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RESEARCH ARTICLE

Yield and soil nutrient balance of a sugarcane plant–ratoon system with conventional and organic nutrient management in sub-tropical India

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Abstract A 3-year field trial of sugarcane, comprising 11 treatment combinations of different organic manures with and without *Gluconacetobacter diazotrophicus* (*Gd*), NPK and an absolute control, on an inceptisol was conducted to assess the effect of these treatments on sugarcane total and economic yield, the benefit:cost ratio, nutrient balance and soil quality in a sugarcane plant–ratoon system. The highest cane yield (78.6 t ha^{-1}) was recorded in the plant crop given vermicompost + *Gd*, whereas ratoon yields (first and second) were highest (80.8 and 74.9 t/ha^{-1}, respectively) with sulphitation press mud cake (SPMC) + *Gd*. In both plant and ratoon crops, a number of different organic manures produced the highest cane yield that was also statistically similar to those obtained with using the recommended NPK levels (76.1, 78.2 and 71.7 t/ha for plant crop and subsequent two ratoons, respectively). The highest benefit:cost (B:C) ratio in the plant and two ratoon crops (1.28, 2.36, 2.03 respectively) were obtained with the addition of SPMC + *Gd*. The nutrient balance for NPK in the soil was highest in the SPMC + *Gd* treatment. The highest increase in organic C (94%) and total N (87%), in comparison to the initial level, and soil microbial biomass C (113%) and soil microbial biomass N (229%), in comparison to the control treatment, was recorded with the addition of SPMC + *Gd*. The maximum decrease in soil bulk density (BD) (12%) with an increase in soil aggregate (17%) and water infiltration rate (35%) was obtained with the addition of SPMC. Overall, the sugarcane crop responded well to different organic manures in a multiple ratooning system with a better economic output and improved soil quality. Strategic planning in terms of an integrated application of these manures with inorganic chemicals will not only sustain our soils but will also be beneficial for our farmers in terms of reducing their dependence and expenditure on chemical fertilizers.

Keywords *Gluconacetobacter diazotrophicus* · Organic carbon · Nutrient balance · Ratoon · Soil quality · Sugarcane productivity

Introduction

Sugarcane is cultivated widely throughout the Indo-Gangetic plains of South Asia. More than 4.2 million hectares are under sugarcane cultivation in India alone, with an average cane yield of 60 t ha^{-1}. Sugarcane is a very exhaustive and extracting crop that removes about 205 kg N, 55 kg P_2O_5, 275 kg K_2O, 30 kg S, 3.5 kg Fe, 1.2 kg Mn, 0.6 kg Zn and 0.2 kg Cu from the soil for a cane yield of 100 t ha^{-1}.

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Consequently, due both to the nature of this crop andextensive cropping, the soils of the Indo-Gangetic plains are becoming nutrient-deficient. In order to sustain productivity, major nutrients – N, P and K – are replenished each year at the recommended application rates, which in the sub-tropical part of India are 150 kg N ha^{-1} for the sugarcane plant crop and 220 kg N ha^{-1} for its ratoon crop as well as 60 kg each of P_2O_5 and K_2O ha^{-1} for both the plant and ratoon crops. However, the efficiency of sugarcane to utilize applied N ranges between 16 and 45% as large quantities of applied N leach down through the soil layers due to the amount of irrigation required by the sugarcane crop (Yadav and Prasad 1992). In addition, the continuous use of chemical fertilizers is Causing an apparent deficiency in other micronutrients. In recent years, the yields of sugarcane crops have plateaued and factor productivity has declined, with a decrease in soil organic matter status and a deterioration in the physico-chemical and biological properties of the soil considered to be the prime reasons for the declining yield and factor productivity (Garside 1997; Speir et al. 2004). In many cases, sugarcane farmers are turning to alternative practices, such as organic farming, eco-farming, natural farming, among others, to make agriculture more sustainable and productive. Such farming practices, combined with the proper management of the farm and concurrently available renewable resources, can result in the rejuvenation of the soils and sustainable, improved crop productivity.

