Nutrient management systems in turmeric: Effects on soil quality, rhizome yield and quality

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Nutrient management systems in turmeric: Effects on soil quality, rhizome yield and quality

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ABSTRACT

Turmeric (*Curcuma longa* L.) is grown in several countries and is commonly used as medicine, condiment, dye and cosmetic. A systematic study on the effects of nutrient management systems on turmeric yield & quality (curcumin content, oleoresin content, and oil content), nutrient uptake and relevant soil quality parameters is lacking. Hence, field experiments were conducted for three years from 2010 to 13 involving three nutrient management regimes viz., organic nutrient management (ONM) involving application or organic manures (Farmyard manure + neem cake + vermicompost + ash + *Azospirillum lipoferum* + *Pseudomonas fluorescens*), conventional nutrient management (CNM) involving application of inorganic fertilizers (60–50–120 kg ha^{-1} NPK applied as diammonium phosphate and muriate of potash, respectively) and integrated nutrient management (INM) involving a combination of inorganic fertilizers (50% N + full dose of P and K, i.e. 30–50–120 kg ha^{-1} NPK) and organic manure (20.0 t ha^{-1} FYM + *Bacillus megaterium* var. *Phosphaticum*).

The mean data across the three years revealed that soil pH was greatest in the ONM treatment (5.80), mineral N level in the INM treatment (197.0 ± 109.0 mg kg^{-1}) and exchangeable —K level in both INM and CNM treatments (213.0 ± 81.0 and 209.0 ± 82.0 mg kg^{-1}, respectively). Similarly, exchangeable —Ca level was significantly higher in the ONM treatment (749 ± 122 mg kg^{-1}) followed by the INM treatment (552 ± 128 mg kg^{-1}), while the CNM treatment registered a 53.0–65.0% lower exchangeable —Ca level. Conversely, large accumulation of Bray P was evident (80.0 ± 57.5 mg kg^{-1}) in the CNM treatment and the mean level was greater by 36.9% compared to INM treatment and by 236.0% compared to ONM treatment. Application of organic manures enhanced soil organic C (SOC) levels and the greatest level was observed in the ONM treatment (mean 17.4 ± 0.24 g kg^{-1}), followed by the INM treatment (mean 16.6 ± 0.18 g kg^{-1}) and lowest in the CNM treatment (mean 15.1 ± 0.17 g kg^{-1}). Lower SOC level in the CNM treatment resulted in decreased soil microbial biomass C (C_{MIC}), acid phosphatase, β-glucosidase and dehydrogenase activities. The turmeric rhizome yield was consistently higher in the INM treatment (mean 22.5 ± 10.2 Mg ha^{-1}) during the three years followed by CNM (mean 20.0 ± 10.4 Mg ha^{-1}) and lastly by the ONM treatment (mean 17.8 ± 9.2 Mg ha^{-1}). Similarly, most of the nutrient elements (N, P, K, Mg, Zn) registered significantly higher uptake in the INM treatment followed by CNM and then by ONM. However, the quality of turmeric measured in terms of oleoresin, curcumin, volatile oil and its constituents like α-phellandrene, pinene, AR Turmeron + β Turmeron and α-Turmeron did not show any significant variations among the nutrient management systems. Principal component analysis indicated the degree of interdependence of various factors. Overall, the study indicated the distinct possibility of reducing chemical N fertilizer by 50% when applied in combination with organic manure for enhanced soil quality, rhizome yield and nutrient uptake in turmeric.

1. Introduction

Turmeric (*Curcuma longa* L.; Family: Zingiberaceae) is rhizomatous plant cultivated in many warm regions of the world encompassing the Caribbean Islands, China, Japan, India, Korea, Pakistan, Philippines, Malaysia, Myanmar, Sri Lanka, Thailand Vietnam, and Central America. Among these, India dominates the

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world turmeric market with 80% of the production and more than 60% share in trade (http://turmericworld.com/production.php; accessed on 02/02/16).

While the rhizomes contain carbohydrates (69.4%), fat (5.1%), protein (6.3%) and minerals (3.5%), volatile oil (5.0–6.0%) and oleoresin (7.9–10.4%), the yellow colour is due to curcumin or diferuloylmethane (2.5–6.0%) consisting of curcumin I or curcumin (94%), curcumin II or demethoxycurcumin (6%) and curcumin III or bisdemethoxycurcumin (0.3%; Chempakam and Parthasarathy, 2008). Besides being anti-malarial, anti-inflammatory and anti-tumor forming, it is also known for its antimutagenic, anticarcinogenic, antioxidant and chemotherapeutic properties (Prasad et al., 2014).

Turmeric is grown in varying soil types and requires good supply of nutrients and organic matter for sustained yield. Hence, the fertilizer requirement (inorganic or organic) required to produce a successful crop varies with variety, soil, and weather conditions. After rhizome sprouting, the crop undergoes phases of moderate growth, active growth, slow growth, and a phase-approaching senescence (Sivaraman, 2007). Nevertheless, the maximum uptake of nutrients occurs during the active growth phase (fourth and fifth month), suggesting that early application of nutrients especially N, P, and K to the crop is imperative (Sivaraman, 2007).

Exogenous application of nutrients to turmeric usually involves either exclusive application of chemical fertilizers (conventional method) or organic manures (organic method) or a combination of organic manures and chemical fertilizers (integrated method). Nonetheless, the gap between potential yield and realized yield in a location can be markedly reduced with an appropriate nutrient management technique. Besides, enhanced rhizome yield, a suitable nutrient management technique can enhance rhizome quality and can also reduce the deleterious impact of fertilization by eliminating nutrient overuse. Studies on the impact of organic manures (Sanwal et al., 2007), organic manures and biofertilizers in combination with different rates of NPK fertilizers (Kamble et al., 2009; Roy and Hore, 2009), and chemical NPK fertilizers alone in different combinations (Akamine et al., 2007) on turmeric have been reported. However, studies dealing with the effects on varying nutrient management techniques (organic, chemical or conventional and integrated) on turmeric yield and quality, besides their effects on physico-chemical and biochemical parameters influencing soil quality are lacking. Therefore, a field experiment was initiated in 2010 and repeated every year till 2013 with the prime objective of determining the influence of nutrient management techniques (organic, conventional and integrated) on turmeric rhizome yield. The secondary objective was to determine the effects of these nutrient management regimes on quality of turmeric rhizome measured in terms of curcumin content, oleoresin content, and volatile oil content. We also measured the levels of various soil physico-chemical parameters (pH, organic carbon, Bray-P, exchangeable —K, —Ca, —Mg, available Zn, Cu, Fe & Mn) including sensitive parameters like microbial biomass C and activities of hydrolytic enzymes involved in N cycle (urease), P cycle (acid phosphatase), C cycle (β-glucosidase) including the activity of dehydrogenase, which reflects overall soil microbial activity. The uptake of nutrients by turmeric in response to these nutrient management regimes was also studied. Principal component analysis was done to ascertain the degree of relationship among the array of parameters measured.

