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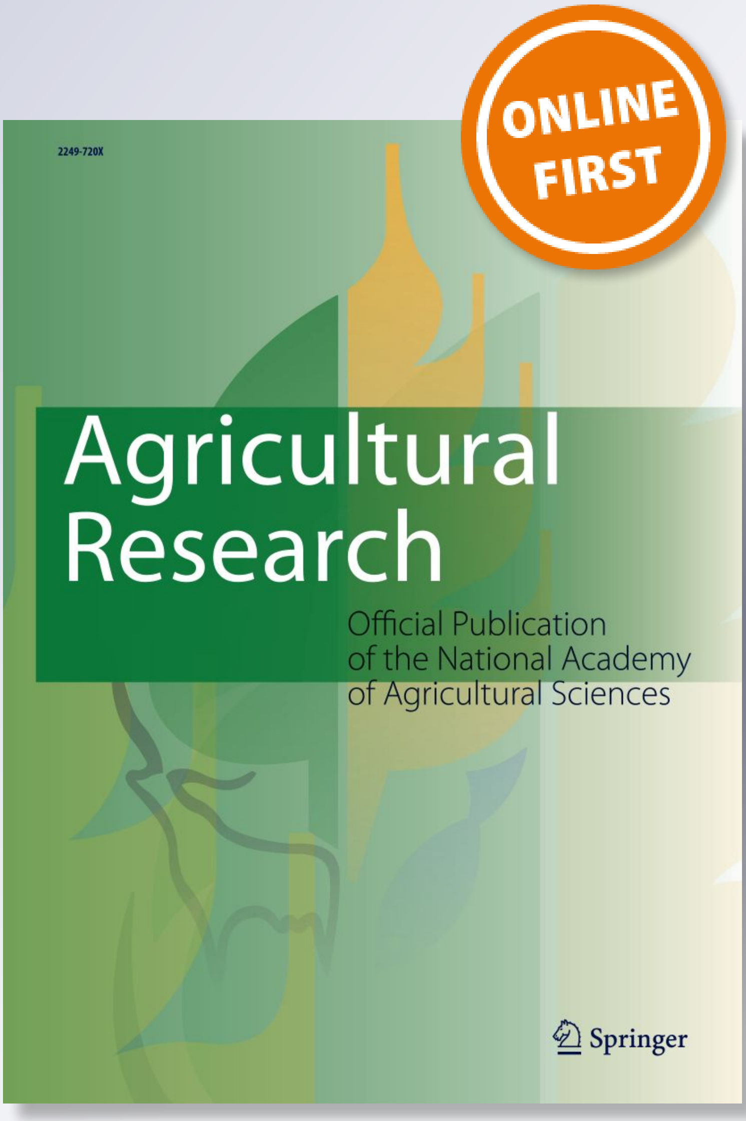

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FULL-LENGTH RESEARCH ARTICLE

Variations in Soil Properties, Rhizome Yield and Quality as Influenced by Different Nutrient Management Schedules in Rainfed Ginger

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Abstract While there are numerous reports on nutrient management in ginger (*Zingiber officinale* Roscoe), a comprehensive study dealing with the simultaneous influence of different nutrient management schedules on ginger yield, rhizome quality, nutrient uptake (oleoresin, essential oil, essential oil constituents) and soil properties (physico-chemical and biochemical) is found wanting. Hence, field experiments were conducted between 2007 and 2016 involving (1) organic nutrient management (ONM) consisting of exclusive use of biological fertilizers, viz. *Bacillus megaterium*, *Azospirillum lipoferum*, farmyard manure, vermicompost, neem cake and ash, (2) chemical nutrient management (CNM) consisting of only inorganic sources of nutrients, viz. nitrogen, phosphorus and potassium applied @ 75–50–50 kg ha^{-1} in the form of urea, rock phosphate and muriate of potash, respectively, and (3) integrated nutrient management (INM) encompassing both organic sources and biological fertilizers, viz. FYM and N applied at 50% of CNM and P, K applied at 100% of CNM, i.e. 37.5–50–50 kg ha^{-1}. The results on soil properties revealed that soil pH was lowest in CNM (5.03), while soil organic carbon (SOC) level was markedly higher by 39.0% in ONM and by 32.8% in INM compared with CNM. Bray P level was greater in ONM by 119.0% compared with CNM and by 72.0% compared with INM. Exchangeable Ca and Mg were greater in ONM and INM, and among available micronutrients, available Cu and Fe levels were greatest in ONM and available Mn level was greatest in CNM. Among the soil biochemical parameters, microbial biomass C increased markedly by 81.0% in ONM and 48.0% in INM. This was responsible for enhanced β-glucosidase, acid phosphatase and dehydrogenase activities in ONM and INM, though urease activity was greatest in CNM. In case of rhizome yield, CNM registered significantly lower yield (mean 11.14 Mg ha^{-1}) in comparison with ONM and INM (mean 18.64 and 18.50 Mg ha^{-1}, respectively) across all the years. With regard to rhizome quality, the essential oil content in ONM and CNM was almost identical (1.0–1.7%), while it was slightly higher at 1.32–4.0% in INM. Results on rhizome oil components showed that pinene, *d*-camphene and β-phellandrene contents were higher in CNM, β-citral (neral) and citronellol in ONM and α-citral (geranial) in INM. The study, in general, indicated the distinct possibility of reducing or avoiding application of chemical fertilizers while simultaneously sustaining ginger rhizome yield and quality through ONM or INM.

Keywords Essential oil · Ginger · Microbial biomass · Nutrient management · Nutrient uptake · Organic manures · Soil properties · Biological fertilizers · *Bacillus megaterium* · *Azospirillum lipoferum* · Farmyard manure · Vermicompost · Neem cake

Introduction

Ginger (*Zingiber officinale* Roscoe) is one of the major spices used across the world and is grown in tropical and subtropical countries. Besides being a key ingredient in many world cuisines and food processing industry, ginger

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possesses anti-carcinogenic, antioxidant and anti-inflammatory properties [2, 60, 65]. The characteristic flavour and pungency of ginger are attributed to its essential oil and oleoresin contents, and the former is mainly constituted by mono- and sesquiterpene derivatives, whereas the latter is composed of non-volatile phenolics [2, 31].

