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Impact of organic and inorganic nutrition on soil–plant nutrient balance in arecanut (*Areca catechu* L.) on a laterite soil

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ABSTRACT

The study assessed the impact of continuous application of vermicompost and chemical fertilizers nitrogen, phosphorus and potassium (NPK) on arecanut in India. Key parameters examined were biomass production, nutrient uptake, yield, soil fertility and net benefit. Pooled analysis of 8-year data revealed that nutrient application registered significantly higher yield (2585–3331 kg ha^{-1}) than no nutrition (1827 kg ha^{-1}). Yields in organic nutrition were around 85% of the yields obtained in inorganic NPK. The concentrations of leaf N and K were significantly higher with NPK than with vermicompost. Vermicompost significantly increased soil organic carbon and the availability of calcium (Ca), magnesium (Mg), manganese (Mn) and copper (Cu), but reduced exchangeable K in soil. The total uptake of K and Ca together contributed positively to 75% variability in total biomass production. Nutrient removal of iron (Fe), P, K and Cu positively influenced the yield with about 81% variability. Biomass partitioning and nutrient uptake pattern are important for fertilization program of arecanut.

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KEYWORDS
Arecanut; laterite soil; vermicompost; chemical fertilizers; yield

Introduction

Soil fertility decline is perceived to be widespread in tropics (Hartemink, 2006). The focus of agricultural research is shifting towards minimization of external inputs and maximization of resource use efficiency. Despite increased use of inputs and new technologies, returns on investment in crop production systems are diminishing. Tropical regions face a shortage of fertilizer inputs which are crucial for maximum yields (Pal and Shehu, 2001). Fertilizers contribute to yield increase of 40–60% in several crops (Stewart et al., 2005). The depletion of fossil fuel sources will lead to increased cost of fertilizers in future. Supplementary and complementary role of organics is being increasingly felt for preserving the soil quality and environment. Limited availability and higher cost of organic manures necessitate the need for recycling of locally available organic wastes. It may be a viable approach to reduce input costs, finite fossil fuel consumption and promote proper recycling of organic manures. Recycling of organic wastes is important for conserving natural resources and mitigating environmental hazards. Tiesson et al. (1994) pointed out that organic matter recycling is related to agricultural potential of soils. The disadvantages associated with organic manures must also be considered before using them in agricultural production systems (Havlin et al., 2005). Though organic farming is criticized for relying on the build-up of soil phosphorus and potassium (Nguyen et al., 1995; Gosling and Shepherd, 2005; Andrist-Rangel et al., 2007), its acceptance and popularity are growing due to environmental and health related concerns (Stockdale et al., 2001; Biao et al., 2003; Galantini and Rosell, 2006).

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Arecanut (*Areca catechu* L.), which belongs to family Palmae, is a major cash crop in humid tropics of India. The palm grows to a height of about 10–15 m and produces 8 to 9 leaves per year. The dry kernel is mainly used for masticatory purpose in Asia. India ranks first in area (0.39 m ha) and production (0.47 m tonnes) of arecanut in the world (GOI, 2011). The productivity remained stagnant during the last two decades (1188–1268 kg ha^{-1}). It is often ascribed to the absence of adequate information on soil fertility and plant nutrition. Shallow root system, huge trunk biomass and low nutrient use efficiency are major constraints in arecanut cultivation. It is predominantly grown in acidic laterite soils (Ultisols) and inherent constraints of these soils are widely reported (Lal, 1995; Perur, 1996; West et al., 1997; Shiva Prasad et al., 1998). Low nutrient use efficiency is a serious drawback in tropical agroecosystems (Oenema et al., 2006). Nutrient management is indispensable to tackle these constraints and to make the production system self-sustainable. Quantification of nutrient flows and stocks is important for development of sustainable land use systems (Hartemink, 2005).

Arecanut generates about 2.3 to 3.3 million tonnes of organic wastes annually in India. These wastes contain considerable nutrients, but are slowly biodegradable and rich in lignin, cellulose and polyphenol. Most of these wastes have traditionally been disposed of by burning or dumping in the form of heaps. Burning results in various environmental problems like carbon deposits as well as the warming of the atmosphere. During the rainy season, the phenols from heaped leaf wastes might leach into the soil, thereby leading to soil pollution. Alternate way is to convert these wastes into useful organic manure. Direct recycling of plantation wastes would not meet the crop nutrient demand immediately due to high carbon:nitrogen (C:N) ratio and immobilization of nitrogen. Vermicomposting is an environmentally acceptable means of converting recyclable organic wastes into nutritious compost (Edwards, 1988; Orozco et al., 1996) and is better in terms of nutrient quality than normal composting (Chowdappa et al., 1999).

In the past much research directed at improving soil fertility and nutrient management has focused on individual nutrients or on single component technologies or approaches (Oenema et al., 2006). Nutrient balance in soil-plant system is important for sustaining the yield and soil fertility in perennial systems. Requirement of major nutrients for arecanut was standardized, but comprehensive studies are lacking on soil-plant nutrient balance and its relation to yield. The nutrient recommendation algorithms in arecanut at present do not consider crop nutrient demand, supply and efficiency. Understanding nutrient uptake-biomass-yield relations in arecanut is thus a crucial step for developing widely applicable nutrient recommendations. Recent studies indicated higher N and K requirement (Bhat and Sujatha, 2012) than current fertilizer recommendations for arecanut. It is essential to know whether organic matter recycling as vermicompost can meet the total nutrient demand of arecanut. This 14-year study assessed the impact of vermicompost application as a nitrogen (N) source alone and in combination with chemical fertilisers in arecanut nutrition programme. This study also assessed the implications of vermicompost (VC) and nitrogen, phosphorus and potassium (NPK) application at both recommended and higher levels on biomass production, nutrient uptake, soil fertility and yield.

