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Effect of bio-manures on soil quality, cane productivity and soil carbon sequestration under long-term sugarcane (*Saccharum officinarum*) plant - ratoon system in Indian sub-tropics

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ABSTRACT

Multi-ratooning increases productivity and profitability of the sugarcane (*Saccharum officinarum* L.) production system, however the cane yields decline in subsequent ratoon crops owing to declining soil health. The present field experiment was conducted to assess the long-term effect of bio-manure addition on yield, soil quality and carbon sequestration in sugarcane plant-ratoon system during 2003-2013. It consisted of 10 treatments, viz. farmyard manure (FYM) (10 t/ha), biogas slurry (BS) (10 t/ha), sulphitation press mud cake (SPMC) (10 t/ha), vermi-compost (VC) (10 t/ha) alone and each in combination with *Gluconacetobacter diazotrophicus* (*Gd*), control and recommended dose of fertilizers (RDF). The plant and ratoon crops yields with farmyard manure, sulphitation press mud cake (SPMC), biogas slurry and vermi-compost added alone (10 t/ha) or with *Gluconacetobacter diazotrophicus* (*Gd*) were at par with RDF till the fourth ratoon crop. However, significant increase in ratoon crop yield with bio manures addition over RDF were recorded from fifth to ninth ratoon crop. Bio manure addition enhanced soil quality through increased SOC, infiltration rate (up to 47.5%), soil aggregates (up to 20.3%), soil microbial biomass carbon (SMBC) and microbial biomass nitrogen (SMBN) and decreased bulk density (up to 12.1%). The highest increase in SOC (72%), SMBC (413.86%) and SMBN (113.88%) were registered with SPMC + *Gd* addition. A two fold increase was recorded in average annual rate of soil carbon sequestration (1.05 to 1.97 t/ha/yr) against control (0.49 t/ha/yr). A linear relationship existed between SOC, carbon sequestration rate, cane yield and gross carbon input.

Key words: Bio manures, Long term plant-ratoon system , Sequestration, Soil carbon, Soil quality, Sugarcane

Soil quality holds the prime importance for productivity of long duration high biomass producing crops like sugarcane (*Saccharum officinarum* L.) as it describes the sum total of physical, chemical and biological properties of soil and thus regulate the nutrient and moisture availability dynamics and rooting behaviour. Fortunately, sugarcane production system comprise of ratooning (practice of growing succeeding crop from the stubble of previous plant crop) and is practiced to take advantage of savings on land preparation and seed and planting costs. Besides, this helps improving the soil health conspicuously by addition of organic residues in the form of root biomass and resultant improvement in soil physical as well as microbial properties (Singh *et al*. 2007).

Sugarcane cultivation in many countries (Brazil, Ethiopia, Australia, *etc*.) as a plantation crop, characterized by 8-10 harvestings of once planted crop with meagre soil disturbance, effectively harvests the positive influence of multi-ratooning (growing as many number of ratoon crops as possible after single planting) and lead to soil enrichment as a natural process provided green cane harvesting is practiced. Gunshiam *et al*. (2014) reported that long term sugarcane cultivation resulted in sequestration of sugarcane derived-C which adequately compensated the losses occurred in native SOC stock. Similarly, advantage of zero/minimum tillage in terms of buildup of SOC has been reported by Bhaduri *et al.* (2014) from Indo-Gangetic plains which was positively correlated with the crop as well as cropping system productivity. On the contrary, in sugarcane growing soils of Indo-Gangetic plains, sugarcane stubbles are immediately uprooted to facilitate sowing of succeeding crop in the same field after harvest of plant or a ratoon crop. Such a practice robs of positive influences of ratooning on soil

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quality and leaves the soils diminished in terms of physical, physico-chemical and biological properties leading to overall decline in the soil quality. Consequently, a management responsive and high nutrient requiring crop like sugarcane suffers adversities including inadequate nutrient availability, moisture stress and sub-optimal growth and development. As a corrective measure integration of various nutrient sources, viz. bio-manures, fertilizers and bio-fertilizers are being increasingly advocated and adopted (Singh *et al*. 2007) to restore soil fertility, in particular and quality, in general. However, under such management strategies where only one ratoon crop is taken SOC enrichment remain short lived as only labile organic carbon increases are brought about by intermittent addition of organic resources.