India ranks first and contributes about 29.0% of total world's ginger production followed by China (26.0%), Indonesia (14.0%) and Nigeria (10.0%). During 2014–2015, India produced 7.60 lakh tons of ginger from an area of 1.41 lakh ha. The productivity in most of these growing countries is, however, hampered due to poor crop management which in turn is exacerbated by poor soil fertility, pest and diseases and more importantly poor nutrient management.

A wide array of soils, viz. clay loams, sandy loams, lateritic or alluvial soils, are suitable to grow ginger. In India, it is grown on red lateritic soils and in China and Japan on well-drained paddy lands and marshy sites [74], while moderate-to-heavy soils are used in Australia. Nevertheless, well-drained deep, loose and friable soils with at least 30 cm depth, good nutrient status and organic matter level are more suitable.

Besides soil type, nutrient management is critical to achieve optimum growth and productivity in ginger. It is a nutrient-exhaustive crop and therefore requires an adequate supply of nutrients at important growth stages [15]. Nutrient management options to the crop include chemical fertilization (chemical nutrient management—CNM) or organic manuring (organic nutrient management—ONM) or a mixture of inorganic fertilizers and organic manures (integrated nutrient management—INM) [16]. However, reports suggest that the nutrient requirement, be it through organic or chemical means, differs considerably with crop variety, soil type and geographical location. Ideally, the recommended dose of fertilizers (RDF) is given in splits in order to meet the crop demand at various stages of growth, and it is possible to considerably reduce the difference between prospective yield and actual yield with a suitable nutrient management schedule. In turn, this can help in reducing the overuse of chemical fertilizers, thereby safeguarding environment quality.

Numerous results from studies on nutrient management schedules in ginger are already available [6, 42, 58, 62, 63]. Also, an earlier study by us dealt with the short-term (1 year) effects of nutrient management regimes on biochemical and microbial properties on soils under ginger [17]. However, there are very few reports that involve a series of field experiments that simultaneously delve on the influence of different nutrient schedules on ginger yield and quality. In this study, we evaluated a set of nutrient management schedules with the primary objective of determining their effects on rhizome yield and quality of ginger grown under rainfed condition, while simultaneously determining their effects on an array of soil physico-chemical and biochemical parameters. The first field experiment was conducted in 2007, and subsequently, four more field experiments with identical treatments were conducted until 2016.

Materials and Methods

Experimental Site

The experimental site (11°35′0″N 75°49′0″E) is characterized by a humid tropical climate with a mean annual rainfall of 4374.0 mm, with most of the rainfall occurring between May and December. The relative humidity hovers between 75.0 and 90.0%, and the temperature (max 35 °C) seldom goes below 18 °C.

The soil here is a Ustic Humitropept with clay loam texture. The physico-chemical characteristics of the initial soils before start of each field experiment are given in Table 2. In general, soils were acidic (range 4.5–5.5), while EC levels were very low (0.15–0.28 dSm^{-1}). Likewise, very little variation existed in CEC 12.6–13.2 me 100 g^{-1}) and organic C content (16.0–17.6 g kg^{-1}) of soils during various years of experimentation. Among the available nutrient levels, mineral N levels were low to medium (111–152 mg kg^{-1}), Bray P levels were medium (2.5–8.9 mg kg^{-1}), while exchangeable K levels were low to medium (67–195 mg kg^{-1}). In case of secondary nutrients, both exchangeable Ca and Mg levels were found to be low at all the sites (275–350 and 37–55 mg kg^{-1}, respectively). With regard to available micronutrients, the levels of available Fe (34–41 mg kg^{-1}) and available Mn (10.6–15.2 mg kg^{-1}) were high, but the levels of available Zn (0.62–1.2 mg kg^{-1}) and Cu (0.66–1.2 mg kg^{-1}) were low at all the sites.

Experimental Details

The first field experiment was conducted in 2007–2008. Subsequently, four more field experiments with identical treatments were conducted in 2009–10, 2010–2011, 2013–2014 and 2016–2017. Since ginger is a nutrient-exhaustive crop, and due to serious incidence of diseases when grown in the same soil, the field experiments were not conducted at the same site during the subsequent years, but were conducted in different sites in the same location with similar soil type.

Land Preparation and Planting

Being rainfed, ginger was grown on elevated soil beds with dimensions of 3 × 1 × 0.30 m ($l \times b \times h$). For making such beds, the site was thoroughly weeded and tilled to a fine soil texture, followed by application of lime @500 kg ha^{-1}, thorough mixing and levelling. Beds of the above dimensions were then made by maintaining a space of 40 cm between beds. During planting, shallow pits were made on the beds with a spacing of 20 × 25 cm and seed rhizomes (20–25 g) of ginger (variety: IISR-Varada) were placed at a depth of 4.0–5.0 cm in these pits and covered with soil. Subsequently, mulching with *Gliricidia sepium* (Jacq.) Kunth ex Walp., @15 t ha^{-1} was done to all the beds to prevent the planted rhizomes from being exposed during heavy showers as well as to secure the beds against soil erosion. At 45 and 90 days after planting (DAP), weeding of the beds was done, followed by fertilizer application as per the treatments and application of green leaf mulch @7.5 t ha^{-1}.

Nutrient Management Schedules

For the study, we adopted the following nutrient management regimes for each bed of 3 m × 1 m:

- Organic nutrient management—ONM: 20 kg farmyard manure (FYM) + 1.0 kg neem cake (NC) + 0.5 kg ash + 50 g talc-based *Azospirillum lipoferum* (10^9 colony-forming units (CFU)g^{-1} soil) + 50 g talc-based *Bacillus megaterium* (10^9 CFU g^{-1} soil) + 2.0 kg vermicompost (VC, applied at 45 DAP).
- Chemical nutrient management—CNM: NPK applied as urea, rock phosphate (RP) and muriate of potash (MOP) @75–50–50 kg ha^{-1}, respectively. Urea and MOP were applied in two splits (45th and 90th DAP), while RP was applied as basal.
- Integrated nutrient management—INM: 10 kg FYM bed^{-1} + N applied at 50% of CNM and P, K applied at 100% of CNM, i.e. 37.5–50–50 kg ha^{-1}.