Materials and methods

Site and soil

The long term field experiment was conducted during 1998–2012 at Central Plantation Crops Research Institute, Regional Station, Vittal, Karnataka, India (12°15′N latitude and 75°25′E longitude, 91 m above sea level). The climate of the experimental site is humid tropical and the forty-three year average annual rainfall is 3686 mm. The annual rainfall during 1997–2011 varied from 2869 to 4325 mm. Mean temperature ranges from 21 to 36°C. The average relative humidity varies between 61 to 94%. The soil of the study site is sandy clay loam classified as kaolinitic Kanhaplic Haplustults in Ultisols order. The textural composition of the soil is 50% sand, 14% silt and 36% clay at 0 to 60 cm 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, 1.5% organic carbon, 10 mg kg^{-1} P and 53 mg kg^{-1} K at 0–30 cm soil depth.

Table 1. Nutrients added though vermicompost and chemical fertilizers in different treatments.

Treatment	Nutrients added through VC/CF (g per palm per year) N	P	K
Vermicompost 100% N equivalent	100	23–25	34–71
Vermicompost 200% N equivalent	200	46–50	68–142
100% NPK	100	18	117
200% NPK	200	36	234
50% NPK + vermicompost 50%	100	21–22	75–94
100% NPK + vermicompost 100%	200	42–44	150–188
50% NPK + vermicompost 150%	200	44–46	110–165
150% NPK + vermicompost 50%	200	39–40	193–211
Absolute control	—	—	—

The quantity of P and K varied due to variation in N content of VC.

Experimental details

Arecanut plantation in a field plot size of 2930 m^2 was established in 1997 by planting 1-year old seedlings (cv. Mohitnagar) at a spacing of 2.7 m × 2.7 m. The experiment was laid out in Randomized Block Design (RBD) with nine treatments and three replications in September 1998. Each treatment included eight palms as net plot that accounts to 58.32 m^2 area. Recommended fertilizer dose for arecanut is 100:18:117 g N: P: K per palm per year. The vermicompost (VC) was applied on N equivalent basis as that of chemical fertilizer (CF) requirement. The treatments applied were: 100% vermicompost on N equivalent basis (T1), 200% vermicompost on N equivalent basis (T2), 100% NPK (T3), 200% NPK (T4), 50% NPK + 50% vermicompost (T5), 100% NPK + 100% vermicompost (T6), 50% NPK + 150% vermicompost (T7), 150% NPK + 50% vermicompost (T8) and absolute control (T9). The nutrients applied though VC and CF in each treatment is given in Table 1. Fertilizers were applied around the base of the palm at a distance of 60–75 cm after opening the basin to a depth of 15 cm followed by application of vermicompost. Then it was forked to mix fertilizers and compost with soil. About 1/3rd and 2/3rd of recommended fertilizers were applied in the first and second years of planting, respectively. The sources of fertilizers were urea, rock phosphate and muriate of potash (potassium chloride). The crop was irrigated through basin method at irrigation water (IW)/cumulative pan evaporation (CPE) ratio of one during post monsoon season (December–May). 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} calcium (Ca), 4.0–7.5 mg kg^{-1} magnesium (Mg), 1.7 mg kg^{-1} of zinc (Zn) and 0.16 mg kg^{-1} of iron (Fe) with a pH of 6.9. Bordeaux mixture (1%) was sprayed on bunches twice at 45 days interval during June–September to prevent fruit rot incidence caused by *Phytopthora palmivora*.

Estimation of above-ground biomass

Above ground biomass (trunk, leaf, kernel and husk) and growth parameters like trunk height, girth and number of leaves were recorded in 15-year old arecanut palm in 2011. Standing trunk biomass (Y) was estimated using regression equation, $Y = 0.01435\,h + 0.3442\,g - 1.0017$ (h = height of the trunk and g = girth of the trunk). Five leaves from each treatment were collected and oven dried to estimate leaf biomass. Average leaf biomass was multiplied with number of leaves to arrive at total leaf biomass per palm. The biomass of leaf, dry kernel and husk was added to trunk biomass to arrive at total. Harvesting of arecanut was spread over a period of six months from October to March. Ripe nuts were harvested as and when ready and dried to 8% moisture. Dried nuts were de-husked and kernel weight was recorded for computing the yield.

Analysis of plant, soil and vermicompost samples

The samples from different parts of arecanut palm viz., leaf, kernel, husk and trunk were collected in 2011 and analyzed for nutrients to find out nutrient uptake pattern. Trunk samples were collected through drilling device at different points and mixed. Leaf samples were collected from the middle portion of 4th and 6th leaves separately for analysis. Leaf samples were cleaned with tap water followed by distilled water, 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. Soil samples were collected at 0- to 30 and 30- to 60-cm soil depths in arecanut basin at 60 cm distance from the trunk in 2011 for nutrient analysis. The air-dried soil samples were ground to pass through a 2.0-mm sieve and kept in labelled plastic bags for further analysis.