The application of organic matter from such resources as animal manures, crop residues and green manuring has been shown to replenish organic C and improve soil structure and fertility (Guisquiani et al. 1995; Parham et al. 2002; Saviozzi et al. 2002). Moreover, several kinds of microbial agents capable of fixing N or mobilizing P and other nutrients are becoming an integral component of Integrated Nutrient Management System of crops. *Gluconacetobacter diazotrophicus* (earlier known as *Acetobacter diazotrophicus*), a N-fixing bacteria associated with sugarcane as an endophyte, is present in high numbers (as high as 10^6 counts g^{-1} plant tissue) in the root, shoot and leaves (Cavalcante and Dobereiner 1988). The exact role of such endophytic colonization, either individually or in a complex endophytic community,has not yet been elucidated, but the few inoculation experiments that have been carried out on micro-propagated plants suggest that positive colonization contributes to plant growth and development in terms of improved plant height, nitrogenase activity, leaf N, biomass and yield. Field trials conducted in India have shown that inoculation by *G. diazotrophicus* together with other diazotrophs or vascular arbuscular mycorrhiza can match yield levels equal to the application of 275 kg N ha^{-1} (James et al. 1994; Sevilla et al. 2001; Oliveira et al. 2002; Muthukumarasamy et al. 2002). In contrast, high levels of N fertilization negatively affect the population of such endophytic diazotrophic bacteria in sugarcane. In Brazil, Baldani et al. (2002) have reviewed the successful application of sugarcane N fixation in sugarcane breeding programmes involving both local and introduced materials. In none of these programmes were large amounts of N fertilizer utilized and because of this, their best materials have little demand for N fertilizers and an effective association has developed between endophytic N-fixing bacteria and the plant. Apart from N fixation, other properties associated with *G. diazotrophicus* are P-solubilization, the production of the plant growth hormone indole acetic acid (IAA) and the suppression of red rot disease (Muthukumarasamy et al. 1999; Suman et al. 2001).

Suman et al. (2000) reported that the native occurrence of *G. diazotrophicus* in sugarcane varieties of sub-tropical India is very low and that through the inoculation of efficient indigenous isolates, their number, plant N uptake and nutrient use efficiency could be increased at different N levels (Suman et al. 2005). Sugarcane has been found to respond positively to organic sources to meet its nutrient requirements; however, the effect of organic sources of nutrients together with *G. diazotrophicus* on crop yield and the availability and balance of nutrients in the soil along with biological and physical status and overall sustainability of the system need to be ascertained. With this aim, the present study was designed to evaluate the effect of different organic manures in combination with *G. diazotrophicus* on the sugarcane plant and its subsequent ratoons in terms of their effect on:

- the productivity of the sugarcane plant crop and subsequent ratoons;
- the availability, uptake and balance of soil nutrients;

– soil microbial activity and other physico-chemical properties.

The ultimate goal of the present study is to develop a strategy wherein by utilizing recyclable farm/sugar factory waste along with suitable bioagents, nutrient needs of sugarcane plant crop and subsequent ratoons can be met in a sustainable manner. This would not only help the farmer community economically by lowering production costs but also improve the soil quality.

Material and methods

Experimental site, climate and soil

The field experiment was conducted during 2003–2006 at research farms of the Indian Institute of Sugarcane Research, Lucknow, India located at 26°56′ N, 80°52′ E and 111 m above mean sea level. The climate of the experimental site is semi-arid and sub-tropical, with dry, hot summers and cold winters. The average annual rainfall is approximately 976 mm, and nearly 80% of the total precipitation falls during the north-west monsoon season (July–September). The average monthly minimum temperatures fluctuate from 6.9 to 8°C in January (the coldest month) and from 25.9 to 28°C in May (the hottest month). The respective maximum temperature ranges from 21.2 to 23°C in January and 39.0 to 40.6°C in May. The soil of the experimental site is a sandy loam, non-calcareous mixed hyper-thermic *udic Ustochrept* (13.3% clay, 24.5% silt and 62.3% sand) of Indo-Gangetic alluvial origin having a pH of 7.5,a bulk density (BD) of 1.40 Mg m^{-3}, an aggregate size (>0.25 mm) of 15.2%, an infiltration rate of 4.0 mm h^{-1}, 0.32% organic C, 230 kg ha^{-1} available N, 21.5 kg ha^{-1} available P and 217.9 kg ha^{-1} available K

Treatment and crop culture

The experiment consisted of 11 treatment combinations: T_1, vermicompost; T_2, farmyard manure (FYM); T_3, biogas slurry; T_4, sulphitation press mud cake (SPMC); T_5, vermi-compost + *G. diazotrophicus*; T_6, FYM + *G. diazotrophicus*; T_7, biogas slurry + *G. diazotrophicus*; T_8, SPMC + *G. diazotrophicus*; T_9, green manuring with *Sesbania aculeate* as an intercrop + *G. diazotrophicus*; T_{10}, recommended dose of NPK (150:60:60 kg ha^{-1}); T_0, an absolute control in which there was no addition (inorganic or organic) to the sugarcane system. The application rate for each of the organic manures in treatments T_1–T_8 was 10 t ha^{-1}, and the organic manures were applied manually to field plots each year for 3 years (plant and two ratoons). The press mud was obtained from the local sugar mill, FYM, the biogas slurry and vermicompost were obtained from the State Department. The average composition of organic manures used is given in Table 1. All of the treatments were in a randomized block design with three replications. The plot size was 48 m^2 (8 × 6 m). Three budded sets of sugarcane variety CoSe 92423 were planted at in furrows, with six rows in each plot and 75 cm between rows. The experiment was initiated in March 2003, and the first plant crop was harvested in February 2004, after which the first ratoon was allowed to grow, with harvesting in January 2005, followed by harvesting of the second ratoon in January 2006. At the time of ratoon initiation all treatments were superimposed in each plot. A total of six irrigations and three inter-cultural operations (hoeing) were provided uniformly to all treatments.