The relevant chemical constituents of FYM, VC, NC and ash are given in Table 1. The biofertilizers, *A. lipoferum* and *B. megaterium* @ 10^9 CFU g^{-1} soil were mixed with FYM prior to application, while NC, VC, FYM and ash were incorporated manually into the soil. The crop was harvested at maturity (∼ 240 DAP). The design of experiment followed was randomized block with six replications.

Soil Sampling

The treatment-wise soil samples (4 nos per bed) were taken after harvest, cleared of organic/plant debris, bulked and transferred into plastic bags. Before analyses, the soil samples were sieved to < 2.0 mm. After estimation of moisture content, subsamples for determination of biochemical parameters were stored at 4 °C. For the determination of mineral N and SOC, a second set of subsamples were sieved using 0.5 mm mesh.

Estimation of Soil Physico-Chemical Parameters

Available P was estimated using the Bray extractant [55], mineral N by steam distillation [50], soil organic C (SOC) by wet oxidation [53] and exchangeable K [29], Ca and Mg [67] by NH_4OAc extraction. Micronutrients (Cu, Zn, Mn and Fe) were estimated by DTPA extraction [44].

Estimation of Soil Biochemical Properties

The chloroform fumigation method [71] was employed for the estimation of microbial biomass C (MBC) by employing k_{EC} of 0.45 [77]. Acid phosphatase was assayed using *p*-nitrophenyl phosphate as the substrate [68], urease (UR) using urea as the substrate [37], β glucosidase (BG) using *p*-nitrophenyl-β-D-glucopyranoside as the substrate [20] and dehydrogenase (DH) using 2,3,5-triphenyltetrazolium chloride (TTC) as the substrate [11].

Table 1 Important characteristics of the organic amendments used in the study

	OC (g kg^{-1})	N	P	K	Ca	Mg	S	Fe	Mn	Zn	Cu
Farmyard manure	90.5	6.00	2.00	4.0	13.0	3.90	1.20	5.73	0.518	0.040	0.024
Neem cake	270.7	18.0	2.40	17.0	5.00	2.20	1.00	3.05	0.227	0.017	0.026
Vermicompost	94.0	10.0	3.00	3.00	33.0	11.0	0.80	3.86	0.268	0.427	0.018
Ash	ND	2.00	54.0	121.0	68.0	18.0	1.00	7.00	0.749	0.144	0.020

ND not determined

Estimation of Rhizome Nutrient Concentration

The harvested rhizome samples were first washed rigorously to remove adhering soil particles and organic debris, shade-dried and then oven dried at 60 °C and powdered (< 0.5 mm) using a Wiley mill. For estimation of N content, subsamples were digested in 5:2 diacid mixture ($H_2SO_4/HClO_3$) and the total N was estimated using the micro-Kjeldahl procedure [33]. Total P, K, secondary nutrients (Ca, Mg) and micronutrients (Fe, Cu, Zn and Mn) in the rhizomes were estimated by digesting subsamples in 9:2:1 tri-acid mixture ($HNO_3/H_2SO_4/HClO_3$). Total P in the extract was estimated using the vanadomolybdate method [33], and total K, secondary nutrients and micronutrients were determined using atomic absorption spectrophotometer.

Estimation of Rhizome Quality

Subsamples of the oven-dried rhizomes were pulverized using a mixer grinder fitted with a 0.5 mm mesh. Oleoresin was estimated gravimetrically following cold percolation with acetone [3], fibre content using the acid–alkali-reflux method [4] and essential oil using the modified Clevenger method [5]. The essential oil of ginger rhizomes was further analysed for its various constituents using GC–MS with RTX—5 column (30 m × 0.25 mm, 0.25 µm film thickness). Helium gas with flow rate of 1.67 mL min^{-1} served as the carrier. Other conditions include injection port temperature 250 °C, detector temperature 220 °C, oven temperature 60 °C for 5 min increased to 110 °C at the rate of 5 °C min^{-1}, followed by increased to 170 °C at the rate of 3 °C min^{-1}, and further increased to 220 °C at the rate of 5 °C min^{-1}; the column was retained for 3 min at this temperature. The split ratio was maintained 1:40 with ionization energy of 70 eV. For identification of the compounds, the retention indices and mass spectra were compared with those of authentic samples available in the library [39].

Statistics

All values reported are means of six replications expressed on an oven-dry (105 °C) basis. One-way ANOVA was employed to test the significance of treatments. When the *F* value was significant, the least significance difference (LSD) test was used for the post hoc comparison of treatment means at $P < 0.05$ or 0.01. The relationship between two relevant parameters was estimated using Pearson's correlation. SPSS version 11.0 for Windows was used to perform all statistical analyses.

Results and Discussion

Soil Physico-Chemical Properties

Soil pH

The soil pH was, in general, acidic in all the treatments over the years (Table 3) and did not vary significantly compared with the initial soil pH (mean 5.0; Table 2). Mean levels indicated that it varied within a narrow range of 5.03–5.68 and it was significantly ($P < 0.05$) higher in treatments with organics (ONM and INM). This can be attributed to steady release of bases during organic manure decomposition [32] and also due to buffering from carbonates and bicarbonates [43]. Besides, the carboxyl and phenolic hydroxyl groups of the organic acids in the organic manure have been implicated in buffering soil acidity and increasing soil pH [76]. Contrarily, in the CNM treatment, the mean pH (4.53) was even lower than the original mean pH of 5.04 (Table 2) measured before the initiation of the study. This is possibly due to rapid nitrification of the applied urea followed by release of H^+ ions [14, 43] and production of organic acids by the soil microbial community [30, 81].