The trunk, leaf, kernel and husk samples were analyzed for total N using micro-Kjeldahl digestion method (Jackson, 1973). The powdered plant samples were digested in a 1:3 perchloric-nitric acid mixture for total P, K and micronutrient estimation. Phosphorus was determined by vanadomolybdate method (Piper, 1966). The concentration of K, Ca, Mg, Cu, Zn, Fe and Mn was estimated in Atomic Absorption Spectrophotometer. Soil samples were analysed using standard procedures (Jackson, 1973). Soil organic carbon (SOC) was measured by Walkley and Black method. Available P was estimated by ascorbic acid reductant method for color development after extraction with Bray's reagent. Available K, Ca and Mg were estimated in atomic absorption spectrometer (AAS) using ammonium acetate extractant. The concentration of micronutrients was estimated in AAS using diethylene triamine pentaacetic acid (DTPA) extractant (Lindsay and Novell, 1978). The vermicompost samples were analyzed as plant samples. Nutrient uptake was calculated by multiplying nutrient content and oven-dry biomass produced. Nutrient removal (NR) was computed by adding the uptake of nutrients by leaf, nut and husk. Total nutrient uptake was arrived at by adding nutrient removal to the nutrients immobilized in the trunk.

Nutrient composition of vermicompost

The fallen leaves were collected from arecanut plantation regularly and vermicomposted using Eudrilus euginae as per standard methodology (Chowdappa et al., 1999). Total leaf biomass collected from the plantation varied from 5 to 8.5 tonnes in different years. Recovery of vermicompost from these wastes was quantified as 80%. The total concentrations of nutrients in vermicompost in different years were 1.38–2.64% N, 0.35–0.60% P, 0.90–0.98% K, 1.6–1.9% Ca, 0.45–0.66% Mg, 2561–4412 mg kg^{-1} Fe, 242–502 mg kg^{-1} Mn, 351–396 mg kg^{-1} Zn and 70–120 mg kg^{-1} Cu.

Economic analysis

For estimating cost of production the annuity value approach was followed (Gattinger, 1981). The total investment was amortized in to an annuity value bearing 10% interest rate. The annuity value thus obtained was added to annual maintenance cost to arrive at total annual cost of cultivation. The farm gate price of Rs. 70 per kg of kernel was considered for computing the gross returns obtained from each treatment. The net profit per rupee investment was worked out as the quotient of total cost of cultivation over the net profit per hectare for a given treatment and expressed in Rs Re^{-1}.

Statistical analysis

Statistical analysis was done using standard analysis of variance (ANOVA) technique in MSTATC (MSTAT-C, Michigan State University, East Lansing, MI, USA). Correlation and stepwise multiple regression were worked out to establish the quantitative relationship between soil nutrients, leaf nutrients and nutrient uptake with yield. The average kernel yield of five years (2007–2011) was considered for developing quantitative relationship between yield and nutrients in soil and leaf. This nullifies the influence of weather and other external factors on yield (Walworth et al., 1986). Contrast analysis was done by grouping organic, inorganic and integrated treatments with control as separate group using four predefined contrasts.

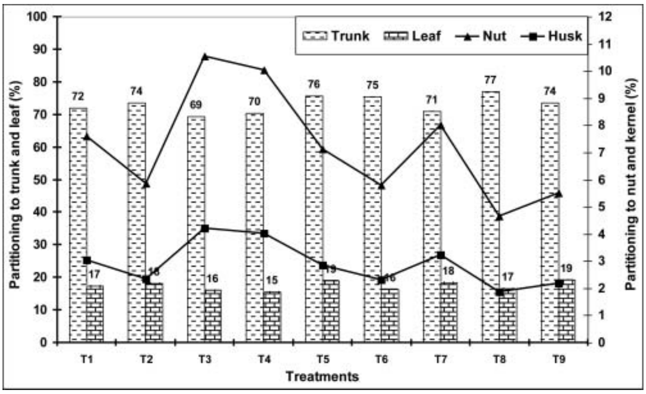

Figure 1. Biomass partitioning to different parts in 15-year-old arecanut palm in different treatments (LSD (5%)-3.9 for total biomass). T1-100% vermicompost (38), T2 - 200% vermicompost (37), T3-100% NPK (43), T4-200% NPK (42), T5-50% NPK +50% vermicompost (39), T6-100% NPK + 100% vermicompost (39), T7-50% NPK+ 150% vermicompost (38), T8-150% NPK + 50% vermicompost +(41), T9-Control (36). Values parenthesis in corresponding treatment indicate total biomass in kg per palm.

Results

Biomass partitioning and nutrient concentration in different parts

The influence of different treatments on biomass partitioning along with total standing biomass is depicted in Figure 1. Total standing biomass (kg palm^{-1}) in 15-year-old arecanut palm was significantly higher with 100% and 200% NPK (42–43) than vermicompost+NPK (38–41) than vermicompost (37–38) and control (36). Biomass partitioning to kernel varied between 4.4 to 10.5% in different treatments with mineral fertilizers registering higher partitioning of above 10%. The variation in nutrient content of trunk, kernel and husk samples of arecanut was negligible among different treatments. The average concentration of macro, secondary and micronutrients in trunk, kernel and husk samples of arecanut palm is given in Table 2. The variation in leaf nutrient status of arecanut due to different treatments in 2011 is shown in Figure 2. The concentrations of leaf N and K were significantly higher in NPK than in vermicompost applied palms. Mineral fertilizers maintained significantly higher leaf K (1.02%) compared to vermicompost application (0.6%). The concentrations of P, Ca, Mg, Fe and Zn did not vary significantly among different treatments. Leaf Mn and

Table 2. Nutrient concentration in different parts of arecanut palm and nutrient uptake pattern in 15-year old arecanut palm.