2. Materials and methods

2.1. Site details

The field experiment was conducted in the experimental farm (11°35′0″N 75°49′0″E) of the ICAR-Indian Institute of Spices Research, Kozhikode, Kerala, India. The tropical monsoon climate provides rainfall (mean 4374.0 mm) for seven months from May to December, though the temperature does not go below 18 °C even in the coolest months. The relative humidity ranges from 75.0–90.0% and the dry season lasts from December to April, which is characterized by persistent high temperatures (Max- 35 °C). The soil of the study site is a clay loam Ustic Humitropept with pH-5.18; electrical conductivity—0.13 dS m^{-1}, organic C- 13.9 g kg^{-1}; mineral N- 125 mg kg^{-1}; Bray P- 11.6 mg kg^{-1}, exchangeable K- 176 mg kg^{-1}, bulk density- 1.48 Mg m^{-3}, particle density- 2.6 Mg m^{-3} and water holding capacity- 0.74 mm cm^{-1}.

2.2. Experiment details

The field experiment was initiated in May 2010 and was repeated every year till 2013. The treatments from 2010 through 2013 were similar. The field experiments each year were not repeated in the same site but was taken up in new sites within the experimental farm; the nutrient exhaustive nature of turmeric and lowered yield due to heavy incidence of soil borne diseases when repeated in the same site being the obvious reasons.

2.2.1. Land preparation

Turmeric is generally grown on raised beds under rainfed conditions. Beds were made by clearing the land of weeds, fine tilling the soil with a tractor mounted disk harrow and levelling. The soil being inherently acidic, lime ($CaCO_3$) was applied @ 500 kg ha^{-1} and mixed uniformly with the soil before levelling. Subsequently, raised beds of size 3 × 1 × 0.30 m (l × b × h) were made using a garden spade. The spacing between the beds was maintained at of 40 cm. Small shallow pits with a spacing of 30 × 20 cm were made on the beds and seed-rhizome (20–30 g) of turmeric (variety: IISR-Prathiba) with at least two sprouted eyebuds was placed 3.5–5.0 cm deep in these pits. The pits with rhizome were then covered with soil.

Immediately after planting, green leaf mulch (leaves of *Gliricidia sepium* (Jacq.) Kunth ex Walp.) @ 15 t ha^{-1} was done to all the beds, irrespective of the nutrient management regime. This is normally done to protect the raised beds from heavy showers, thereby preventing soil erosion and exposure of planted rhizomes. Mulching with green leaves was repeated @ 7.5 t ha^{-1} at 45 and 90 DAP after weeding, application of fertilizers and earthing up.

2.2.2. Nutrient management regimes

For the study, three nutrient management regimes were. Details are as follows:

(i) Organic nutrient management (ONM): FYM (30.0 t ha^{-1}) + neem cake (2.0 t ha^{-1}) + ash (1.0 t ha^{-1}) + vermicompost (4.0 t ha^{-1}) + rhizome treatment with biofertilizers [*Pseudomonas fluorescens* @10^8 CFU and *Azospirillum lipoferum* @ 10^8 Colony forming units (CFU)].
(ii) Conventional nutrient management (CNM): 60–50–120 kg ha^{-1} NPK applied as diammonium phosphate and muriate of potash, respectively, applied in two splits (45th and 90th DAP). Any deficit in N applied due to use of diammonium phosphate was balanced through urea.
(iii) Integrated nutrient management (INM): FYM (20.0 t ha^{-1}) + 50% inorganic N + full dose of inorganic P and K (i.e. 30–50–120 kg ha^{-1} NPK applied exactly as in CNM) + P solubilising bacteria (*Bacillus megaterium* var. *phosphaticum* @10^8 CFU g^{-1} soil).

Table 1 provides the nutrient composition of the organic manures used in the study. Regular weeding, other intercultural operations and plant protection measures were followed in all the treatments. The crop was harvested at 240 DAP. The treatments were imposed in quadruplicate laid out in randomized block design.

Table 1
Relevant characteristics of the organic manures used in the study.

	OC ($g\,kg^{-1}$)	N	P	K	Ca	Mg	S	Fe	Mn	Zn
Farmyard manure	90.5	6.0	2.0	4.0	13.0	3.9	1.2	5.73	0.518	0.040
Neem cake	270.7	18.0	2.4	17.0	5.0	2.2	1.0	3.05	0.227	0.017
Vermicompost	94.0	10.0	3.0	3.0	33.0	11.0	0.8	3.86	0.268	0.427
Ash	ND[a]	2.0	54.0	121.0	68.0	18.0	1.0	7.0	0.749	0.144

[a] ND—Not determined.

2.3. Soil properties

2.3.1. Soil sampling

Soil samples (four per bed) were taken at 120 DAP (i.e. one month after application of 2nd split of diammonium phosphate) and after clearing the litter layer. Any organic debris in the sample was removed and a composite sample was made by bulking the four samples. In the laboratory, after determination of moisture content, the biochemical parameters were estimated in subsamples sieved to pass a 2.0 mm while the physico-chemical properties were determined in subsamples sieved to pass a 0.5 mm mesh.

2.3.2. Soil nutrient status

Soil mineral N was estimated by steam distillation (Mulvaney, 1996), soil organic C (SOC) by the Walkley–Black method (Nelson and Sommers, 1982) and Bray P using the dilute acid–fluoride extractant (Kuo, 1996). Exchangeable —K, —Ca & —Mg in the NH_4OAc extract (Helmke and Sparks, 1996) and available Zn, Cu, Fe & Mn in the DTPA extract (Lindsay and Norvell, 1978) were estimated using an atomic absorption spectrophotometer (Varian AA 240FS).