Table 1 Elemental composition (%) of different organic manures

Elements	SPMC	Vermicompost	FYM	Biogas slurry	*Sesbania* (green manure)
N	1.50	1.50	0.50	1.20	2.64
P	0.75	0.50	0.27	0.75	0.75
K	0.50	0.80	0.25	0.80	4.0
Ca	3.20	0.44	0.91	–	–
Mg	2.00	0.15	0.19	–	–
S	0.50	–	–	–	–

SPMC, Sulphitation press mud cake; FYM,farmyard manure

Since incidence of disease and pests were below the economic threshold, no plant protection measures were adopted.

Preparation and application of *Gluconacetobacter diazotrophicus*-based culture

An efficient isolate of *G. diazotrophicus* IS I00 (Suman et al. 2005) was used for preparing the biofertilizer. The IS I00 isolate was grown in LGI broth (Cavalcante and Dobereiner 1988) to a titer of 10^9 counts ml^{-1}, and the culture broth suspension was then mixed with a sterilized charcoal:soil (1:1) carrier to a final strength of 10^8 counts g^{-1} carrier. Approximately 150 g of this carrier-based biofertilizer (application rate:15 kg ha^{-1}) was mixed with the required quantity (50 kg) of organic manure for each plot and sprinkled over the sugarcane setts in furrows (at plant crop initiation) and near stubbles with one hoeing and earthing up (subsequent ratoon initiation).

Soil and plant sampling and analysis

Before the experiment was started in March 2003, five soil samples were taken randomly from the fields at depths of 0–15 cm using a 8-cm (diameter) core sampler; the samples were thoroughly mixed and bulked. Similarly, soil samples from all the treatments were drawn after the completion of each crop cycle, which comprised plant crops and subsequent two ratoons. After removing the visible plant residues and pebbles, a representative soil sample was passed through a 2-mm mesh sieve and stored in plastic bags at 4°C. All measurements were conducted within 45 days of sampling. Before measuring microbial activities, soil moisture was adjusted to 60% of water-holding capacity, and the samples were preincubated for 2 days at 28°C. Soil samples were analyzed for total organic C by the Walkley and Black method, for total N by the micro-Kjeldahl method, for extractable N using 2 *M* KCl, for extractable P using 0.5 *M* $NaHCO_3$ and for extractable K using NH_4OAc (1:6 soil/solution), following Page et al. (1982). Soil microbial biomass C and N were determined using the chloroform fumigation–incubation method (Jenkinson and Powlson 1976). Soil pH was determined in 1:2.5 soil water suspensions using a glass electrode pH meter. The BD of the soil was measured using core sampler and mechanical analysis was done following the International Pipette Method (Piper 1966), and aggregate size distribution (wet sieving) was determined using the method of Yodor (1936).

At the harvesting of each crop, five plants taken randomly from each plot were chopped, homogenized and dried at 70°C in a hot air oven to a constant dry weight. The dried samples were ground in a stainless steel Wiley mill and wet digested in concentrated H_2SO_4 for determination of total N and in a di-acid mixture (HNO_3:$HClO_4$, 4:1 ratio) for determination of the total P and K (Jackson 1973). Extracted juice from ten sugarcane plants randomly taken from each plot was analyzed for commercial cane sugar (CCS) using an Autopol Sucrolyser.

Calculations and statistical analysis

Data are expressed on an oven-dry soil weight basis. Factorial analysis of the data was tested by ANOVA, and Duncan's multiple-range test was used as a post-hoc analysis to compare the means (Snedecor and Cochran 1967). Soil net gain or loss of N, P and K was calculated as: $Final_{N/P/K} - Initial_{N/P/K}$ after harvesting plant and two ratoons.