	Macro- and secondary nutrients (%)					Micronutrients (mg kg^{-1})			
Part	N	P	K	Ca	Mg	Fe	Mn	Zn	Cu
Trunk	0.39	0.03	0.41	0.38	0.04	92	11.9	4.3	6.5
Kernel	1.18	0.13	0.45	0.09	0.038	407	17.1	ND	10.3
Husk	0.89	0.08	1.00	0.21	0.085	869	34.7	8.1	63.6
			g palm^{-1}				mg palm^{-1}		
Total uptake*									
Vermicompost	273	27	161^{b}	153	27	5321	1395^{b}	1022	430^{b}
NPK	344	30	211^{a}	168	29	7132	2253^{a}	1089	493^{a}
Vermicompost +NPK	303	27	195^{b}	168	28	6095	1660^{b}	1119	335^{c}
Control	261	25	178^{b}	166	27	5134	1295^{b}	958	347^{bc}
Mean	300	27	189	165	28	6013	1666	1070	387
Nutrient removal*									
Vermicompost	177^{b}	20	60^{c}	60	17	3069	1104^{b}	917	271^{a}
NPK	238^{a}	22	99^{a}	64	18	4608	1899^{a}	971	315^{a}
Vermicompost +NPK	198^{b}	19	85^{b}	66	17	3612	1339^{b}	1003	160^{b}
Control	153^{b}	17	64^{c}	60	16	2571	963^{b}	838	166^{b}
Mean	197	19	80	63	17	3597	1369	958	219

Values with same letters do not differ significantly.

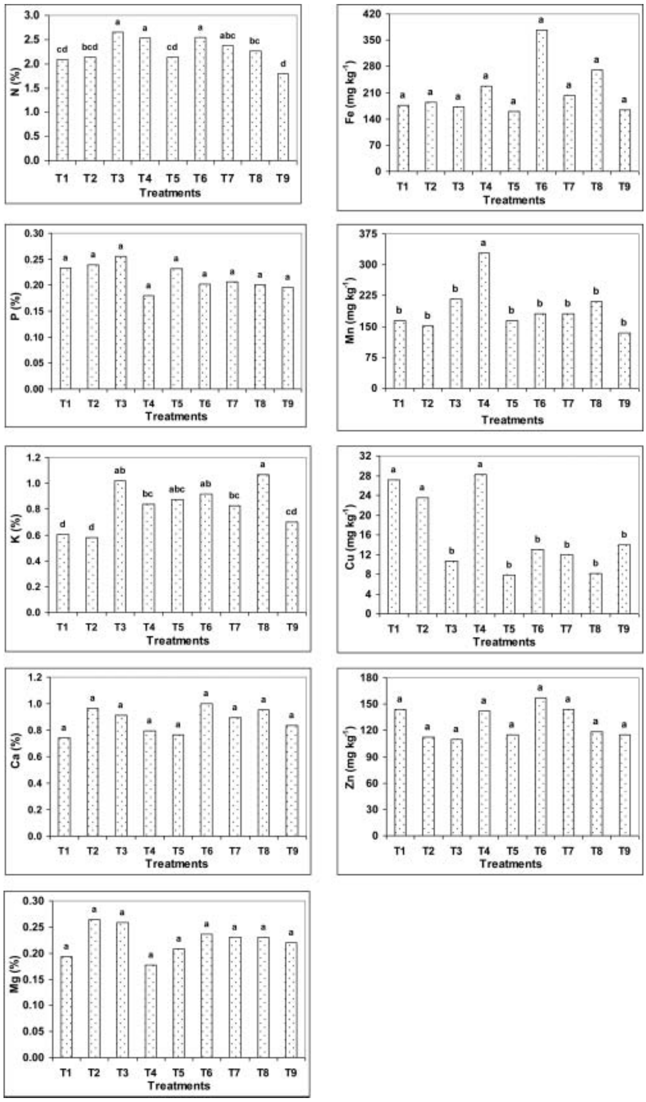

Figure 2. Nutrient concentration in arecanut leaf as influenced by treatments. Bars with same letters do not differ significantly. T1 - 100% vermicompost, T2 - 200% vermicompost, T3 - 100% NPK, T4 - 200% NPK, T5 - 50% NPK + 50% vermicompost, T6 - 100% NPK + 100% vermicompost, T7 - 50% NPK + 150% vermicompost, T8 - 150% NPK + 50% vermicompost, T9 – Control.

Cu were significant but showed no definite trend among different treatments. Temporal variability in leaf nutrient status between 2009 (Sujatha and Bhat, 2013b) and 2011 clearly indicated significant reduction in the concentration of N, P, K and Mg. The concentration of Ca, Mn, Zn and Cu increased in leaf during the same period but only Cu showed significant variation.

Nutrient uptake pattern

Nutrient uptake pattern in arecanut indicated that total uptake of macronutrients was in the order of N > K > Ca > P > Mg (Table 2). The uptake of N, K, Fe, Mn, Zn and Cu was significantly influenced due to different treatments. Nutrient removal pattern showed similar trend as total uptake pattern. Inorganic fertilizers significantly improved nutrient removal and total uptake of N, K and Fe over vermicompost application. But, no definite trend was noticed with respect to removal and uptake pattern of other nutrients among treatments. Thus, the total uptake and nutrient removal patterns are given in