2.3.3. Soil biochemical properties

Microbial biomass-C (C_{MIC}) in the soil was estimated using the fumigation–extraction method (Vance et al., 1987) using k_{EC} of 0.45 (Wu et al., 1990). Dehydrogenase (DH) activity was estimated using 2,3,5-triphenyltetrazolium chloride (TTC) as the substrate (Casida et al., 1964) and urease (UR) activity using urea as the substrate (Kandeler and Gerber, 1988). Acid phosphatase (AcP) activity was estimated using *p*-nitrophenyl phosphate as the substrate (Tabatabai and Bremner, 1969), while β-glucosidase (BG) activity was estimated using *p*-nitrophenyl-β-D-glucopyranoside as the substrate (Eivazi and Tabatabai, 1998).

2.4. Plant nutrient concentration

The plant samples collected during harvest were oven-dried at 60 °C and ground in a Wiley mill to pass a 0.5 mm sieve. The ground samples were digested with triacid mixture (HNO_3: H_2SO_4: $HClO_3$ in the ratio of 9:2:1) with exception of total N for which di-acid mixture (H_2SO_4: $HClO_3$ in the ratio of 5:2) was used. Total N was determined by the micro-Kjeldahl procedure (Jackson, 1973), while total P was by the vanadomolybdate method (Jackson, 1973) using a spectrophotometer. The other nutrients (K, Ca, Mg, Fe, Cu, Zn and Mn) were determined in the extract using atomic absorption spectrophotometer (Varian AA 240FS).

2.5. Rhizome quality parameters

The harvested rhizomes were washed thoroughly to remove the adhering soil and cooked in boiling water for one hour and sun dried to 8.0% moisture content. The dried rhizomes were then powdered using a mixer grinder to uniform mesh (0.5 mm). Curcumin content (sum of curcumin I–III) in the rhizome powder was extracted using EtOH and absorbance measured at 425 nm using a spectrophotometer (ASTA, 1997a), oleoresin was determined by cold percolation with acetone and computed gravimetrically (AOAC, 1975) and the volatile oil extraction was performed by the modified Clevenger method (ASTA, 1997b). After extraction, the volatile oil was analyzed for its various constituents like α- phellandrene, pinene, AR Turmeron + β Turmeron and α-Turmeron using a Shimadzu- GC2010 gas chromatograph equipped with QP 2010 mass spectrometer and RTX-Wax column (30 m x 0.25 mm; film thickness 0.25 μm). The carrier gas was helium with a flow rate of 1.0 $mL\,min^{-1}$. The injection port was maintained at 240 °C and the detector temperature at 220 °C. The oven temperature was initially set at 60 °C for 5 min and then increased up to110 °C at the rate of 5 °C min^{-1}, then increased at the rate of 3 °C min^{-1} until 200 °C, then up to 220 °C at the rate of 5 °C min^{-1} and held there for 5 min. The split ratio was adjusted to 1:40. The constituents of the oil were then identified by comparison of retention indices with those reported in the literature and by matching the mass spectral data with those stored in NIST and WILEY library

2.6. Statistics

Each data point pertaining to soil parameters are expressed on an oven-dried basis (105 °C). One-way ANOVA was employed to determine the significance among treatments followed by post hoc comparison of means using the least significance difference (LSD) test. The intrinsic relationships between various parameters were determined by Principal component analysis (PCA). For clarity during interpretation of uncorrelated components, Varimax rotation was employed during PCA (Flury and Riedwyl, 1988).

3. Results and discussion

3.1. Soil properties

3.1.1. Soil pH

Mean soil pH varied from 4.7–5.8 (Table 2). It tended to increase in treatments with organic manures (5.8 and 5.3 in the ONM and INM treatments, respectively), but decreased to 4.7 in CNM treatment. Interestingly, the decrease in the CNM treatment was even lower than the mean initial soil pH of 5.18 registered at the experimental site. This decrease can be attributed to release of H^+ ions consequent to nitrification of ammonium fertilizer and subsequent leaching of NO_3 (Czarnecki and Düring, 2015; Liang et al., 2012). Conversely, moderation from bicarbonates (Whalen et al., 2000) released during decomposition of the manure and a direct liming effect (Benke et al., 2010; Naramabuye et al., 2008) increased pH in treatments with organic manures (ONM and INM). During the process of decomposition, organic manures continuously supply bases, form alkaline humates, decrease exchangeable-soil Al by precipitation and form organic colloid-Al complex thereby enhancing soil pH (Hue and Amien, 1989; Hue et al., 1986).

3.1.2. Mineral N, available P and exchangeable —K

Mean mineral N level was almost identical in ONM and CNM treatments, but was higher by 8.24% in the INM treatment (Table 2). This possibly indicated lower reactive N loss due to lower input of chemical fertilizer in combination with organic manures (Wu

Table 2
Effect of nutrient management regimes on relevant physico-chemical properties (mean ± SD) of soils under turmeric at 120 days after planting.

Treatments	pH (1:2.5 H_2O)	Organic C ($g\,kg^{-1}$)	Mineral N ($mg\,kg^{-1}$)	Bray P	Exchangeable K
ONM	5.8 ± 0.2	17.4 ± 0.24	182 ± 84	23.8 ± 5.9	158 ± 51
CNM	4.7 ± 0.7	15.1 ± 0.17	183 ± 106	80.0 ± 57.5	209 ± 82
INM	5.3 ± 0.6	16.6 ± 0.18	197 ± 109	58.4 ± 56.9	213 ± 81
LSD	**	**	*	**	*

Mean of three years (2010–2013).
ONM—Organic nutrient management.
CNM—Conventional nutrient management.
INM—Integrated nutrient management.
SD—Standard deviation.
LSD—Least significant difference.

and Ma, 2015) in the INM treatment. With regard to exchangeable K, there was little difference between CNM and INM treatments, though the level was comparatively lower by 24.0–25.0% in the ONM treatment. Nonetheless, marked differences existed in Bray P levels among the treatments (Table 2), with CNM treatment registering the greatest P accumulation among the three treatments. In fact, Bray P level in CNM treatment was greater by 36.9% compared to INM treatment and by a whopping 236.0% compared to ONM treatment. The results indicated enhanced labile P accumulation due to chemical fertilization (in both CNM and INM treatments) even though the soil in the experimental site is reported to possess high P fixation capacity due to inherent acidity (Srinivasan et al., 2000). Such high labile P accumulation due to chemical fertilization further underlines the importance of reducing exogenous inorganic P application to prevent P runoff, leaching, and subsequent surface and groundwater pollution (Wang et al., 2012).