Results

Crop yield, CCS and benefit:cost ratio

The application of organic manures was able to sustain sugarcane yield levels at par with those obtained using recommended chemical NPK applications even up to the second ratoon stage (Table 2), whereas in control treatment, where no manure or chemical fertilizer was added, there was a 13 and 9% reduction in cane yield in the first and second ratoon, respectively. A 34–48% increase in plant crop yield compared to the control was observed following the application of different combinations of organic manures, with the highest cane yield in treatments consisting of vermicompost + *G. diazotrophicus* (78.6 t ha^{-1}) and SPMC + *G. diazotrophicus* (77.5 t ha^{-1}). An additional increase of 1.8–3.1 t ha^{-1} was due to the inclusion of *G. diazotrophicus* with organic manures. *Sesbania* intercropping was not as productive for the plant crop of sugarcane (65.0 t ha^{-1}) as other organic manures, and there

Table 2 Cane yield, commercial cane sugar (CCS) and benefit:cost ratio as influenced by different treatments (*Gd Gluconacetobacter diazotrophicus*)

Treatment	Cane yield (t ha^{-1})			CCS (t ha^{-1})			Benefit:cost (B:C) ratio[a]		
	Plant	Ratoon I	Ratoon II	Plant	Ratoon I	Ratoon II	Plant	Ratoon I	Ratoon II
T_0 control	53.0 f	46.3 g	41.9 h	6.12 e	5.44 f	4.31 g	0.77 g	1.30 e	0.96 f
T_1 vermicompost	76.7 a	77.7 a	70.4 bc	8.95 c	9.01 a	8.52 b	0.31 h	0.60 g	0.47 h
T_2 FYM	70.9 b	70.7 bc	68.3 c	8.19 c	8.01 c	8.72 b	1.18 e	2.13 a	1.89 c
T_3 biogas slurry	71.9 b	70.4 bc	68.8 c	8.50 b	8.00 c	8.72 b	1.20 e	2.08 a	1.83 c
T_4 press mud	75.3 a	77.9 a	72.5 b	8.87 b	8.82 b	8.84 b	1.22 e	2.26 a	1.88 c
T_5 (T_1 + *Gd*)	78.6 a	79.1 a	71.6 b	9.32 a	9.91 a	9.17 a	0.34 h	0.62 g	0.49 h
T_6 (T_2 + *Gd*)	74.0 b	72.2 b	69.7 c	8.55 b	8.28 b	8.98 b	1.26 e	2.17 a	1.93 b
T_7 (T_3 + *Gd*)	75.0 ab	72.7 b	69.8 c	8.90 b	8.64 b	9.13 a	1.28 e	2.16 a	1.91 b
T_8 (T_4 + *Gd*)	77.5 a	80.8 a	74.9 ab	9.09 a	9.44 a	9.74 a	1.28 e	2.36 a	2.03 a
T_9 (*Sesbania* + *Gd*)	65.0 de	72.5 b	66.7 c	7.44 d	8.17 c	8.66 b	0.97 f	2.25 a	1.77 d
T_{10} (NPK)	76.1 a	78.2 a	71.7 b	8.92 b	8.77 b	8.89 b	1.20 e	2.07 a	1.81 c

F-interaction analysis for cane yield: crop cycle ©), NS (non-significant); manure treatment (T), S (significant); inoculation factor (F), S; C×T, NS; C×F, NS; T×F, S; C×T×F, NS. Interaction analysis for CCS: C, NS; T, NS; F, NS; C×T, NS; C×F, S; T×F, S; C×T×F, NS. Means followed by the same letter within one parameter for plant and ratoon crops do not differ significantly at $P < 0.05$ by Duncan's multiple-range test

[a] Benefit:cost ratio has been calculated from the mean cane yield

was an increase of 23% in plant crop yield with *Sesbania* green manuring and *G. diazotrophicus* inoculation. The first and second ratoon yields were highest with the SPMC + *G. diazotrophicus* inoculation treatment (80.4 and 74.9 kg ha^{-1}, respectively). The overall effect of the organic manure and inoculation treatments was found to be significant at $P = 0.5$, whereas the interaction of crop cycle with organic treatments and inoculation was non-significant. A significant increase in CCS was recorded following various treatments in the plant crops as well as in both ratoon crops (Table 2). The application of vermicompost + *G. diazotrophicus* inoculation produced the highest CCS (9.32 and 9.91 t ha^{-1}) in the plant crop as well as in the first ratoon, whereas in second ratoon, the highest CCS – 9.74 t ha^{-1} – was recorded in the SPMC + *G. diazotrophicus* treatment. The inoculation of *G. diazotrophicus* with different organic manures had a positive effect on cane sucrose accumulation compared to uninoculated treatments. The interaction of crop cycle and organic manure treatments with *G. diazotrophicus* inoculation was significant, whereas the other interactions were non-significant.