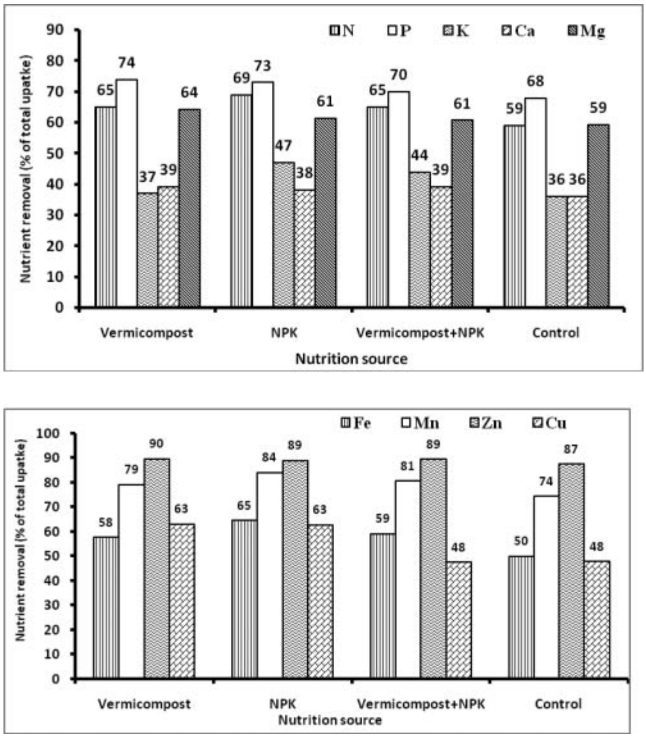

Figure 3. Percentage of nutrient removal to total uptake by 15 year old arecanut palm as influenced nutrient sources.

Table 2 after grouping the treatments as vermicompost, NPK, vermicompost + NPK and control for better conclusions. The nutrient removal pattern clearly indicated slight variations in percentage removal of nutrients with NPK compared to large fluctuations in other groups of nutrition (Figure 3).

Kernel yield of arecanut and net return per rupee investment

The yields registered during 2010 and 2011 along with pooled data of 8-years are given in Table 3. Previous report from this study indicated yield variation of 2369–3060 kg ha^{-1} during 2004 to 2009 (Sujatha and Bhat, 2013b). The 6-year yield data of previous report was utilized only for pooled analysis (2004–2011) in this paper. Year wise variation in kernel yield of arecanut was significant due to long-term application of vermicompost and NPK alone or in combination. Pooled data of 8-years indicated that all nutrition treatments registered significantly higher yield (2585–3331 kg ha^{-1}) than control (1827 kg ha^{-1}). The kernel yields obtained with NPK 100% and 200% were at par (3000–3331 kg ha^{-1}). Application of 100% NPK registered significantly higher yield than vermicompost (2585–2809 kg ha^{-1}) or vermicompost + NPK (2562–2783 kg ha^{-1}). The kernel yields in 2010 and 2011 were significantly influenced due to different treatments. In 2010, the kernel yield was highest with 100% NPK (3481 kg ha^{-1}) followed by 200% NPK and 100% vermicompost. Application of vermicompost alone or combined with NPK at different doses registered similar yields. In 2011, all nutrition treatments except 100% NPK+ vermicompost 100% and 150% NPK+ vermicompost 50% were at par (2992–3778 kg ha^{-1}). The net return per rupee investment was highest with chemical fertilizers (1.76–2.22) compared to vermicompost application alone (1.03–1.54) integrated application (1.18–1.63). Returns were negative with no nutrition (0.95).

Soil fertility status

Soil fertility status in this study i.e., in 2011 (Figure 4) showed variability compared to the previous report on soil fertility in 2003 and 2009 (Sujatha and Bhat, 2012). Limited differences were

Table 3. Kernel yield of arecanut (kg ha^{-1}) and net return as influenced by different treatments.

Treatment	2010	2011	Pooled (2004–2011) *	
			Mean yield	Net return per rupee investment (Rs Re^{-1})
Vermicompost 100% N equivalent	2931^{bc}	3051^{ab}	2809^{bc}	1.54
Vermicompost 200% N equivalent	2339de	3032^{ab}	2585^{c}	1.03
100% NPK inorganic fertilizers	3481^{a}	3778^{a}	3331^{a}	2.22
200% NPK	3234^{ab}	3345^{ab}	3000^{ab}	1.76
50% NPK + vermicompost 50%	2421^{cde}	2992^{abc}	2783^{bc}	1.63
100% NPK+ vermicompost 100%	2825^{bcd}	2737^{bc}	2769^{bc}	1.34
50% NPK + vermicompost 150%	2665^{cde}	3676^{a}	2673^{bc}	1.18
150% NPK + vermicompost 50%	2429^{cde}	2626^{bc}	2562^{c}	1.23
Absolute Control	2213^{e}	2077^{c}	1827^{d}	0.95
LSD (5%)	516	925	388	—
Year mean	2726	3035	2704	
LSD (5%) for years			473	

*Data of 2004 to2009 published by Sujatha and Bhat (2013b) but utilized only for pooled data in this paper