Soil Organic C

The mean soil organic C (SOC) level was 17.0 mg kg^{-1} (Table 2), which increased markedly in ONM and INM treatments. In fact, SOC level increased by 21.0% in ONM treatment and by 16.5% in INM treatment. In contrast, SOC level decreased by 12.3% in CNM treatment compared with the initial level. Among the nutrient management treatments, mean SOC level was significantly higher ($P < 0.05$) in ONM followed by INM and lastly by CNM (Table 3). In fact, in ONM, SOC level was higher by 39.0%, while in INM it was higher by 32.8% compared with CNM, which had the lowest levels of SOC (14.9 g kg^{-1}). This suggested that SOC accumulated at greater levels in systems encompassing organic manures compared with systems that received only chemical fertilizers [9, 61, 64]. This is due to direct contribution of C from the added manures and due to indirect C additions through enhanced primary production [8, 75]. Lower SOC level in CNM was primarily because there was no direct incorporation of organic manures into the soil. Besides, exclusive inorganic fertilization possibly induced a favourable priming effect [61], which reduced the rate of SOC accumulation.

Nevertheless, the treatments with organic manures (ONM and INM) showed an increase in SOC levels compared to the original SOC status in the experimental site

Table 2 Physico-chemical properties of the initial soil samples during each year of field experimentation

	2007–2008	2009–2010	2010–2011	2013–2014	2016–2017	Range	Mean
pH (1:2.5 H_2O)	5.4	5.1	4.5	5.5	4.7	4.5–5.5	5.04
Organic carbon (g kg^{-1})	17.6	17.3	16.0	17.0	17.0	16.0–17.6	17.0
EC (dS m^{-1})	0.18	0.19	0.21	0.15	0.28	0.15–0.28	0.20
CEC (me 100 g^{-1})	13.1	12.9	12.6	13.0	13.2	12.6–13.2	13.0
	mg kg^{-1}						
Mineral N	111	118	134	114	152	111–152	125.8
Bray P	5.8	2.7	8.9	2.5	5.3	2.5–8.9	5.0
Exchangeable K	67	195	188	105	130	67–195	137
Exchangeable Ca	305	342	257	300	350	257–350	311
Exchangeable Mg	52	55	49	47	37	37–55	37
Available Zn	1.20	0.62	1.17	0.70	0.78	0.62–1.20	0.89
Available Cu	0.95	0.75	0.82	1.20	0.66	0.66–1.20	0.88
Available Fe	36	38	41	34	34	34–41	37
Available Mn	12.9	10.6	11.8	15.2	12.6	10.6–15.2	12.6

Table 3 Physico-chemical properties (mean ± SD) of soils under ginger as influenced by nutrient management regimes

	ONM	CNM	INM	LSD ($P < 0.05$)
pH (1:2.5 H_2O)	5.68 ± 0.26	5.03 ± 0.83	5.49 ± 0.59	0.35
Organic carbon (g kg^{-1})	20.7 ± 3.9	14.9 ± 3.2	19.8 ± 4.5	2.3
	mg kg^{-1}			
Mineral N	189.8 ± 88.5	174.6 ± 84.9	196.6 ± 124.8	NS
Bray P	10.14 ± 5.30	4.62 ± 2.77	5.87 ± 3.23	2.0
Exchangeable K	203.5 ± 103.1	235.0 ± 116.3	242.0 ± 131.5	NS
Exchangeable Ca	873.2 ± 145.0	413.4 ± 234.7	613.2 ± 193.4	148.3
Exchangeable Mg	159.5 ± 30.8	75.8 ± 9.9	100.5 ± 8.9	18.4
Available Zn	1.87 ± 1.54	1.16 ± 0.59	1.25 ± 0.55	NS
Available Cu	18.8 ± 2.15	2.4 ± 0.46	13.7 ± 2.35	0.86
Available Fe	50.5 ± 1.89	37.6 ± 1.75	40.1 ± 2.47	1.63
Available Mn	13.6 ± 2.0	22.3 ± 2.2	20.2 ± 1.6	2.0

Mean of 5 years (2007–2008, 2009–2010, 2010–2011, 2013–2014 and 2016–2017)

ONM organic nutrient management, *CNM* conventional nutrient management, *INM* integrated nutrient management, *SD* standard deviation, *LSD* least significant difference

(Table 2), though it tended to decrease in the CNM treatment. This is in contrast to the results of a global meta-analysis of SOC dynamics under different nutrient managements, which indicated that chemical fertilizers increased SOC by as low as 10.0–15.5% because their contribution to enhancing C input was only through belowground biomass, thus resulting in a lower rate of increase than sites with chemical fertilizer + straw incorporation and chemical fertilizer + manure incorporation [25]. Nevertheless, results on the effects of chemical fertilization on SOC are discrepant with reports of either increased or decreased SOC pools [18, 54, 61] or no effects, whatsoever [10], on SOC accumulation.

Mineral N, Bray P, Exchangeable K

The effect of treatments on mineral N and on exchangeable K levels in soil was non-significant ($P < 0.05$), though the mean levels were slightly higher in INM and ONM (Table 3). Contrary to N and K, a marked increase in Bray

P level was registered in ONM and was greater by 119.0% and 72.0% in comparison with CNM and INM, respectively, suggesting lower accumulation of available P in chemically fertilized plots. This could be due to direct contribution from the applied manures or by neutering of the P fixing capabilities of exchangeable Al and Fe oxides by the applied manures owing to complexation. Our results are in agreement with the findings that the application of poultry manure compost or organic fertilizer [78, 79] or agro-industrial wastes [12] increased available P in soil.

Compared with the initial mineral N status (mean 125.8 mg kg^{-1}; Table 2), all the nutrient management treatments registered markedly higher mineral N levels and the increase was greatest with INM (56.3%) followed by ONM (51.0%) and lastly by CNM (38.8%). Similarly, in case of Bray P, the increase was greatest with ONM (101%), followed by INM (16.6%), while it tended to decrease by 8.3% in CNM. Exchangeable K levels increased in all the treatments compared with the initial levels, and the increase was greatest in INM (76.6%), followed by CNM (71.5%) and lastly by ONM (48.5%).