The benefit:cost ratio (B:C ratio) was the highest (1.28, 2.36 and 2.03) with the SPMC + *G. diazotrophicus* treatment relative to the recommended NPK treatment, whereas the B:C ratios were 1.20, 2.07, and 1.81 for plant crop and first and second ratoon, respectively (Table 2).

Nutrient uptake and balance in soil

Sugarcane is a highly nutrient exhaustive crop as evident from nutrient removal (uptake) data presented on a collective basis for one plant crop and two ratoon crops. The plant crop at the recommended level of added NPK removed 777.1 kg N ha^{-1} compared to 357.4 N kg ha^{-1} under control conditions (Table 3). Among the organic manure treatments, the highest N was taken up by the crop where SPMC + *G. diazotrophicus* was used (761.6 kg ha^{-1}), followed by vermicompost + *G. diazotrophicus* (759.3 kg ha^{-1}). The net N balance was found to be negative in the control treatment, whereas it was positive in all other treatments. The highest net gains of 69 and 60 kg N ha^{-1} were recorded with the SPMC + *G. diazotrophicus* and SPMC alone treatments, respectively, followed by the vermicompost + *G. diazotrophicus* treatment (44.0 kg ha^{-1}). The minimum net gain of 20 kg N was observed under the conditions of recommended NPK supply

Table 3 Effect of different treatments on the N balance in the soil after the harvest of the sugarcane plant crop and the subsequent two ratoons (*Gd Gluconactobacter diazotrophicus*)

Treatment	Soil extractable N (kg ha^{-1})			N uptake by crop above ground (kg ha^{-1})	N balance[a] (kg ha^{-1})
	Initial level before planting	Amount added through organic manure/chemical	Final level after harvesting plant crop + two ratoon crops		
T_0 control	230.0	–	164.0	357.4	−66.0 g
T_1 vermicompost	230.0	450.0	266.0	656.0	+36.0 d
T_2 FYM	230.0	225.0	250.0	550.5	+20.0 f
T_3 biogas slurry	230.0	420.0	257.0	588.4	+27.0 e
T_4 press mud	230.0	450.0	290.0	689.7	+60.0 b
T_5 (T_1 + *Gd*)	230.0	450.0	274.0	759.3	+44.0 c
T_6 (T_2 + *Gd*)	230.0	225.0	259.0	641.9	+29.0 e
T_7 (T_3 + *Gd*)	230.0	420.0	264.0	689.9	+34.0 d
T_8 (T_4 + *Gd*)	230.0	450.0	299.0	761.6	+69.0 a
T_9 (*Sesbania* + *Gd*)	230.0	150.0	264.0	582.7	+34.0 d
T_{10} (NPK)	230.0	450.0	250.0	777.1	+20.0 f

Mean N balance followed by the same letter do not differ significantly at $P < 0.05$ by Duncan's multiple-range test. F-interaction analysis for N balance: manure treatment (T), S (Significant); inoculation factor (F), S; T × F, S

[a] N balance, $\text{Final}_N - \text{Initial}_N$ (after plant + ratoon crops)

through fertilizers. The contribution of *G. diazotrophicus* inoculation ranged from 7 to 9 kg ha^{-1} with different organic manures. The net balance was positive in all treatments except for the control treatment.

The removal of P was the highest (119 kg ha^{-1}) following the vermicompost + *G. diazotrophicus* inoculation, followed by 113.9 kg ha^{-1} removed following the SPMC + *G. diazotrophicus* inoculation (Table 4). After completion of the crop cycle of one plant crop and two ratoons, a net gain of 11.2 kg P ha^{-1} was found with the treatment comprising SPMC + *G. diazotrophicus* inoculation; this was followed by a net gain of 10.5 kg ha^{-1} P following SPMC application. The uptake of K was the highest (651.6 kg K ha^{-1}) in the vermicompost + *G. diazotrophicus* treatment, followed by vermicompost alone (646.5 kg K ha^{-1}) or SPMC (646.0 kg K ha^{-1}) + *G. diazotrophicus* inoculation (Table 5). The highest net gain of K in the soil was recorded with the SPMC + *G. diazotrophicus* treatment (72.1 kg K ha^{-1}), followed by the recommended NPK application through fertilizers (38.1 kg K ha^{-1}).

Soil physico-chemical and biological properties

Soil BD and water infiltration rates were changed due to incorporation of organic manures in the plant and ratoon crops. The plots receiving organic manures showed a decline in BD from 1.4 to 1.24 Mg m^{-3}, and the water infiltration rate in soil was improved by 30–35% over the initial status (Table 6). No change in BD was observed in control and chemically fertilized plots, and there was a variability of 5 and 2.5% in the infiltration rate in the control and chemically fertilized plots, respectively.