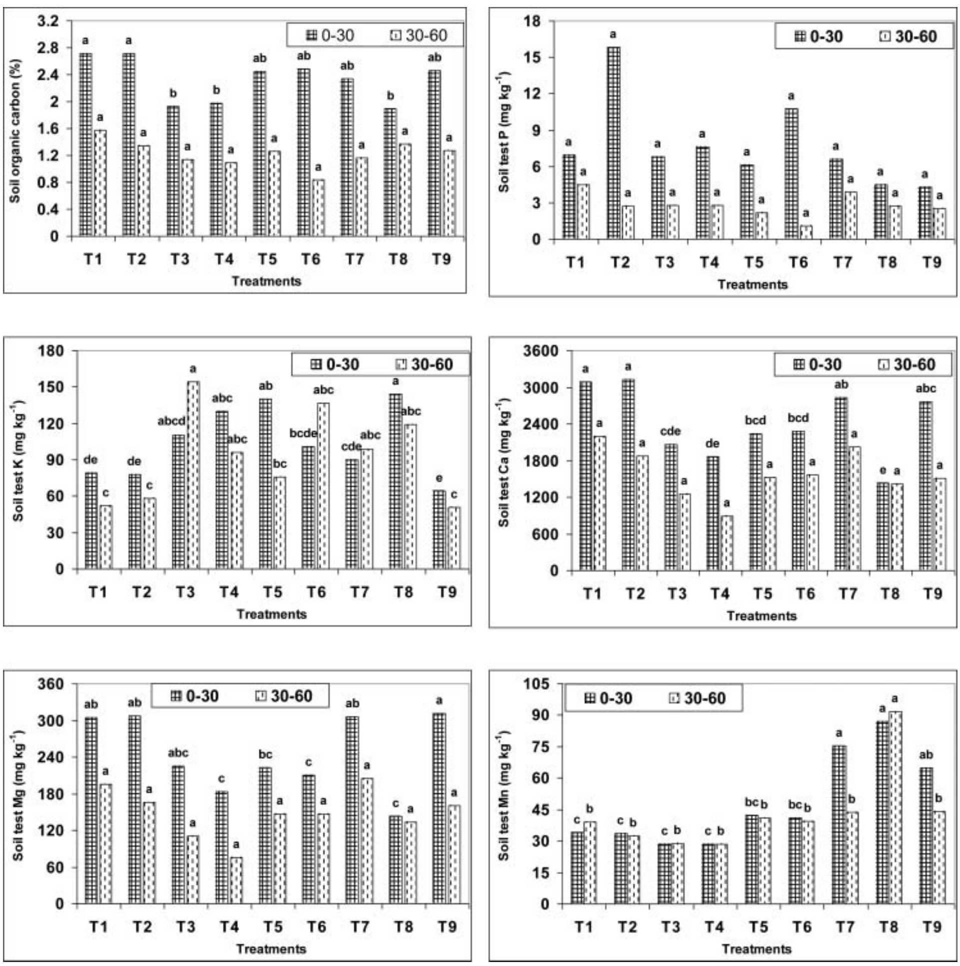

Figure 4. Soil fertility status as influenced by treatments at different depths. Bars with same letters do not differ significantly. T1 - 100% vermicompost, T2 - 200% vermicompost, T3 - 100% NPK, T4 - 200% NPK, T5 - 50% NPK + 50% vermicompost, T6 - 100% NPK+ 100% vermicompost, T7 - 50% NPK + 150% vermicompost, T8 - 150% NPK + 50% vermicompost, T9 – Control.

seen among different treatments for soil test P, Fe (21–38 mg kg^{-1}), Cu (15.5–28.7 mg kg^{-1}) and Zn (0.6–3.4 mg kg^{-1}) at 0–30 cm soil depth in 2011. Similar trend was noticed at second depth. Soil organic carbon and the availability of Ca, Mg, Mn and Cu increased, while availability of P, K, Fe and Zn reduced in soil. In 2011, vermicompost (2.71–2.72%) significantly enriched the SOC over chemical fertilizer application (1.93–198%) at 0–30 cm depth. Soil exchangeable K was significantly higher with inorganic fertilizer application (110–144 mg kg^{-1}) than with vermicompost (78–79 mg kg^{-1}). The availability of soil Ca and Mg increased with vermicompost application. The availability of DTPA-extractable micronutrients except Mn was similar in all treatments. Similar trend was noticed at 30–60 cm soil depth.

Relationship between yield and soil/leaf nutrients and removal/uptake of nutrients

Correlations were negative between yield and soil fertility parameters like SOC, P, Fe and Mn (Table 4). Leaf N, K, Zn and Cu showed significant positive relation with yield (r = 0.19–0.21). Application of stepwise regression technique to identify the nutrient variables with a significant influence on the kernel yield (Y) and total biomass (TB) resulted in significant equations in 2011. The total uptake of Ca, K and N positively influenced the total biomass production and that of Mg and Mn negatively in 2011 with high degree of variability (Eqn. 1). The total uptake of K and Ca together contributed positively to 75% variability in total biomass production. The nutrient removal of Fe, P, K and Cu positively influenced the yield with about 81% variability, while Ca and Zn showed negative impact on yield with about 16% variability in 2011 (Eqn. 2).

$$TB = 7.52 + 0.097\ Ca + 0.06\ K - 0.23\ Mg + 0.006\ Cu - 0.001\ Mn + 0.02\ N\left(R^2 = 0.915\right) \quad (Eqn - 1)$$

$$Y = -0.42 + 0.0005\ Fe + 0.09\ P + 0.016\ K + 0.003\ Cu - 0.001\ Zn - 0.013 Ca\left(R^2 = 0.795\right) \quad (Eqn - 2)$$

Discussion

Several climatic, crop and soil constraints affect the productivity of perennial arecanut ecosystem. Balanced nutrition is indispensable to counteract these constraints. There was growing interest in organic farming by smallholder arecanut farmers and the adoption rate has increased tremendously. At the same time disorders are increasingly noticed in farmer's plantations with excess soil fertility. It was anticipated that vermicompost produced from recyclable arecanut wastes would improve the nutrient use efficiency in arecanut. Cassman et al. (2002) stated that achieving synchrony between inorganic and organic nutrient supply and crop demand is the key for optimizing trade-offs between yield, profit and environmental protection. Thus, comprehensive assessment of organic and inorganic nutrition on soil-plant nutrient balance and yield of arecanut was attempted. Nutrient uptake pattern in arecanut, and optimum nutrient norms for laterite soils and arecanut (Bhat et al., 2012; Bhat and Sujatha, 2012, 2013) are considered for interpreting the results in the following discussion.