Further, for sugarcane production system, the number of ratoon crops determines the performance in terms of cane yield, sugar recovery and overall profitability. However, a decline in the yield of successive ratoons, termed as *ratoon decline*, occurs universally owing to varietal, environmental and agronomic management, the last being the most important (Ramburan *et al*. 2013) for its overriding effects on all the three and final impact on soil quality. Since soil fertility management practices including the source of nutrients play major role in determining the soil quality and system productivity, the present work was carried out to assess the long term effect of different bio-manures on sustainability of soil quality, cane productivity and soil carbon sequestration. Improvement in cane productivity and soil properties (Singh *et al*. 2007) and the status of SOC build up in sugarcane soils up to fourth subsequent ratoon (Archna *et al*. 2009) has already been reported. However, investigation was continued up to 9th ratoon to compare the long term effect of bio-manure addition on soil nutrient balance, soil quality indicators, soil carbon sequestration and cane productivity in comparison to that with application of RDF.

MATERIALS AND METHODS

Field experiment comprising a sugarcane plant crop and subsequent nine ratoons was carried out during 2003-2013 at the ICAR-Indian Institute of Sugarcane Research, Lucknow (26^{0}56'N, 80^{0}52'E, 111 m above mean sea level). Climate of the location is characterized as semi-arid sub-tropics with cold winter and dry hot summer. The bulk of rainfall is received during June to September through south-west monsoon, average being 976 mm annually. The soil of the experimental site was a sandy loam, non-calcareous mixed hyper thermic *udic Ustochrept* (13.3% clay, 24.5% silt and 62.2% sand) of Indo-Gangetic alluvial origin having a pH of 7.68, a bulk density (BD) of 1.4 Mg/m^3, an aggregate size (>0.25 mm) of 15.2%, infiltration rate of 4.0 mm/hr, 0.32% organic carbon, 230 kg/ha available N, 21.5 kg/ha P and 217.9 kg/ha K. Ten treatments comprising 10 t/ha farmyard manure (FYM), 10 t/ha biogas slurry (BS), 10 t/ha sulphitation press mud cake (SPMC) and 10 t/ha vermi-compost (VC) alone and each in combination with *Gluconacetobacter diazotrophicus* (*Gd*), control (no nutrient application) and recommended dose of fertilizers (RDF) supplying NPK (150: 60:60 kg/ha) were evaluated in RBD with three replications. Average nutrient composition of bio-manures applied to the soil continuously for all 10 crops is recorded in Table 1. Sugarcane (CoSe 92423) was planted in spring 2003 at 75 cm row spacing using three-bud setts. Inoculation with bio-fertilizer *Gd* was done through sett treatment wherein sugarcane setts were dipped before planting in culture solution containing 10^7 cfu/ml for 30 min. Recommended dose of fertilizers in relevant treatments were applied in three splits comprising basal application of half dose of nitrogen and full dose of P and K and two top dressings of equal splits of remaining N at 45 and 90 days after planting/ratoon initiation. Bio-fertilizer application in ratoons was done by drenching of root zone at the time of ratoon initiation. All the crops were managed as per the recommended package of practices for plant and ratoon crops of sugarcane. Plant crop was harvested at 12 months and the first ratoon crop was initiated in February 2004, however the subsequent eight ratoon crops were initiated in the month of January every year.