The application of organic manures brought about a substantial increase (56–94%) in the organic C content pool of the soil in comparison to the initial content (Table 6), with the highest relative increase (94%) occurring in the plots receiving SPMC + *G. diazotrophicus*. There was only a 9.3% increase in organic C in the control plot compared to 44% in the chemically fertilized plots. Intercropping of *Sesbania aculeata* between two sugarcane rows enhanced soil organic C content by 62.5% over the initial value. An enhancement of 58–87% in the total N content of the soil over the initial values was recorded in different

Table 4 Effect of different treatments on P balance in soil after the harvest of the sugarcane plant crop and the subsequent two ratoons (*Gd Gluconacetobacter diazotrophicus*)

Treatment	Soil extractable P (kg ha^{-1})			P uptake by crop above ground (kg ha^{-1})	P balance[a] (kg ha^{-1})
	Initial level before planting	Amount added through organic manure/chemicals	Final level after harvesting plant + two ratoon crops		
T_0 control	21.5	–	15.85	46.4	−5.65 f
T_1 Vermicompost	21.5	150.0	23.61	103.4	+2.11 d
T_2 FYM	21.5	81.0	22.20	89.6	+0.70 e
T_3 Biogas slurry	21.5	225.0	24.61	91.3	+3.11 c
T_4 Press mud	21.5	225.0	32.06	102.2	+10.56 a
T_5 (T_1 + *Gd*)	21.5	150.0	25.41	119.0	+3.91 c
T_6 (T_2 + *Gd*)	21.5	81.0	24.66	100.6	+3.16 c
T_7 (T_3 + *Gd*)	21.5	225.0	24.21	98.3	+2.71 d
T_8 (T_4 + *Gd*)	21.5	225.0	32.73	113.9	+11.23 a
T_9 (*Sesbania* + *Gd*)	21.5	45.0	31.41	83.2	+9.91 b
T_{10} (NPK)	21.5	180.0	30.70	97.4	+9.20 b

Mean P balance followed by the same letter does not differ significantly at $P < 0.05$ by Duncan's multiple-range test. F-interaction analysis for P balance: manure treatment (T), S (Significant); inoculation factor (F), NS (non-significant); T × F, NS

[a] P balance, $\text{Final}_P - \text{Initial}_P$ (after plant + ratoon crops)

Table 5 Effect of different treatments on K balance in the soil after the harvest of the sugarcane plant crop and the subsequent two ratoons (*Gd Gluconacetobacter diazotrophicus*)

Treatment	Soil extractable K (kg ha^{-1})			K uptake by crop above ground (kg ha^{-1})	K Balance[a] (kg ha^{-1})
	Initial before planting	Added through organic manure/Chemical	Final after harvesting plant + 2 ratoon crops		
T_0 control	217.9	–	246.0	321.1	+28.1 c
T_1 vermicompost	217.9	240.0	267.0	646.5	+49.1 b
T_2 FYM	217.9	75.0	266.0	592.4	+48.1 b
T_3 biogas slurry	217.9	240.0	268.0	569.4	+50.1 b
T_4 press mud	217.9	150.0	270.0	605.4	+52.1 b
T_5 (T_1 + *Gd*)	217.9	240.0	269.0	651.6	+51.1 b
T_6 (T_2 + *Gd*)	217.9	75.0	268.0	632.9	+50.1 b
T_7 (T_3 + *Gd*)	217.9	240.0	268.0	598.0	+50.1 b
T_8 (T_4 + *Gd*)	217.9	150.0	290.0	646.0	+72.1 a
T_9 (*Sesbania* + *Gd*)	217.9	240.0	268.0	547.4	+50.1 b
T_{10} (NPK)	217.9	180.0	256.0	645.0	+38.1 c

Mean K balance followed by the same letter does not differ significantly at $P < 0.05$ by Duncan's multiple-range test. F-interaction analysis for K balance: manure treatment (T), NS (non-significant); inoculation factor (F), NS; T×F, NS

[a] K balance, $\text{Final}_K - \text{Initial}_K$ (after plant + ratoon crops)

Table 6 Effect of different treatments on physico-chemical and biological properties of soil after harvest of sugarcane plant crop and subsequent two ratoons (*Gd Gluconacetobacter diazotrophicus*)