This long-term study highlighted the importance of optimal supply of major nutrients especially N and K for higher biomass production, nutrient uptake and yields (Figure 1 and Tables 2–5). Besides, combined effect of crop, soil and climatic constraints had impact on yield levels with different sources and doses of nutrients. Inorganic fertilizers at 100% and 200% registered higher yield increase of 64–82% followed by vermicompost 100% and 200% (41–54%) and integrated treatments (40–52%) than no nutrition (Table 3). Yields in organic nutrition were around 85% of the yields obtained in the inorganic source. Yield increase to the tune of 12% with vermicompost in 2010 and 2011 over 8-year average can be attributed to changes in rainfall pattern with well-distributed rainfall and less number of high intensity rainfall events resulting in reduced nutrient losses and fruit rot incidence. But discontinuation of nutrient application either through vermicompost or inorganic NPK reduced the yield levels

Table 4. Pearson correlation coefficients for yield and soil fertility variables at two soil depths.

	Yield	SOC	pH	P	K	Ca	Mg	Cu	Zn	Fe
	0–30 cm									
SOC	−0.19*									
pH	−0.12	0.36**								
P	−0.37**	0.54**	0.20*							
K	−0.04	−0.36**	−0.30**	0.00						
Ca	0.03	0.68**	0.56**	0.23*	−0.60**					
Mg	0.10	0.46**	0.59**	0.00	−0.54**	0.91**				
Cu	0.04	0.48**	0.09	0.08	−0.28*	0.57**	0.52**			
Zn	−0.12	0.38**	0.15	0.43**	−0.16	0.39**	0.23*	0.13		
Fe	−0.21*	0.41**	−0.05	0.12	−0.16	0.17	0.07	0.60**	0.08	
Mn	−0.29**	0.11	−0.04	−0.17	−0.12	0.07	0.08	0.36**	−0.17	0.77**
	30–60 cm									
SOC	0.11									
pH	−0.20*	−0.02								
P	0.19*	0.62**	−0.11							
K	0.06	−0.21*	−0.52**	−0.10						
Ca	−0.09	0.40**	0.18	0.52**	−0.14					
Mg	−0.15	0.35**	0.10	0.56**	−0.14	0.92**				
Cu	−0.04	0.51**	0.05	0.24*	−0.21*	0.20*	0.11			
Zn	0.23*	0.23*	−0.34**	0.18	0.20*	−0.28*	−0.26*	0.18		
Fe	−0.02	0.64**	−0.15	0.13	−0.13	0.04	0.06	0.68**	0.17	
Mn	−0.25*	0.24*	−0.20*	−0.12	0.03	−0.11	−0.14	0.30**	−0.15	0.58**

*Significant at the 0.05 level.
**Significant at the 0.01 level.

drastically to 650–1530 kg ha^{-1} in this trial (Personal communication). This clearly highlights the significance of nutrient application besides alternate bearing nature of the palm. The significant aspect of organic waste recycling as vermicompost is sustenance of yields and reduction in yield gap by 125% over national average of 1200 kg ha^{-1}.

Some reports indicated initial lower yields with organic approach (Liebhardt et al., 1989; MacRae et al., 1993), but previous report from this study indicated similar yields with organic, inorganic and integrated nutrition during initial 4 years of bearing (Sujatha and Bhat, 2013b). Higher biomass partitioning to trunk or leaf or both and lesser partitioning to kernel resulted in lower yields with integrated and higher doses of nutrition (Figure 1 and Table 3). During pre and initial bearing stage, the nutrients supplied by vermicompost are sufficient for sustenance of yields. After stabilized bearing stage i.e., after 8 years, nutrient supply of N and K is not tune with the crop demand as nutrient requirement especially for K increases. Arecanut requires higher N and K in same proportion (Bhat and Sujatha, 2012). But, the proportion of N and K supply by vermicompost and higher doses of nutrients is not similar creating K deficit. Besides, nutrient use efficiency might have reduced due to increase in high rainfall events up to December during 2000–2009 and application of vermicompost in single split and 2/3rd dose of NPK in September-October. Low CEC of 11.4 cmol$_c$ kg^{-1}, presence of kaolinite and absence of K fixation sites might have enhanced the process of K leaching. In general, soils with kaolinite minerals contain less available and exchangeable K (Martin and Sparks, 1985). Higher yields of arecanut and maintenance of optimum soil K with drip fertigation (Bhat et al., 2007; Bhat and Sujatha, 2009) and better response to fertigation of vermicompost extract (Sujatha and Bhat, 2013a) highlight the constraints in laterite soils.

The differential yield response to different sources of nutrition can also be explained by biomass partitioning, leaf nutrient status, nutrient uptake pattern and soil fertility (Figures 1–4 and Tables 2–4). Multivariate analysis indicated the importance of nutrient uptake on yield and explains the reasons for variations in yield levels. Similar opinion was expressed by Janssen and Willigen (2006a, 2006b). The uptake of major nutrients positively influences the total biomass and yield of arecanut under optimum management (Bhat et al., 2012). In this study also, positive influence of P and K removal with explained variability of 33% (Eqn. 2) and positive correlations of leaf N/K on yield was discernible.