Exchangeable Ca and Mg

Exchangeable Ca and Mg levels were significantly higher ($P < 0.05$) in ONM followed by INM compared with CNM (Table 3). Exchangeable Ca in ONM was greater by 111.0%, while in INM it was greater by 48.3% compared with CNM. Likewise, exchangeable Mg was greater by 110.0% in ONM and by 32.6% in INM compared with CNM. This can be attributed to direct contribution of Ca and Mg from the organic manures, and it is, therefore, not surprising that exogenous organic manure additions smother acidity by decreasing Fe and Al concentrations through their liming effect, thereby increasing soil pH. Therefore, the increase in pH registered in the ONM and INM treatments can very well be ascribed to enhanced Ca and Mg levels in soil. Likewise, among the micronutrients, the significant ($P < 0.05$) variation in available Cu levels among the treatments is expected; in OM and INM, drenching of Bordeaux mixture (BM) @ 1.0% was done twice at 60 and 90 DAP to manage fungal pathogens. Application of BM could also be the reason for the enhanced exchangeable Ca levels in ONM and INM.

Significant increase in exchangeable Ca and Mg levels was manifested due to the nutrient management treatments compared with the initial levels (Table 2). Exchangeable Ca increased by a whopping 873% in ONM treatment, by 97.3% in INM treatment and by a marginal 33.0% in CNM treatment. Likewise, exchangeable Mg increased by 232.3% in ONM treatment, by 109.4% in INM treatments and by 57.9% in the CM treatment. As said earlier, this increase in exchangeable Ca and Mg levels in ONM and INM treatments is due to direct contribution of Ca and Mg from the organic manures.

DTPA Extractable Micronutrients

With regard to micronutrients, available Fe and Cu levels were markedly higher in ONM followed by INM compared with CNM, while variation in available Zn levels was non-significant ($P < 0.05$) among the treatments (Table 3). The significant ($P < 0.05$) variation in available Cu levels among the treatments is expected; in ONM and INM, drenching of Bordeaux mixture (BM) @ 1.0% was done twice at 60 and 90 DAP to manage fungal pathogens. Application of BM could also be the reason for the enhanced exchangeable Ca levels in ONM and INM treatments.

Compared with the initial soil status (Table 2), available Zn levels increased by 110.0% in ONM treatment, by 40.5% in INM treatment and by 30.3% in CNM treatment. Similarly, available Cu level also increased by a staggering 2036.0% and 1456.8% in ONM and INM treatments, respectively. In the CNM treatment, the increase was only 172.7%. As stated earlier, such marked increases in available Cu levels in ONM and INM treatments are apparently due to application of BM to manage fungal pathogens. The increase in available Mn level was greatest in CNM (76.9%), followed by INM (60.3%) and lastly by ONM treatment (7.9%) compared with the initial Mn status. Available Fe levels increased by 38.0% in ONM, by 9.6% in INM and by 2.73% in CNM compared with the initial level.

Soil Biochemical Parameters

Biochemical parameters are considered to be very sensitive indicators of both short-term and long-term changes in soil quality [13, 17, 46] and include parameters that have a direct bearing on microbial activity (microbial biomass C and dehydrogenase) and activities of extracellular hydrolytic enzymes that play vital roles in nutrient cycles. In this study, we determined the activities of β-glucosidase (C cycle), urease (N cycle) and acid phosphatase (P cycle).

Microbial Biomass C

Mean MBC level was lowest in CNM (256 ± 29 μg g^{-1}), while it increased significantly ($P < 0.05$) by 81.0% in ONM (464 ± 43 μg g^{-1}) and 48.0% in INM (378 ± 31 μg g^{-1}; Fig. 1). That said, if the initial MBC level at the experimental site (190.0 μg g^{-1}) is considered, CNM registered a 34.7% increase in MBC, while

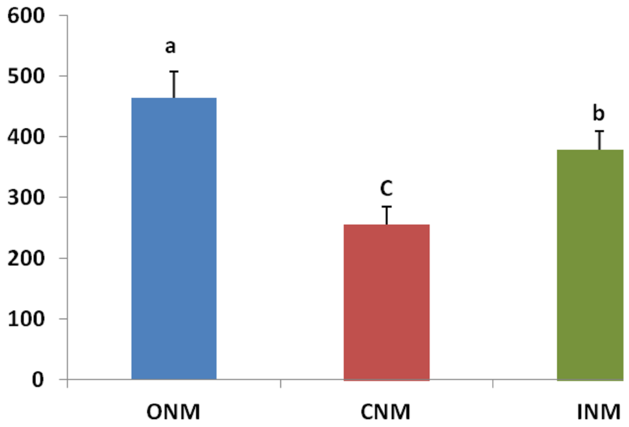

Fig. 1 Soil microbial biomass C (μg g^{-1}) as influenced by different nutrient management regimes (*ONM* organic nutrient management, *CNM* chemical nutrient management, *INM* integrated nutrient management) [bars indicate standard deviation; different letters indicate significant differences at $P < 0.05$ (LSD)]

corresponding increases in INM and ONM were markedly higher at 99.0% and 144%, respectively.

Greater MBC levels in ONM and INM are not surprising since application of organic manures has been found to stimulate MBC due to enhanced accessibility of substrates like dissolved C and N [26, 69]. The positive correlation ($P < 0.01$; $n = 60$) between MBC and SOC ($r = 0.78$) observed in this study further supported the dependence of MBC on C accumulation in soils. More often than not, organic manures in different states of disintegration contribute a plethora of substrates that improve soil microbial activity [7, 28] and concurrently encourage SOC accumulation [22]. Furthermore, exogenous additions of organic C are imperative for microbial community change and very little alterations will occur in its absence [51]. In contrast, significantly ($P < 0.05$) lower MBC due to exclusive chemical fertilization (CNM) is possibly due to decreased pH which has been reported to affect soil microbial activity and labile C such as MBC [9, 18, 21]. However, a marginal increase in MBC level was observed in CNM compared with the level observed before the start of the study. This is presumably due to decreased microbial N limitation [41]. Ergo, in this study, exclusive chemical fertilization (CNM) did not decrease MBC as has been observed in several meta-analytical studies where inorganic N additions decreased MBC by 40.0–59.0% [72], 15% [70], 20% [45] and 35.0% [56]. As opposed to these reports, an increase in MBC level at lower N application rates [41] or no effects on MBC level after two years of N application [35] have also been reported. Apparently, such divergent effects of inorganic N additions suggest that variations in soil MBC overly depend on a surfeit of factors such as soil type, soil pH, soil moisture content, SOC level and rate of inorganic N additions [40], though the processes underlying the effects of these factors are yet to be fully understood. In spite of chemical N fertilization, albeit at reduced levels (50% of N applied in CNM), INM registered relatively higher MBC level than CNM, which suggested that organic amendments along with inorganic fertilizers could lead to enhancement in microbial activity and, therefore, MBC accumulation in soil.