Treatment	Bulk density, Mg m^{-3a}	Soil aggregate mean wt. diameter, %[a]	Infiltration rate, mm h^{-1a}	Soil organic C, %[a]	Soil total N, %[a]	SMBC, mg C–CO_2 kg^{-1} soil[b]	SMBN, mg N-NH_4 kg^{-1} soil[b]
T_0 control	1.39 a (1.4)	15.3 b (0.7)	4.2 b (5.0)	0.35 e (9.3)	0.041 e (7.9)	687 e (0.0)	7.81 e (0.0)
T_1 vermicompost	1.25 b (10.7)	17.6 a (15.8)	5.4 a (35.0)	0.55 b (75.0)	0.066 b (73.7)	1136 c (65.4)	13.68 d (75.2)
T_2 FYM	1.25 b (10.7)	17.4 a (14.5)	5.2 a (30.0)	0.50 c (56.3)	0.060 c (57.9)	1035 d (50.7)	8.67 e (11.0)
T_3 biogas slurry	1.25 b (10.7)	17.3 a (13.8)	5.2 a (30.0)	0.51 c (59.4)	0.061 c (60.5)	1068 d (54.5)	11.04 e (41.4)
T_4 press mud	1.24 b (12.1)	17.8 a (17.1)	5.4 a (35.0)	0.56 b (75.0)	0.070 a (84.2)	1368 b (99.0)	22.22 b (184.5)
T_5 (T_1 + *Gd*)	1.25 b (10.7)	17.6 a (15.8)	5.4 a (35.0)	0.56 b (75.0)	0.070 a (84.2)	1236 c (79.9)	15.85 c (102.9)
T_6 (T_2 + *Gd*)	1.25 b (10.7)	17.4 a (14.5)	5.3 a (32.0)	0.51 c (59.4)	0.060 c (57.9)	1075 d (56.5)	11.04 e (41.4)
T_7 (T_3 + *Gd*)	1.25 b (10.7)	17.4 a (14.5)	5.2 a (30.0)	0.52 c (62.5)	0.061 c (60.5)	1148 c (67.1)	12.31 d (57.6)
T_8 (T_4 + *Gd*)	1.24 b (12.1)	17.8 a (17.1)	5.4 a (35.0)	0.62 a (93.8)	0.071 a (86.8)	1466 a (113.4)	25.68 a (228.8)
T_9 (*Sesbania* + *Gd*)	1.25 b (10.7)	17.4 a (14.5)	5.2 (30.0)	0.52 c (62.5)	0.068 b (78.9)	1336 b (94.5)	13.12 d (68.0)
T_{10} (NPK)	1.40 a (0.0)	15.6 b (2.6)	4.1 b (2.5)	0.46 d (43.8)	0.056 d (47.4)	880 e (28.1)	7.95 e (1.8)
Initial value	1.40 a	15.2 b	4.0 b	0.32 e	0.038 e	476 f	3.86 f

SMBC, Soil microbial biomass C; SMBN, Soil microbial biomass N. Means followed by the same letter do not differ significantly at $P < 0.05$ by Duncan's multiple-range test

[a] Values in parenthesis denote the percentage increase over the initial status

[b] Values in parenthesis denote the percentage increase over the control

organic manure treatments against a 47% increase in the chemically fertilized plots (Table 6). The observed increases in soil microbial biomass C (SMBC) varied according to the different treatments (Table 6). SPMC + *G. diazotrophicus* inoculation resulted in a 113% increase in SMBC relative to the control plots, followed by a 99% increase by SPMC alone. The supply of nutrients through chemical fertilizers enhanced SMBC by 28% in comparison to the control. The trend in soil microbial biomass N (SMBN) was similar to that of SMBC: the highest increase (229%) was recorded in plots treated with SPMC + *G. diazotrophicus*, while the lowest (2%) was with the chemical fertilizer treatment.

Discussion

In order to develop a strategy for the sustainable production of sugarcane while at the same time not compromising the productivity level, we have evaluated different organic manures that may be available to farmers in the form of farm or sugar industry in terms of their effect on crop yield, economic yield and soil biological and chemical quality. Different organic manures produced cane yields comparable to those obtained using the recommended levels of chemical NPK fertilizer. Organic manures are not only sources of major nutrients, but they also provide other micronutrients and plant growth-promoting molecules, which together lead to good crop yields (Mader et al. 2002). The sugarcane variety CoSe 92423, which was used in this study, responded well to organic manures, and the yield levels did not decline even after the second ratoon harvest.

Statistically, the at par cane yield in the plant and subsequent two ratoon crops with fertilizer application (76.1, 78.2 and 71.7 t ha^{1}) as well as that with most of the organic treatments may be attributed to their similar effects on growth and yield-attributing characters, such as cane length, cane thickness, cane weight and number of millable cane (data not shown). This effect is also reflected in the economic analysis as well: the B:C ratio was high in plots treated with SPMC + *G. diazotrophicus*. The increases in the B:C ratios in the ratoon crops were mainly due to the reduced cost of cultivation (approx. 30% lower than the plant crop) on account of the reduced costs for land preparation, seed and planting labour, etc.