The results of contrast analysis also indicate the similar impact (Table 2). The nutrient removal (leaf + nut + husk) of K and Ca was 40% of the total uptake, while removal of other nutrients accounted for 60–90%. Positive influence of total uptake of Ca and K with 75% variability on total biomass and positive impact of K on yield highlight the importance of these nutrients in arecanut nutrition. The negative influence of Ca removal on yield can be explained by above optimum range of Ca in leaf (Figure 2). These results imply that large parts of K and Ca are immobilized in trunk and K partitioning to other parts is important for higher yields. The removal of nutrients in a balanced manner as in inorganic nutrition is important for higher yields compared to large fluctuations noticed with vermicompost and vermicompost +NPK (Figure 3). Biomass partitioning and nutrient uptake pattern are important criteria for optimum fertilization program in perennial arecanut. Alva et al. (2003) and Hartemink (2005) expressed similar opinion.

Significant reduction in leaf N and K concentrations with vermicompost application over NPK can be attributed to the following factors. Arecanut is a heavy feeder of K and vermicompost contains high total N and low total K. Nitrogen is also supplied by many other sources like atmospheric N, irrigation water and rainfall interception. Application of vermicompost based on N demand supplies only 35–71 g of K (Table 1) against the recommended level of 117 g K per palm per year. Both leaf K and soil test K was grossly below optimum in vermicompost applied treatments (Figures 2 and 4). Low K has reduced leaf N also to below optimum due to reduced nitrogen use efficiency. Similar opinion was expressed by several workers (Blevins, 1985; Andrist-Rangel et al., 2007; Bhat and Sujatha, 2007; Li et al., 2009). These results indicate that the yield levels in vermicompost can be sustained and improved in this perennial palm by supplementing K on a long-term basis.

Increases in soil organic matter under organic management are widely reported (Liebig and Doran, 1999; Stockdale et al., 2001; Pulleman et al., 2003). The significant aspects of vermicompost application for long term are enrichment in SOC, increased availability of P, Ca and Mg (Figure 3) and soil pH increase (Sujatha and Bhat, 2012). This gives scope for considerable saving in input and application cost by way of skipping or reducing the quantity of vermicompost after 10 years of continuous application. But the correlation (r) between SOC and yield was negative for VC (0.34) and positive for CF (0.67) and vermicompost + NPK (0.35). Contrast analysis showed organic, inorganic and integrated nutrition had significant impact on yield but not on SOC. It clearly indicates that inorganic NPK can maintain SOC level at par with vermicompost due to higher root production and insitu root decay. Previous reports (Vogt, 1991; Bhat and Sujatha, 2009) substantiate the above findings.

Exhaustion of soil K is noticed with vermicompost application (Figure 4). Strong positive correlations among SOC, Ca and Mg, and negative correlation between SOC and K (Table 3) clearly describe the indirect influence of SOC on soil K availability. Further, competition from other nutrients with soil K can be explained from the strong positive correlations among SOC, P and micronutrients (Table 3). Evidence exists for more competitive nature of trivalent and divalent cations in binding with SOM than monovalent cations (Stevenson, 1982) and the inability of K^+ and other monovalent cations to replace sorbed micronutrients (Stevenson, 1982; Hue et al., 1986). Thus, the low K in soil and leaf might be due to high Ca and Mg concentrations (Figures 2 and 4) since these conditions are known to suppress soil K availability and plant uptake (Marschner, 1995; Brady and Weil, 1999). The potassium concentration in soil solution influences the rate and extent of K uptake by plants (Pal et al., 1999). This one negative point of organic waste recycling as vermicompost can be easily corrected by K supplementation through alternate sources. Organic K sources are rare and not easily available. If organic farming is the preference, further studies are required on organic nutrition with the use of locally available gliricidia (2.3% K) and arecanut husk (1% K) as potential K sources.

The general implications of this study are as follows. On an average 2.2 m tonnes of vermicompost can be obtained by recycling 2.3–3.3 m tonnes of waste biomass as 80% recovery of vermicompost is expected. All the wastes when recycled as vermicompost with average nutrient composition of 2% N: 0.4% P: 0.9% K can supply substantial quantity of nutrients amounting to 4400 t of N, 880 t of P and 1980 t of K. Thus, vermicompost has potential to reduce the dependence on imported N and P fertilizers and to some extent K fertilizers. Recycling of arecanut wastes as vermicompost is beneficial to all farmers and environment. Inclusion of production cost for vermicomposting and 15% lower yields have reduced the net benefit due to vermicompost application (Table 2). If farmers attempt vermicomposting in situ, the net benefit from organic waste recycling would increase considerably. In the likely scenario of steep increase in fertilizer prices, vermicompost becomes a viable alternative to inorganic fertilizers.

Conclusions

It can be concluded from this long-term study that sources of nutrients influence the yield of perennial arecanut grown on a laterite soil. The response of arecanut to inorganic sources was more pronounced due to optimum K supply compared to vermicompost alone and integrated treatments. The yield levels can be sustained at around 2700 kg ha^{-1} due to organic waste recycling. Soil fertility changes and yield trends clearly indicate the need for discontinuation of blanket application of nutrients after 10 years. Recycling of organic wastes can meet the N and P demand of arecanut. Application of K through alternat sources should be explored to improve the efficiency of vermicompost. This study gives scope for nutrient recommendations based on yield and biomass production.

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