Soil sampling at initial stage was done with the help of tube-type auger from 0-to 15-cm and 15-30 cm depths. Determination of organic carbon content (Walkley and Black 1934), soil N by the Kjeldahl method (Jackson 1973) and available N by alkaline permanganate method (Subbiah and Asija 1956) was done separately for each plot. Available P was assessed by phosphate extraction in 0.5 M sodium bicarbonate solution (pH 8.5) and colorimetric determination by blue color method (Jackson 1973). Available potassium (K) was extracted with normal neutral ammonium acetate solution by displacement of the exchangeable cations and estimated by flame photometer (Jackson 1973). Soil pH determination was done in a 1:2.5 soil water suspension using a glass electrode pH meter. A core sampler was used for measuring the bulk density (BD) at initial and harvest stage of 9th ratoon crop. Aggregate size distribution- wet sieving (Yodor 1936), water infiltration rate measured *in situ* using double ring infiltrometer (Bertrand 1965) and mechanical analysis was done according to international pipette method (Piper 1966). Soil microbial biomass carbon (SMBC) and microbial biomass nitrogen (SMBN) were determined using the chloroform fumigation extraction method (Anderson 1982). Annual rate of change in soil organic carbon (SOC)

Table 1 Average composition of nutrients in bio-manures on dry weight basis

Bio-manure	Nutrient composition (%)			
	Organic carbon	N	P	K
Vermi-compost	40	1.50	0.50	0.80
FYM	46	0.75	0.27	0.25
Biogas slurry	55	1.40	0.75	0.80
SPMC	40	1.50	0.75	0.50

N, Nitrogen; P, phosphorus; K, potassium; FYM, farmyard manure; SPMC, sulphitation press mud cake was calculated. Soil organic C- sequestration in different treatments was calculated as net increase of SOC content (t/ha) over unfertilized control (Aulakh *et al*. 2001). Plant biomass accumulation was recorded by estimation of above ground dry weight and added to this was dry weight of fallen leaves (3.7% of above ground biomass) and root biomass taken as 30% of the above ground biomass (Archna *et al*. 2009). The C input in soil was calculated on observed carbon content in various plant parts. The content in leaf, shoot and root biomass was estimated by dry combustion at 550^{o} C as described by Page *et al*. (1982). The contribution of C through rhizo-deposition was calculated by assuming the root exudates to represent 0.15 g/g of the above ground biomass as given by Bronson *et al*. (1988). Plant samples for recording of above ground biomass accumulation and nutrient uptake at harvest were taken as destructive sampling from 1-m row length and oven dried. To assay uptake of nutrients samples were wet digested in concentrated H_2SO_4 for determination of total N, and in di-acid mixture of nitric acid and perchloric acid (4:1) for determination of total P and K (Jackson 1973). Statistical analysis of data was done following standard procedure.

RESULTS AND DISCUSSION

Soil quality indicators

Conspicuous improvement in physical and biological quality indicators of the soil was recorded at 9th ratoon harvest. Enhancement in soil physical properties was evident from reduction in BD to up to 1.23 under different bio-manures from initial 1.40 Mg/m^3, increase in infiltration rate to up to 5.9 mm/hr from the initial 4 mm/hr and enhanced soil aggregates (> 0.25 mm mean weight diameter) from initial 15.2 to 18.3%. SPMC applied alone or in combination with *Gd* brought about 12.1% reduction in BD, 20.39% increase in soil aggregates and 47.5% higher water intake in soil over the corresponding initial status. All other bio-manures were found statistically similar, however application of RDF (150, 60,60 kg/ha NPK) did not record any improvement in BD and only a slight increase in infiltration rate (12.5%) and soil aggregates (1.97%). Control did not show any improvement in soil physical properties (Table 2). Significant enrichment of SOC content from initial 0.32% to up to 0.72%, was recorded with bio-manures, the highest being with the addition of SPMC in combination of *Gd*. Other bio-manures were found statistically similar with each other, except SPMC alone which was similar to SPMC + *Gd*. On the other hand, regular RDF application brought about 46.8% increase in SOC and even control added 25% SOC over the initial. Improvement in soil physical properties, viz. BD, infiltration rate and enhanced stable aggregates due to addition of bio-manures is directly related to SOC content which, in this study, registered perceptible increase over the period (up to 125% with SPMC against just 25% in control and 46.8% with RDF) and owing to its cementing action (Kaur *et al*. 2008) extent of soil aggregates (> 0.25 mm) enhanced by 17.76 to 20.39% under different bio-manures (against mere 1.97% increase in control and RDF) that led to reduction in BD and increase in infiltration rate. Blair and Crocker (2000) held that SOC influences soil structural stability conferring better growing conditions for roots. Increase in SOC under the control might be ascribed to continuous addition of root stubbles over the period.