3.1.3. Exchangeable —Ca, —Mg and available —Zn, —Cu, —Fe & —Mn

Though there were little variations in the levels of exchangeable —Mg, available -Zn, -Cu, -Fe and -Mn, there was, however, a marked and significant variation ($P < 0.01$) among the treatments with respect to exchangeable —Ca (Table 3). In the ONM treatment it was greater by 37.0% compared to the INM treatment and by a very high 189.0% compared to the CNM treatment. Apparently, organic manure application enhanced exchangeable —Ca levels in the treatments involving organic manures (ONM and INM) and this in part explains the increased pH registered in soils under these treatments.

3.1.4. Soil organic carbon

Soil organic C (SOC) is a vital and sensitive parameter governing soil quality, and in this study, SOC accumulation was significantly higher ($P < 0.05$) in the ONM treatment (Table 2). This is not surprising since the treatment involved application of a mixture of organic manures like FYM, VC, neem cake etc. Relative to ONM treatment, the mean SOC in the INM treatment was slightly lower by 4.60%, while it was lower by 13.20% in CNM treatment. In the CNM treatment, exclusive chemical fertilization induced a 'positive priming effect' (Hamer et al., 2009; Russell et al., 2005; Zhang et al., 2015a) which decreased SOC accumulation, more so because no organic residues were added to the soil. This is consistent with Brown et al. (2014), who found that increased N fertilizer application had little effect on SOC, though studies have shown that mineral fertilizer could increase crop residue inputs to the soil thereby increasing SOC reserves, or reduce SOC accumulation by increasing C mineralization (Russell et al., 2005; Zhang et al., 2015c). Nevertheless, SOC levels in all the three treatments were markedly higher than the level of 13.9 $g\,kg^{-1}$ soil registered during the start of the experiment and mean levels (Table 2) suggested increments to the tune of 1.2 $g\,kg^{-1}$ soil in the CNM treatment, 2.7 $g\,kg^{-1}$ soil in the INM treatment and 3.5 $g\,kg^{-1}$ soil in the ONM treatment. This connoted that SOC level increased in all treatments, though the increase was significant ($P < 0.05$) in the ONM and INM treatments alone. These results comply with earlier observations by Zhang et al. (2015b) in a short-term experiment and Giacometti et al. (2014), and Zhang et al. (2015c) in long-term field experiments.

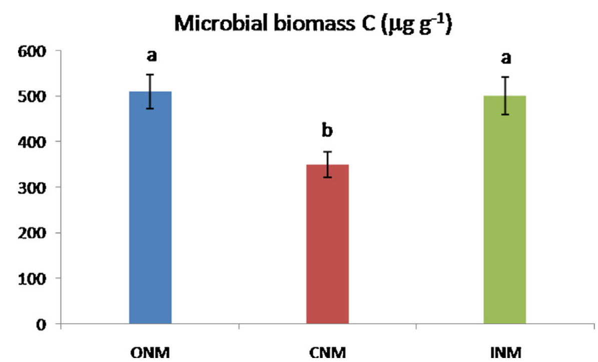

Fig. 1. Effects of nutrient management regimes (organic nutrient management—ONM; conventional nutrient management—CNM; integrated nutrient management—INM) on soil microbial biomass C [Mean of three years; Bars indicate standard deviation; different letters indicate significant differences at $P < 0.05$ (LSD)].

3.2. Soil biochemical parameters

We also measured the levels of important soil biochemical parameters which are considered as sensitive indicators of soil quality in the short- and long-term (Gil-Sotres et al., 2005; Truu et al., 2008; Dinesh and Ghoshal Chaudhuri, 2013). The biochemical parameters included variables directly related to microbial activity (C_{MIC}), and the activities of extracellular hydrolytic enzymes involved in C (ß-glucosidase), N (urease) and P (acid phosphatase) cycles in soil. Besides, the activity of dehydrogenase, an important oxidoreductase enzyme commonly used as an indicator of general soil microbial activity (Quilchano and Marañon, 2002; Gu et al., 2009; Salazar et al., 2011) was also measured.

3.2.1. Microbial biomass carbon

C_{MIC} levels were significantly ($P < 0.05$) higher in ONM and INM treatments compared to the CNM treatment (Fig. 1.). Apparently, in the CNM treatment, C_{MIC} level was lower by 31.0% and 30.0%, respectively compared to ONM and INM treatments. This decrease conforms to an earlier report that indicated that C_{MIC} decreased by an average of 40.0–59.0% due to inorganic N addition (Wallenstein et al., 2006). Besides, ecosystem studies dealing with *meta*-analysis of microbial biomass data revealed that C_{MIC} was lower by an average of 15% in systems relying on inorganic N fertilization (Treseder, 2008). Similarly, Liu and Greaver (2010) observed a 20%

Table 3
Effect of nutrient management regimes on levels of secondary- and micro-nutrients (mean ± SD) in soils under turmeric at 120 days after planting.

Treatments	Exchangeable Ca	Exchangeable Mg	Available Zn	Available Cu	Available Fe	Available Mn
	($mg\ kg^{-1}$)					
ONM	749 ± 122	123 ± 24	1.37 ± 0.11	2.6 ± 1.9	34.0 ± 4.4	7.6 ± 0.8
CNM	259 ± 131	118 ± 38	1.28 ± 0.20	3.0 ± 2.1	42.0 ± 5.5	8.5 ± 1.9
INM	552 ± 128	120 ± 39	1.35 ± 0.14	2.0 ± 0.6	38.0 ± 9.3	9.1 ± 1.6
LSD	**	NS	NS	NS	NS	NS

Mean of three years (2010–2013).
ONM—Organic nutrient management.
CNM—Conventional nutrient management.
INM—Integrated nutrient management.
SD—Standard deviation.
LSD—Least significant difference.

decrease in C_{MIC} across 57 studies. The decrease is possibly because ammonium-based fertilizers at higher levels increase soil acidity and consequently affect microbial biomass due to toxicity (Zhang et al., 2015c).