Enzyme Activities

CNM registered significantly higher ($P < 0.05$) UR activity, while ONM registered markedly higher levels of DH, AcP and BG activities (Fig. 2). UR activity in CNM was greater by 27.0% and 77.0% compared with INM and ONM, respectively, while AcP activity was greater in ONM by 63.8% and 56.5% compared with CNM and INM, respectively. BG and DH activities were also altered to different degrees due to the nutrient management regimes (Fig. 2). BG activity was lowest in CNM, while it was greater by 90.0% in ONM and by 53.3% in INM. Similar to BG activity, DH activity was greater by 35.4% in ONM and 24.5% in INM compared with CNM (Fig. 2).

The increase in mean UR activity in CNM suggested the favourable impact of inorganic N application [1, 64], while decreased AcP, activity in CNM and to a lesser extent in INM was possibly due to application of chemical P fertilizer (@ 50 kg ha^{-1}), since phosphatases are synthesized when available P level in soil is low [48, 49]. Marked suppression in AcP activity due to P fertilization has also been reported in earlier studies [57, 73]. This was, however, not the case with ONM, where both available P and AcP activity was higher, due to direct contribution from the organic manures or a consequence of greater microbial activity and, therefore, greater synthesis of AcP. Several studies have reported the positive effects of organic manure additions on soil phosphatases [38] and enhancements in activity have been related to greater microbial and biochemical activities in soil following application of organic manures.

BG activity is a sensitive indicator of changes in SOC concentrations and reflects the entire array of soil metabolic functions [66]. Therefore, lower BG activity in CNM is a consequence of reduced SOC accumulation and apparently confirms the positive association between BG and SOC [17, 64]. Likewise, positive effects on DH activity in ONM and INM suggested an overall enhancement in microbial activity and MBC due to larger availability of labile substrates, underlining the fact that organic manure additions have more impact on MBC and DH, compared with inorganic fertilizers [47]. Contrarily, CNM seems to have attenuated the activity of DH, suggesting that nutrient additions through chemical means especially N lead to swift adsorption by soil organic matter or

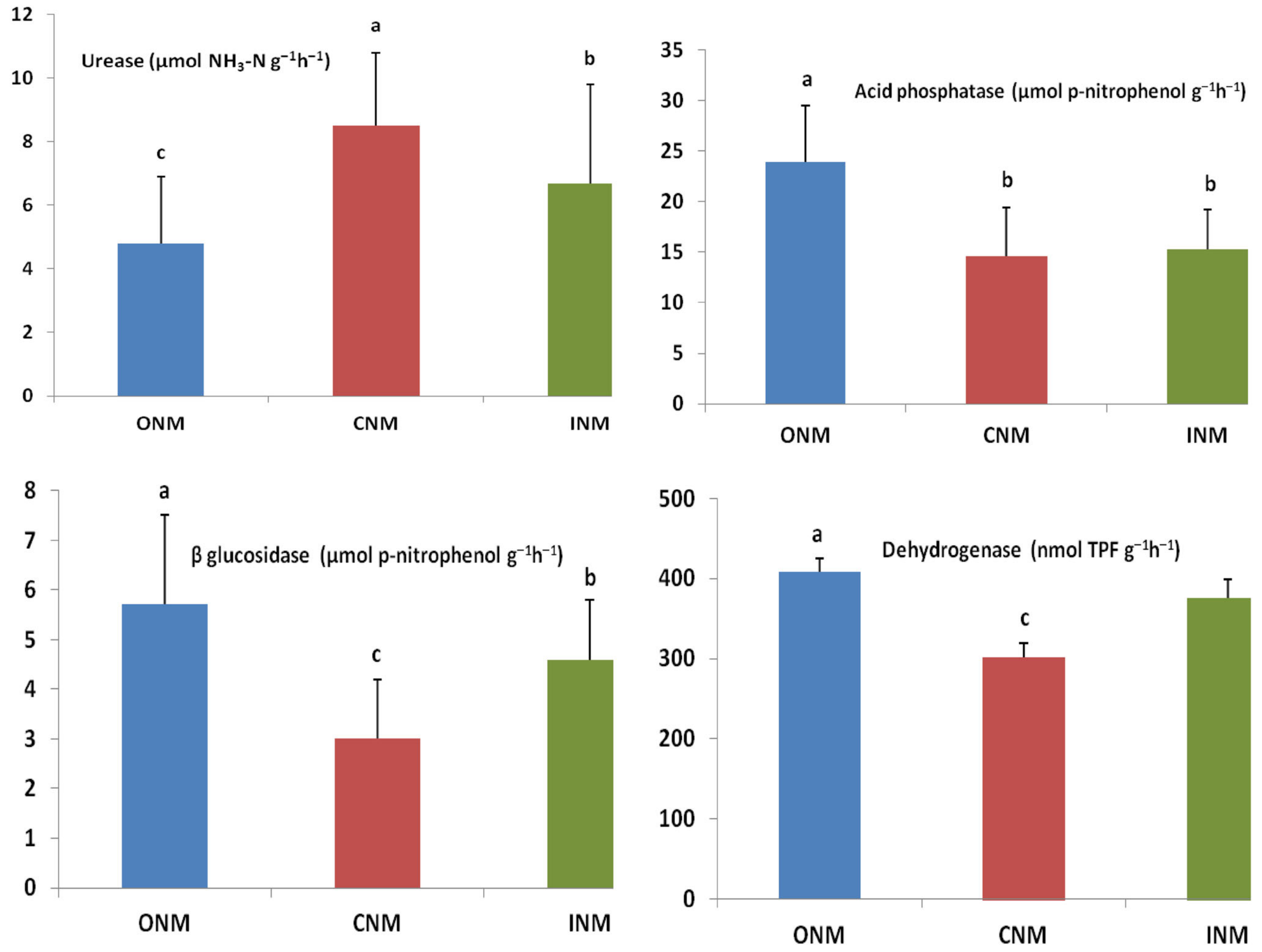

Fig. 2 Soil urease, acid phosphatase, β-glucosidase and dehydrogenase activities as influenced by different nutrient management regimes (*ONM* organic nutrient management, *CNM* chemical nutrient management, *INM* integrated nutrient management) [bars indicate standard deviation; different letters indicate significant differences at $P < 0.05$ (LSD)]