Increase in soil microbial biomass carbon (SMBC) due to different bio-manures varied from 270.5 to 413.8% over the initial (47.6 mg C-CO_2/kg soil/10 day). All the bio-manures under evaluation brought about greater enhancement in SMBC over that with RDF (Table 3). Enhanced N mineralization was evident from palpable increase in soil microbial biomass nitrogen (SMBN) during the period from initial 3.6 to up to 7.7 mg N-NH^4/kg soil/10 day against 3.5 and 2.0 in control and RDF, respectively.

Table 2 Changes in soil physical properties over initial level with bio-manures after harvest of ninth ratoon crop

Treatment	Bulk density (Mg/m^3)	% change over initial	Soil aggregate over 0.25mm (%)	% change over initial	Infiltration rate (mm/hr)	% change over initial
Initial	1.40		15.2		4	
Control	1.39	-0.71	15.5	1.97	4.2	5.0
RDF (NPK: 150, 60, 60 kg/ha)	1.40	00	15.5	1.97	4.5	12.5
Vermi-compost (10 t/ha)	1.24	-11.42	17.9	17.76	5.7	42.5
Farmyard manure (10 t/ha)	1.24	-11.42	17.8	17.10	5.7	42.5
Biogas slurry (10 t/ha)	1.24	-11.42	17.7	16.44	5.7	42.5
SPMC (10 t/ha)	1.23	-12.14	18.3	20.39	5.9	47.5
Vermi-compost (10 t/ha) + *Gd*	1.24	-11.42	17.9	17.76	5.7	42.5
Farmyard manure (10 t/ha) + Gd	1.24	-11.42	17.8	17.10	5.7	42.5
Biogas slurry (10 t/ha) + *Gd*	1.24	-11.42	17.7	16.44	5.7	42.5
SPMC (10 t/ha) + *Gd*	1.23	-12.14	18.3	20.39	5.9	47.5
CD (P=0.05)	0.05				0.28	

RDF, Recommended dose of fertilizers; N, nitrogen; P, phosphorus; K, potassium; FYM, farmyard manure; SPMC, sulphitation press mud cake; *Gd*, *Gluconacetobacter diazotrophicus*

Table 3 Changes in soil biological properties and soil organic carbon content over initial level with bio-manures after harvest of ninth ratoon crop

Treatment	SOC (%)	% change over initial	SMBC (mg C-CO_2/ kg soil /10 day)	% change over initial	SMBN (mg N-NH_4/ kg soil /10 day)	% change over initial
Initial	0.32		47.6		3.6	
Control	0.40	25.00	139.9	193.90	3.5	-2.77
RDF (NPK: 150, 60, 60 kg/ha)	0.47	46.80	146.7	208.19	2.0	-44.44
Vermi-compost (10 t/ha)	0.55	71.87	177.1	272.05	3.3	-8.33
Farmyard manure (10 t/ha)	0.55	71.87	195.5	310.71	5.8	61.11
Biogas slurry (10 t/ha)	0.55	71.87	195.0	309.66	4.5	25.00
SPMC (10 t/ha)	0.70	118.75	244.4	413.44	7.7	113.88
Vermi-compost (10 t/ha) + *Gd*	0.51	59.37	176.4	270.58	3.3	-8.33
Farmyard manure (10 t/ha) + *Gd*	0.56	75.00	195.6	310.92	5.6	55.55
Biogas slurry (10 t/ha) + *Gd*	0.57	78.12	195.0	309.66	4.5	25.00
SPMC (10 t/ha) + *Gd*	0.72	125.00	244.6	413.86	7.7	113.88
CD (*P*=0.05)	0.03	-	-	-	-	-