However, in the INM treatment, C_{MIC} level did not decrease even though inorganic ammonium fertilizer was applied. This was apparently due to reduced level of inorganic N application (50.0%) compared to the CNM treatment. Application of organic manure in combination with relatively lower rate of inorganic N at diminished the negative effects of chemical fertilization on C_{MIC} in the INM treatment. This is in conformity with the results of Dinesh et al. (2012) who found that treatment with FYM applied in combination with reduced amount of chemical fertilizer registered 39.0% enhanced C_{MIC} compared to recommended amount of chemical fertilization in soils under ginger. It is, therefore, evident that the increase in C_{MIC} levels in ONM and INM treatments is due to increase in microbial biomass in response to enhanced availability of readily available substrates like metabolizable C and N contributed by the applied organic manures (Tejada et al., 2006; Hao et al., 2008). Organic amendments in different states of decomposition support SOC sequestration (Ghimire et al., 2014) and simultaneously contribute an array of microbial substrates (Berthrong et al., 2013) that improve soil biological properties. Therefore, Incorporation of organic manures provided unhindered supply of substrates to support the microbial biomass thus reaffirming the fact that soil microbial biomass accumulation and activity is overly dependent on substrate release and availability in soils (Dinesh et al., 2010). The existence of a strong correlation ($p < 0.01$; $n = 36$) between C_{MIC} and SOC ($r = 0.76$) observed in this study further supported the reliance of microbial biomass on C accrual in soils.

3.2.2. Enzyme activities

The nutrient management regimes significantly ($P < 0.05$) influenced the activities of all the hydrolytic enzymes measured, albeit at varying degrees (Fig. 2.). AcP activity was significantly higher in INM (42.8 μmol *p*-nitrophenol g^{-1}), UR in CNM treatment (8.8 μmol NH_3-N $g^{-1}\ h^{-1}$), BG and DH in both ONM (4.9 μmol *p*-nitrophenol g^{-1} and 193.0 nmol TPF g^{-1} soil h^{-1}, respectively) and INM (4.8 μmol *p*-nitrophenol g^{-1} and 205 nmol TPF g^{-1} soil h^{-1}, respectively) treatments. In the CNM treatment, UR activity was enhanced by 29.4% and 66.0% relative to INM and ONM, respectively, while AcP activity was lowered by 31.8% and 64.9% compared to ONM and INM treatments, respectively. Increase in UR activity in the CNM treatment is indicative of the positive influence of N fertilization (Allison et al., 2007; Dinesh et al., 2012) while decreased AcP activity is partly due to negative effects of P application (50 kg ha^{-1}) or accumulation of available P (Allison et al., 2007). This suggested that regardless of P availability, microbial biomass is critical in regulating soil phosphatases (Bowles et al., 2014). Enhanced microbial activity consequent to availability of a higher quantity of biodegradable substrates (García-Orenes et al., 2010) positively influenced DH activity in ONM and INM treatments. In fact, reports suggest that soil management systems that provide higher level of organic matter and ensure steady-state substrate availability stimulate microbial activity and therefore, enzyme synthesis (Chu et al., 2007; Dinesh et al., 2010, 2012).

Consistent with AcP and DH activities, BG activity was also markedly lower in the CNM treatment. The activity of other hydrolytic enzymes notwithstanding, BG activity has been found to reflect the entire gamut of soil metabolic functioning, and is considered to be an early and very sensitive signaller of alterations in SOC dynamics before these changes are disclosed in total or organic C analyses (Green et al., 2007; Roldan et al., 2005; Stott et al., 2009). Hence, reduced BG activity in CNM treatment is possibly due to reduced SOC level since a significant and positive relationship between BG and SOC has been evidenced in a number of studies (Böhme and Böhme, 2006; Piotrowska and Koper, 2010). Lower BG activity in CNM treatment further indicated decrease in organic matter mineralization potential and, therefore, reduced C-cycle functioning (Caravaca et al., 2002).

From the results, it is apparent that enrichment with organic materials in INM and ONM treatments, enhanced soil organic matter content and therefore enzyme activities, since the former plays a key role as a forerunner for enzyme synthesis, and physical stabilization (Tabatabai, 1994; Acosta-Martínez et al., 2007). Besides, increasing enzyme activities with increasing soil microbial biomass mirrored the soil's capacity to decompose crop residues and synthesise organic compounds, thereby enhancing nutrient cycling and turnover. Obviously, this in turn improved the availability of nutrients for the plant in ONM and INM treatments. Furthermore, greater AcP, BG and DH activities suggested better conditions for soil microbial biomass in treatments with organic manures which further underlined the importance of organic matter additions as a direct source of soil enzymes and as facilitators of protective sites for these enzymes. Consistent with our findings, numerous studies have reported activation of enzymes to varying degrees due to organic manure additions (Giacometti et al., 2014; Liang et al., 2012; Sinsabaugh et al., 2014; Zhang et al., 2015c). On the other hand, mineral fertilizers tend to attenuate the activities of hydrolytic enzymes, since activation of enzymes is not imperative when nutrients are in abundance (Zhang et al., 2015c).

3.3. Rhizome yield, nutrient uptake and rhizome quality

The INM treatment consistently registered greater rhizome yield (Table 4) during all the years, suggesting the positive influences of enhanced SOC, C_{MIC} and enzyme activities. Conversely, such positive effects were not manifested per se on rhizome yield in the ONM treatment during the three years under study. The CNM treatment performed better than ONM in 2010–11, but in 2011–12 it registered slightly lower yield than ONM. However, in 2012–13,