overlying plant biomass or immediate loss by leaching before it can impact soil microbial community [36]. Nevertheless, significant reduction in DH activity due to excess N application [19, 59], enhanced activity due to balanced fertilization [19] and organic manuring [47] have been reported.

Rhizome Yield

The rhizome yield varied considerably among the treatments across the years (Fig. 3). Among the treatments, ONM and INM consistently registered greater yields across all the years compared with CNM. Among INM and ONM, the former registered markedly greater yield in 2007–2008, 2009–2010 and 2016–2017, while the latter registered the highest yield in 2010–2011 and 2013–2014. Nevertheless, mean yield across the five years (Fig. 4) indicated almost identical performance by both ONM and INM treatments

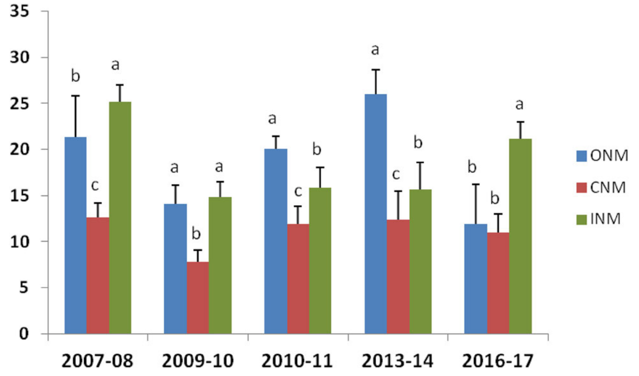

Fig. 3 Ginger rhizome yield (Mg ha^{-1}) as influenced by different nutrient management regimes (*ONM* organic nutrient management, *CNM* chemical nutrient management, *INM* integrated nutrient management) at different years of experimentation [bars indicate standard deviation; different letters indicate significant differences at $P < 0.05$ (LSD)]

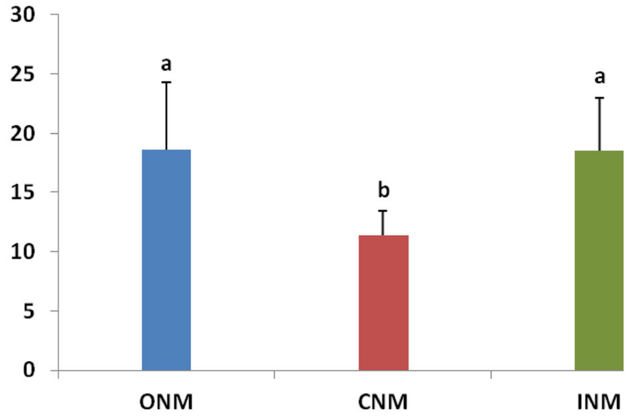

Fig. 4 Mean rhizome yield (Mg ha^{-1}) as influenced by different nutrient management regimes [mean of 5 years; *ONM* organic nutrient management, *CNM* chemical nutrient management, *INM* integrated nutrient management) [bars indicate standard deviation; different letters indicate significant differences at $P < 0.05$ (LSD)]

(18.64 and 18.50 Mg ha^{-1}, respectively) and was greater by 67.3% and 66.1%, respectively, compared with CNM (11.14 Mg ha^{-1}). Higher yield in ONM and INM is primarily due to enhanced availability of nutrients as evidenced by greater levels of Bray P, Ca and Mg in ONM and INM. Besides, synchronization between mineralization of organic components into available forms and crop demand for nutrients, coupled with increasing pH, provided a conducive environment for crop growth in ONM. Similarly, in INM, combined use of inorganic and organic sources enhanced the use efficiency of the former thereby maintaining a higher level of rhizome yield. Besides, under INM, the use efficiency of the inorganic N fertilizer was enhanced probably due to reduced N losses via nitrification, runoff, N_2O emissions, leaching, immobilization and volatilization [24, 27, 80]. Contrarily, reduced pH (5.03), lower SOC levels, reduced availability of nutrients and decreased microbial activity seem to have seriously hampered nutrient cycling, thereby inhibiting rhizome development in CNM.

Nutrient Uptake, Oil and Oleoresin Contents

Significant ($P < 0.05$) variations existed between the treatments with respect to uptake of macronutrients (N, P, K), secondary nutrients (Ca, Mg) and micronutrients (Zn, Cu, Fe, Mn) by ginger rhizomes (Table 4). Mean uptake of N, P, K, Ca, Mg and Fe was greatest in ONM, while uptake of Zn, Cu and Mn was greatest in INM. Exclusive chemical fertilization (CNM) consistently registered the lowest nutrient uptake. Relatively higher nutrient uptake in ONM followed by INM suggested lower loss of applied nutrients and indicated higher use efficiencies of nutrients from organic manures, both when applied alone (ONM) and in combination with chemical fertilizers (INM).

Besides nutrient levels, the rhizome quality was measured with reference to fibre, essential oil and oleoresin contents. Across the years, the essential oil content ranged from 1.0 to 1.7% (mean 1.35 ± 0.21%) in ONM, was almost identical in CNM (range 1.0–1.6%; mean 1.31 ± 0.15%) and was relatively higher in INM (range 1.32–4.0%; mean 1.82 ± 0.79%). However, there was very little variation in oleoresin (3.73–3.75%) and fibre contents (5.0–5.2%) among the treatments. While the fibre content of commercial dried ginger varies from 1.5 to 6.0%, the flavour of ginger is primarily determined by its essential oil make-up and the oleoresin content, which usually vary from 1.0 to 3.0% and 3.5 to 10.0%, respectively [34].