RDF, Recommended dose of fertilizers; N, nitrogen; P, phosphorus; K, potassium; FYM, farmyard manure; SOC, soil organic carbon; SMBC, soil microbial biomass carbon; SMBN, soil microbial biomass nitrogen; SPMC, sulphitation press mud cake; *Gd*, *Gluconacetobacter diazotrophicus*

The highest increase in SMBN (113.8%) over the initial was there with SPMC addition alone or along with *Gd* and the lowest with biogas slurry (25%) with or without *Gd*. Zero nutrient addition resulted in 2.77% reduction in initial SMBN, however the loss was more tepid with RDF application wherein 44.44% reduction was recorded. The nutrient balance sheet, taking into account total addition and removal of nutrients by all the crops, indicate that various manures left a positive N balance ranging from 27 to 33.4 kg/ha against the net loss of 33 kg/ha in control and mere 5 kg positive balance with RDF application. Balance of P in soil remained positive under all the treatments being lowest under control (2.5 kg/ha) and highest with SPMC + *Gd* (31.5 kg/ha). Final P balance under RDF application was 7.5 kg/ha. Exchangeable K was recorded positive under all the treatments and various bio-manures could accumulate additional K ranging from 73.1 kg to 108.1 kg/ha against 3.8 kg in control and 94.1 kg with the application of RDF (Table 4).

Addition of bio-manures in a production system on long term basis enables buildup of SOC upon microbe mediated decomposition of organic matter influenced by

Table 4 Nutrient addition, removal and available balance in soil with bio-manures after harvest of ninth ratoon

Treatment	Soil extractable nutrients (kg/ha)											
	Total amount of nutrient added through fertilizer/bio-manures in 10 years			Final nutrient level after harvest of ninth ratoon crop			Total amount of nutrient removed by crops in 10 years			Available nutrient balance in soil after harvest of ninth ratoon crop		
	N	P	K	N	P	K	N	P	K	N	P	K
Control	-	-	-	197.0	24.0	221.7	751.6	84.8	882.3	- 33.0	2.5	3.8
RDF (NPK: 150, 60, 60 kg/ha)	1500.0	600.0	600.0	235.0	29.0	312.0	1748.4	217.5	1732.2	+ 5.0	7.5	94.1
Vermi-compost (10 t/ha)	1500.0	500.0	800.0	257.0	52.0	291.0	1505.1	211.8	1713.4	+ 27.0	30.5	73.1
Farmyard manure (10 t/ha)	750.0	270.0	250.0	260.3	52.0	311.0	1415.7	187.9	1707.3	+ 30.3	30.5	93.1
Biogas slurry (10 t/ha)	1400.0	750.0	800.0	257.2	50.0	310.0	1447.4	196.6	1623.6	+ 27.2	28.5	92.1
SPMC (10 t/ha)	1500.0	750.0	500.0	263.4	52.8	326.0	1620.1	218.7	1683.4	+ 33.4	31.3	108.1
Vermi-compost (10 t/ha) + *Gd*	1500.0	500.0	800.0	257.0	45.0	292.0	1682.9	232.4	1734.8	+ 27.0	23.5	74.1
Farmyard manure (10 t/ha) + Gd	750.0	270.0	250.0	260.3	46.0	319.0	1523.5	211.6	1700.6	+ 30.3	24.5	101.1
Biogas slurry (10 t/ha) + *Gd*	1400.0	750.0	800.0	257.2	46.0	307.0	1567.0	208.5	1660.7	+ 27.2	24.5	89.1
SPMC (10 t/ha) + *Gd*	1500.0	750.0	500.0	263.0	53.0	316.0	1747.0	247.9	1736.5	+ 33.0	31.5	98.1