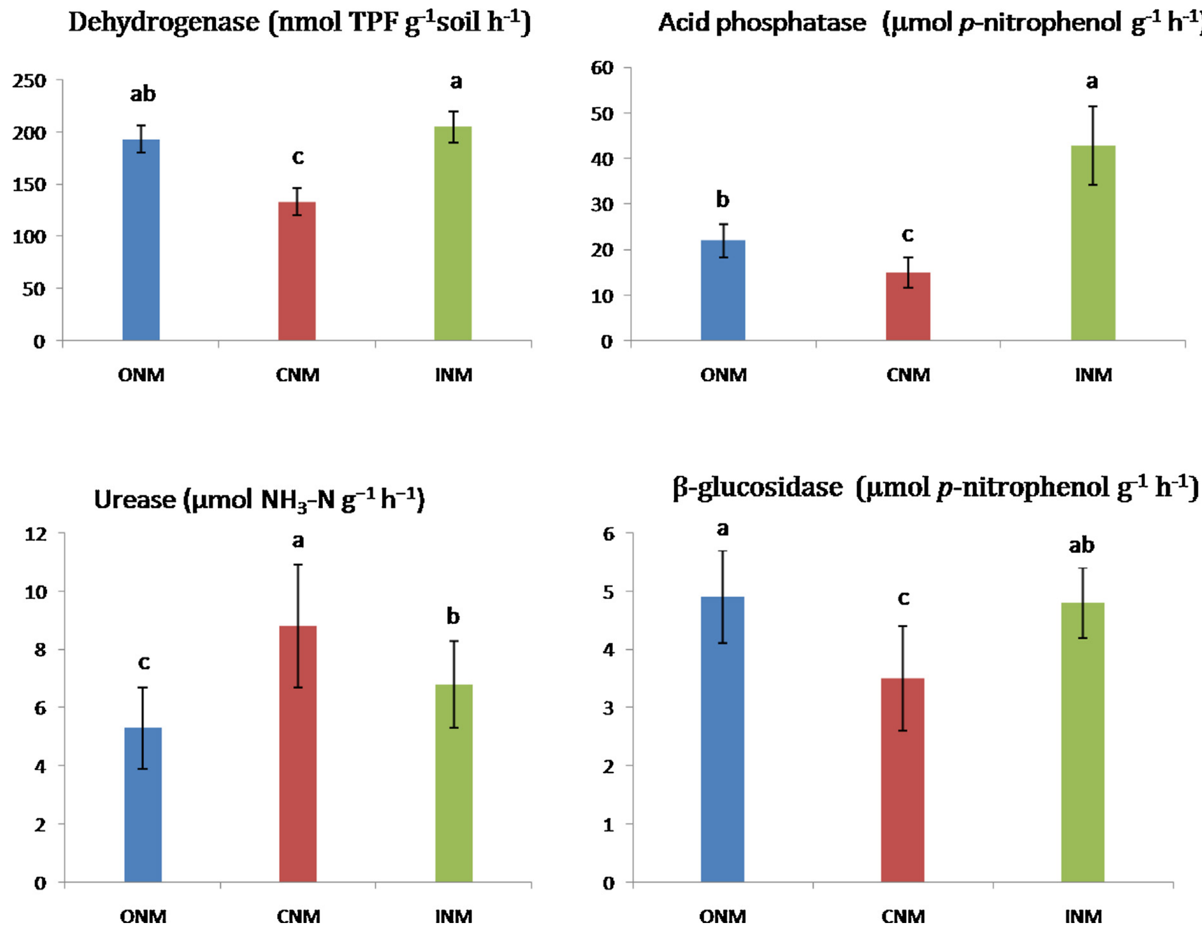

Fig. 2. Effects of nutrient management regimes (organic nutrient management—ONM; conventional nutrient management—CNM; integrated nutrient management—INM) on dehydrogenase, acid phosphatase, urease and β-glucosidase activity in soil [Mean of three years; Bars indicate standard deviation; different letters indicate significant differences at P < 0.05 (LSD)].

Table 4
Effect of nutrient management regimes on yield of turmeric from 2010 to 11 to 2012-13.

Treatments	2010–11	2011–12	2012–13	Mean ± SD
	($Mg\,ha^{-1}$)			
ONM	28.0	10.1	15.3	17.8 ± 9.2
CNM	30.0	9.2	19.8	20.0 ± 10.4
INM	33.0	12.7	21.7	22.5 ± 10.2
LSD (P < 0.05)	*	*	*	

ONM—Organic nutrient management.
CNM—Conventional nutrient management.
INM—Integrated nutrient management.
SD—Standard deviation.
LSD—Least significant difference

the CNM treatment once again superseded ONM by registering significantly (P < 0.05) higher rhizome yield.

The mean data across the three years (Fig. 3.) revealed that the ONM treatment registered relatively lower yield compared to CNM and INM treatments. In fact, compared to the ONM treatment, rhizome yield in the INM treatment was greater by 26.4%, while in the CNM treatment it was greater by 12.4%. Between CNM and INM, the latter registered 12.5% enhanced mean yield. Probably, there was better synchronization between nutrient demand by the crop and nutrient supply from the soil when organic manure and inorganic fertilizers were combined. Besides, the complementary use of chemical and organic sources increased the use efficiency of the former thereby maintaining a consistently higher level of rhizome production compared to sole application of either organic or chemical fertilizers. Under INM practices, the nutrient-use efficiency of applied chemical N fertilizer was enhanced possibly due to reduced leaching, runoff, volatilization, nitrification, emissions and immobilization (He et al., 2014; Zhang et al., 2012).

In CNM, extremely acidic pH (4.7), relatively lower SOC, mineral N, K and exchangeable Ca coupled with excessive P accumulation seem to have negatively influenced rhizome yield. All these combined with lowered microbial and enzyme activities would have hampered nutrient cycling and availability to the crop during critical growth stages. In contrast, the ONM treatment had sufficient level of SOC, exchangeable —Ca, increased pH, and greater levels of C_{MIC} and enzyme activities. Yet, the rhizome yield was lower than CNM. This is probably due to lowered mineral N supply to crops from the added organic manures. Besides inadequate synchronization of available N with crop demand, the N supplied to the crop appeared to be insufficient suggesting low recovery of N from organic amendments and the unpredictability in the timing, release pattern and quantity of N that is released to the crop (Rodrigues et al., 2006). Besides, in spite of the availability of potential indicators of manure quality, such as N content and C/N ratio (Geypens and Vandendriessche, 1996), it is difficult to comprehend the machinations underlying the mineralization–immobilization process in organic residues and, therefore, the generic failure to prevent N losses through volatilization, leaching and denitrification makes N release to crops fairly unpredictable (Rodrigues et al., 2006). In contrast, numerous reports have demonstrated strong and convincing evidence of the advantage of integrated use of organic