The positive soil N, P and K balance that was observed in the plots with the organic manuring treatments after the cycle of sugarcane plant crop and two ratoons may be attributed to the richness of these sources in terms of organic matter and enhanced microbial activity. Although any permanent change in the soil organic C pool is very slow, any substantial increase in the temporary organic C pool of the soil will definitely act as a source of soil nutrients on a long-term basis. Increases in soil organic C due to the application of SPMC has also been reported by Dee et al. (2003) under sugarcane growing conditions, which often witnesses a loss of soil organic matter under conventional agriculture (Haynes and Hamilton 1999). The conspicuous improvement in soil health, including physical properties and microbial activity, upon the addition of organic manures is attributable to the role of organic matter in the granulation of soil particles that encourages a porous condition resulting in low BD (Rai 1995) and to increased spaces per unit volume that help enhance the infiltration rate. The granulation of soil particles under various treatments was corroborated by the increase in the mean weight-diameter of the water-stable aggregates. Each type of soil organism occupies a different niche in the web of life and favours a different substrate and nutrient source. Most soil organisms rely on organic matter for food; thus, a rich supply and varied source of organic matter will generally support a wider variety of organisms. Soil biodiversity can be stimulated by improving soil living conditions, such as aeration, temperature, moisture, and nutrient quantity and quality. In this regard, reducing soil tillage, minimizing compaction and refraining from the use of chemicals are of particular note.

Soil quality has been defined as the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality and promote plant and animal health (Doran and Parkin 1994; Staben et al. 1997). Soil microbial biomass C is a sensitive indicator of soil quality and influenced by many ecological factors, such as plant community composition, soil organic matter level, moisture, and temperature (Wardle 1992). In the present investigation, soil microbial activity, represented as SMBC and SMBN, showed varying degrees of enhancement due to the addition of manures, and at the second ratoon harvest, SMBC accounted for 3.88–5.36% of the soil organic C content, depending on the organic treatment. These values are in agreement with the report that SMBC generally comprises 1–4% of soil organic C (Anderson and Domsch 1989; Sparling 1992). Microbial biomass, although small (1–4% of organic C), plays a key role in governing nutrient recycling and energy flow due to its rapid turnover (Jenkinson and Ladd 1981; Li and Chen 2004). The SMBC:organic C ratio is a useful soil quality indicator as it enables comparisons to be made across soils in terms of organic matter content. Generally, if a soil is being degraded, the microbial C pool will decline at a faster rate than the organic C pool, and the SMBC:organic C percentage will decrease as well. These parameters indicate whether soils are accumulating or losing soil C. None of our treatments reduced the ratio of SMBC:organic C; instead, after harvesting the plant crop and two ratoons, the soil under the different organic treatments was found to accumulate more C. The total mass of micro-organisms in organic systems is generally 20–40% higher than that in the conventional system, and the ratio of microbial C to total soil organic C is higher in organic systems than in conventional systems. Organic management promotes microbial C and, thereby, soil C sequestration potential. Suman et al. (2006) have shown changes in sugarcane rhizosphere soil quality due to intercropping by different crops and their residue incorporation. The incorporation of labile C substrates, such as pulses, led to improved yield and N mineralization, and the buildup of a secondary C pool and microbial C demonstrated, in the case of cereals, mustard and potato, that intercropping can promote long-term stability.

Soil microbial biomass N was also found to be higher in plots receiving the organic manure treatments. An increase in mineralizable SMBN along with mineralizable SMBC, relative to the NPK treatment, indicates an efficient mobilization/immobilization of the nutrients, a condition ideal for the growth of any crop plant. The increase in soil organic C and total N relative to their initial content with SPMC and vermicompost must have resulted from the enhanced activities of microbes and earthworms. On the other hand, thepresence of lignified compound in organic manures could be responsible for the slow release of nutrients, resulting in reduced losses and the build-up of a soil N pool.

Conclusion

We conclude that the sugarcane crop responded well to different organic manures and crop residues recycling in the multiple ratooning system. These not only gave a better economic output, but improved the condition of the soil in terms of a positive nutrient balance and high microbial activity. A strategy involving the integrated application of these manures with inorganic chemicals will not only sustain our soils but will also be beneficial for our farmers in terms of cost-savings (i.e. for chemical fertilizers) and sustainability. Organic agricultural systems enhance the ability of farmers to live in harmony with nature and to derive economic benefit from their land while simultaneously conserving and improving the natural environment

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