Wiley & Sons.

Zhang, R., Y. X. Guo, and C. Q. Nan. 2004. Study of trace elements of wheat grain in different fertilizer treatments. *Acta Bottanica Boreal Occident Sinica* 24:125–129.

Zhang, S. X., X. B. Wang, and K. Jin. 2001. Effect of different N and P levels on availability of zinc, copper, manganese, and iron under arid conditions. *Plant Nutrition and Fertilizer Science* 7:391–396.