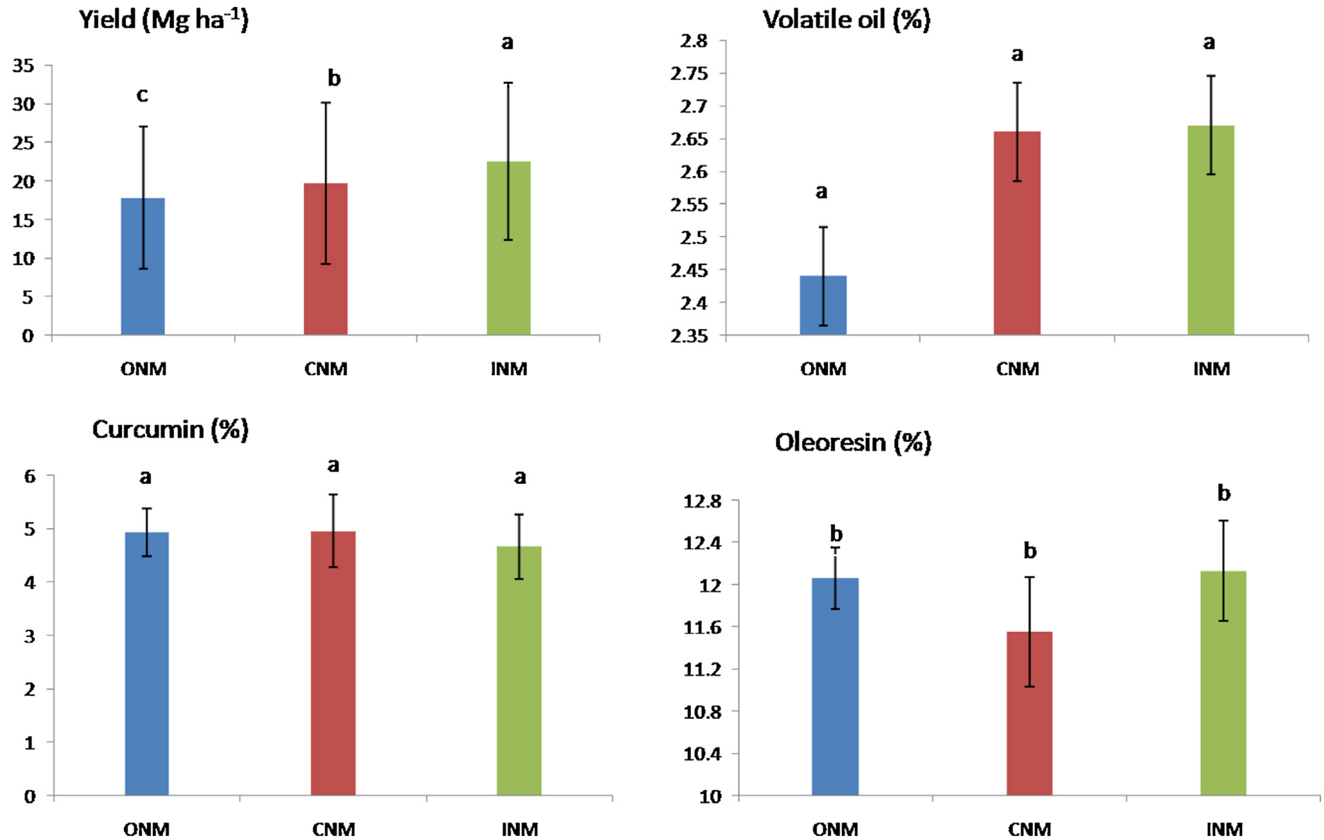

Fig. 3. Effects of nutrient management regimes (organic nutrient management—ONM; conventional nutrient management—CNM; integrated nutrient management—INM) on rhizome yield, volatile oil content, curcumin content and oleoresin content [Mean of three years; Bars indicate standard deviation; different letters indicate significant differences at $P < 0.05$ (LSD)].

Table 5
Effect of nutrient management regimes on nutrient uptake by turmeric rhizomes (mean ± SD) at harvest.

	N	P	K	Ca	Mg	Fe	Mn	Zn	Cu
	(kg ha^{-1})							(g ha^{-1})	
ONM	54.42	14.34	63.40	6.99	7.70	2.64	0.60	172.72	100.46
CNM	56.93	14.42	73.01	8.36	6.14	3.26	1.44	177.93	128.71
INM	66.69	15.79	81.53	6.60	8.28	3.23	1.23	213.39	102.29
LSD	**	NS	NS	NS	**	**	**	*	*

Mean of three years (2010–2013).
ONM—Organic nutrient management.
CNM—Conventional nutrient management.
INM—Integrated nutrient management.
SD—Standard deviation.
LSD—Least significant difference.

manures and chemical fertilizers in enhancing soil quality (Dinesh et al., 2010, 2012; Singh et al., 2014a,b) and crop yield (Das et al., 2014; Phonglosa et al., 2015; Shiva et al., 2015; Wu and Ma, 2015).

The variations among the nutrient management regimes with regard to nutrient uptake by turmeric rhizomes were identical to that observed with rhizome yield (Table 5). Most of the nutrient elements (N, P, K, Mg, Zn) registered significantly ($P < 0.01$; $P < 0.05$) higher uptake levels in the INM treatment. In the CNM treatment, the uptake of Fe was on par with INM but was significantly higher ($P < 0.01$; $P < 0.05$) for Mn and Cu. Among the three treatments, the ONM treatment registered the lowest uptake of all the nutrients. As stated earlier, greater nutrient uptake by the crop in the INM treatment indicated good synchrony between nutrient release and crop requirement during the active vegetative growth stage.

The rhizome quality was measured in terms of volatile oil content, oleoresin content and curcumin content (Fig. 3.). Across the three years, oil content varied from 1.87–3.46% (mean 2.44 ± 0.88) in ONM, 2.11–3.38% (mean 2.66 ± 0.65) in CNM and 2.17–3.53% (mean 2.67 ± 0.75) in INM. Oleoresin content varied from 11.88–12.40% (mean 12.06 ±0.29%) in ONM; 11.00–12.05% (mean 11.55 ± 0.53%) in CNM and 11.58–12.50% (mean 12.13 ± 0.48%) in INM and curcumin content varied from 4.57–5.42% (4.93 ± 0.45%) in ONM, 4.25–5.60% (mean 4.95 ± 0.68%) in CNM and 4.09–5.29% (mean 4.66 ± 0.60%) in INM. Though the rhizome quality parameters did not vary among the treatments, the measured values are within the range of 3.0–5.0% volatile oil, 7.9–10.4% oleoresin (Chempakam and Parthasarathy, 2008) and 2.0–7.0% curcumin (Ravindran et al., 2007) reported in dried and cured turmeric. Volatile oil components like α- phellandrene (range 3.56–4.05%), pinene (0.21–0.29%), AR Turmeron + β Turmeron (47.7–53.1%) and α- Turmeron (19.21–19.67%) also exhibited very little variation among the treatments. Earlier field experiments conducted by us from 2004 to 05 to 2006–07 on similar lines also revealed that these quality parameters showed little difference among the nutrient management regimes (Srinivasan et al., 2010).