The essential oil extracted from the rhizome was further studied for important components (Table 5) like monoterpene hydrocarbons (pinene, *d*-camphene, β-phellandrene); oxygenated monoterpenes (linalool, α- and β-citral); sesquiterpene alcohols (citronellol, eucalyptol, geraniol, nerolidol, elemol, zingiberenol 1 and 2, β-eudesmol); and sesquiterpene hydrocarbons (α-curcumene, α-farnesene, β-sesquiphellandrene, zingiberene). Significant variations ($P < 0.05$) among the nutrient management regimes were found to occur with regard to β-phellandrene, zingiberenol 1, pinene, *d*-camphene, α- and β-citral and citronellol, while the variations in linalool, eucalyptol, geraniol, α-curcumene, zingiberene, α-farnesene, β-sesquiphellandrene, nerolidol, elemol, zingiberenol 2 and β-eudesmol contents in the ginger oil were non-significant (Table 5). Among the treatments, pinene, *d*-camphene and β-phellandrene contents were highest in CNM (1.54%, 5.26% and 3.45%, respectively), β-citral (neral) and citronellol in ONM (2.26% and 1.16%, respectively) and α-citral (geranial) in INM (4.78%). While the fibre content of commercial dried ginger varies from 1.5 to 6.0%, the flavour of ginger is primarily determined by its essential oil make-up and the oleoresin content, which usually vary from 1.0 to 3.0% and 3.5 to 10.0%, respectively [34]. Greater levels of citral content in ONM and INM would result in enhanced citrus or lemon-like flavour as observed in Australian ginger oils [34]. Irrespective of the treatments, we found zingiberene to be the most dominant group (18.29–20.41%) followed by α-farnesene (10.37–12.46%) and β-sesquiphellandrene (10.09–10.33%). These observations are consistent with earlier reports that in ginger essential oil, sesquiterpene hydrocarbons are foremost (50–66%), while the rest is constituted by oxygenated sesquiterpenes, monoterpene hydrocarbons and oxygenated monoterpenes [23, 52].

Table 4 The effects of nutrient management regimes on the uptake of macronutrients (N, P. K), secondary nutrients (Ca, Mg) and micronutrients by ginger rhizomes

	N kg ha^{-1}	P	K	Ca	Mg	Fe	Mn	Zn g ha^{-1}	Cu
ONM	57.5	12.2	36.6	7.3	5.2	1.5	0.49	108.2	79.6
CNM	30.0	5.7	20.1	3.8	2.5	1.0	0.31	47.5	63.0
INM	50.8	11.3	32.9	5.4	4.2	1.4	0.60	127.3	92.7
LSD ($P < 0.05$)	2.67	0.63	1.75	0.3	0.3	0.1	0.33	6.2	4.9

Mean of 5 years (2007–2008, 2009–2010, 2010–2011, 2013–2014 and 2016–2017)

ONM organic nutrient management, *CNM* conventional nutrient management, *INM* integrated nutrient management, *SD* standard deviation, *LSD* least significant difference

Table 5 The effects of nutrient management regimes on the composition of essential oil of ginger rhizomes

	ONM (%)	INM	CNM	LSD ($P < 0.05$)
Pinene	0.83	1.09	1.54	0.26
Camphene	3.12	3.80	5.26	0.66
β-Phellandrene	3.11	3.15	3.45	0.13
Eucalyptol	4.21	3.96	4.09	NS
Linalool	2.14	1.78	1.77	NS
Citronellol	1.16	0.99	0.79	0.13
α-Citral	2.84	4.78	2.24	1.19
β-Citral	2.26	2.05	1.50	0.36
Geraniol	1.62	1.64	2.44	0.51
α-Curcumene	7.91	7.03	7.16	NS
Zingiberene	18.29	20.41	18.65	NS
α-Farnesene	10.37	11.54	12.46	NS
β-Sesquiphellandrene	10.09	10.18	10.33	NS
Elemol	1.13	1.00	0.96	NS
Nerolidol	1.89	1.86	1.96	NS
Zingiberenol 1	1.19	0.93	0.34	0.30
Zingiberenol 2	1.29	1.32	1.13	NS
β-Eudesmol	0.59	0.72	1.02	NS

Mean of 5 years (2007–2008, 2009–2010, 2010–2011, 2013–2014 and 2016–2017)

ONM organic nutrient management, *CNM* conventional nutrient management, *INM* integrated nutrient management, *SD* standard deviation, *LSD* least significant difference

Conclusions

Marked influence of nutrient management schedules on soil properties, albeit at varying degrees, was observed across the years. Increasing pH, greater levels of organic C, available P, Ca and Mg in ONM and INM emphasized the positive effects of organics applied either alone or in combination with inorganics. Similar positive effects were also manifested on soil biological properties, viz. MBC, dehydrogenase, acid phosphatase, arylsulphatase and β-glucosidase activities, suggesting higher microbial activity and enhanced nutrient cycling/energy efficiency in ONM and INM systems. Such enhancement in soil quality had a cascading effect on ginger rhizome yield and quality, with INM and ONM registering greater rhizome yield across the years. The essential oil content in the rhizome was higher in INM, while very little variation existed among the nutrient management regimes with respect to oleoresin and fibre contents. Contrarily, decreased pH, relatively lower SOC and nutrient build-up, besides lowered microbial biomass and activity seem to have markedly lowered rhizome yield in CNM. Overall, in this study, ONM and INM seem to have fulfilled three basic tenets of any nutrient management regime, viz. enhanced yield, enhanced soil quality and enhanced mineral content of ginger rhizomes. Hence, a judicious combination of organic and inorganic fertilizers (INM) or exclusive organic fertilization (ONM) would aid in enhancing soil quality and sustaining ginger yield while simultaneously paving the way for low chemical input agriculture.

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