3.4. *Interrelationships between soil properties, nutrient uptake and rhizome quality*

The interrelationship between the parameters in the dataset was done by PCA, which often reveals previously improbable relationships among variables and thereby concedes interpretation that would, under normal circumstances, be impossible (Johnson and Wichern, 1982). The analysis revealed that 100% of the variance was explained by two factors (Table 6). The first (PC1), which accounted for 58.5% of the total variance, was defined positively

Table 6
Loadings of soil properties, nutrient uptake, rhizome yield and quality parameters on the factors identified by principal components analysis. The parameters are grouped according to the maximum fittings to principal components.

	Principal components[a]	
	PC1	PC2
pH	0.99	n.s.[b]
OC	0.99	n.s.
Mineral N	n.s.	0.99
Bray P	−0.95	NS
Exchangeable K	n.s.	0.71
Exchangeable Ca	0.99	n.s.
Exchangeable Mg	0.95	n.s.
Available Zn	0.99	n.s.
Available Cu	n.s.	−0.82
Available Fe	n.s.	NS
Available Mn	n.s.	−0.90
Microbial biomass C	0.96	n.s.
Acid phosphatase	n.s.	0.90
Urease	−0.99	n.s.
β-glucosidase	0.97	n.s.
Dehydrogenase	0.89	n.s.
Volatile oil	NS	0.96
Oleoresin	−0.73	0.69
Curcumin	0.91	n.s.
Rhizome yield	n.s.	−0.97
N uptake	n.s.	0.99
P uptake	n.s.	0.99
K uptake	n.s.	0.94
Ca uptake	−0.85	n.s.
Mg uptake	0.83	n.s.
Zn uptake	n.s.	0.99
Cu uptake	−0.96	n.s.
Fe uptake	−0.78	0.63
Mn uptake	−0.89	n.s.
Explained variance (%)	58.5	41.5

[a] Only principal components with Eigen values >1 and those explaining >10% of the total variance were retained.
[b] n.s.—loadings lower than 0.50.

by pH, SOC, exchangeable —Ca, —Mg, available Zn, C_{MIC}, BG, DH and curcumin content, and negatively by Bray P, UR, oleoresin content and uptake of Ca, Cu, Fe and Mn. The highly positive loadings of SOC and pH in PC1 indicated that organic manure application enhanced the levels of organic substrates, pH and exchangeable —Ca, Mg and Zn levels and therefore positively influenced C_{MIC} and enzyme activities. This reflected that SOC and pH were probably the most sensitive variables affecting soil quality and further underlined the strong interdependence between microbial activity and mineralizable organic matter (Dinesh et al., 2010). The strong loading of curcumin in PC1 indicated the possible effects that soil variables especially pH can have on curcumin synthesis in the rhizomes (Srinivasan et al., 2011). The negative loading of Bray P in PC1 further indicated that high labile P accumulation would reduce nutrient uptake as evidenced by negative loadings of Ca, Cu, Fe and Mn uptake and oleoresin content. This was apparent in the CNM treatment where high P levels presumably resulted in relatively low level of oleoresin (Fig. 3; Mean 11.55%) in the rhizome.

PC2 with 41.5% of the total variation and was positively defined by mineral N, exchangeable K, AcP and uptake of N, P, K, Zn, Fe and volatile oil and oleoresin content. This indicated the positivity between soil nutrient availability and nutrient uptake and their functional role in the synthesis of volatile oil and oleoresin in turmeric. More importantly, the strong loading of mineral N and N uptake in PC2 stressed the crucial role played by N in increasing oil content as reported in aromatic plants (Sangwan et al., 2001). Soil N is the precursor for phenyl propanoid pathway involving curcumin synthesis in turmeric since it forms the structural unit of many proteins (Sandeep et al., 2015). The negative loading of rhizome yield in PC2 suggested a probable decrease in nutrient use efficiency and uptake in treatments with low pH, low exchangeable —Ca & —Mg and available Zn, especially in the CNM treatment. This corroborated with the finding that ammonium fertilizers can markedly reduce soil pH and when the soil pH drops to <5.0, it can significantly inhibit soil microbial activity and crop yields (Geisseler and Scow, 2014)

4. Conclusions

The nutrient management regimes markedly influenced soil physico-chemical properties, microbial biomass and enzyme activities to varying degrees. The conventional nutrient management (CNM) treatment registered significantly lower levels of pH, soil organic C (SOC), microbial biomass C (C_{MIC}), acid phosphatase (AcP), β-glucosidase (BG) and dehydrogenase (DH) but higher levels of Bray P and urease (UR). On the contrary, the integrated nutrient management (INM) treatment had comparatively higher levels of pH, mineral N, Bray P, exchangeable K, SOC, C_{MIC}, AcP, BG, and DH. The organic nutrient management (ONM) treatment registered the highest pH, SOC and C_{MIC} among the three nutrient management regimes and relatively higher AcP, BG and DH compared to the CNM treatment, but the lowest Bray P, mineral N and exchangeable K levels. It was apparent that addition of organic manures through INM and ONM enhanced SOC content and, therefore, C_{MIC} and enzyme activities. Such enhancements in soil C reserve and microbial activity were positively reflected in the INM treatment, which registered significantly higher rhizome yield followed by CNM and lastly by the ONM treatment. The lowest yield level in the ONM treatment can be attributed to disconnect between available N and crop demand and low N recovery by the crop from the organic sources. Contrary to rhizome yield, the quality parameters (oleoresin, curcumin, volatile oil and its constituents) exhibited very little variation among the treatments. The study suggested that nutrient management through integrated use of chemical fertilizers and organic manures would simultaneously improve turmeric yield, nutrient uptake and soil quality. Besides, a 50% cut in application of inorganic N fertilizer through INM would help in diminishing the negative impacts of high analysis chemical fertilizers on the environment.

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