Initial status of extractable nutrient N, P and K are 230, 21.5 and 217.9 kg/ha, respectively. RDF, recommended dose of fertilizers; N, nitrogen; P, phosphorus; K, potassium; FYM, farmyard manure; SPMC, sulphitation press mud cake; *Gd*, *Gluconacetobacter diazotrophicus* temperature, rainfall and ambient soil conditions (Murphy *et al*. 2007) which leads to release of plant nutrients in a slow but steady rate suiting to nutrient uptake pattern of sugarcane crop reported to lack the matching uptake capacity for fluxes of inorganic N released in fertilized sugarcane soils (Brackin *et al*. 2015). Mentionable here is the fact that in the same study after first ratoon, soil P and K balance was found negative under all the bio-manures and RDF (Singh *et al*. 2007) which turned positive over the period along with available N. This can be ascribed to enhanced SOC stock that functioned as reservoir of these nutrients because of high negative charge and resultant cation exchange capacity (Kaur *et al*. 2008), besides the physical protection of nutrients within soil macro-aggregates (Sodhi *et al*. 2009) which kept these safe from fixation and other losses. Marked increase in SMBC due to different bio-manures indicate proliferation of microbes and their activity owing to yearly amplification of substrate in the soil and the residual decomposition of organic matter added previously. Continuous release of plant nutrients from added bio-manures for longer time compared with mineral fertilizers (Ginting *et al*. 2003) might be responsible for sustaining the microbial activity at a higher rate over that with RDF. Microbial carbon was found to contribute from 3.22 to 3.55% to SOC under different bio-manures against that of 3.12% in RDF. Higher final SOC under bio-manures than RDF show positive correlation between SOC and microbial carbon. Further, the substantial enhancement in the proportion of microbial C to SOC at the end of the production system, i.e. from initial 1.48 to up to 3.55% depicts the improvement in soil quality due to addition of bio-manures as microbial C (generally 1- 4% of organic C) regulates the nutrient cycling and energy flow owing to its fast turn over (Li and Chen 2004). Ratio of microbial C to organic C, however small, represents the C accumulation in soil and its quality. As soils under different bio-manures recorded enhanced microbial to organic C ratio over the initial it can be safely inferred that bio-manure addition effectively contributed towards soil quality improvement over the period in sugarcane plant-ratoon system.

Nutrient availability for uptake by the crop depends among many factors on release of nutrients and accumulation in the labile pool. Our study revealed that SMBN finally enhanced by 25 to 113.88% due to different bio-manures over the initial, however, a slight reduction (8.33%) was noticed under vermi-compost addition alone or with *Gd* against 44.44 and 2.77% reductions under RDF and control, respectively. This highlights slow release of N from added amendment upon microbial decomposition and its subsequent accumulation in the soil. It has been reported by Brackin *et al*. (2015) that flux of available N exceeds the N acquisition ability of sugarcane roots under inorganic N supply at all the crop growth stages and it has an ability to meet its N requirement through uptake of organic N particularly during grand growth stage (Vinall *et al*. 2012). These findings explain the loss of N under RDF and soil enrichment with N under bio-manures. Further we can assume that availability of organic N under bio-manures must be higher over that of RDF which keeps the crop well-nourished during grand growth phase and hence higher biomass accumulation and yield. It has been reported that amino acids, peptides, proteins and quarternary ammonium compounds and other organic forms present in soil are metabolized and taken up by the plants and fluxes of amino acids were found significantly higher in organic fertilized soils than inorganic and un-fertilized soils (Brackin *et al*. 2015).

Total uptake of major nutrients (N, P and K) by crops over a period of time and by different crops in a system in the long run indicate about the efficacy of an amendment as a nutrient source and its capability to make the nutrients available at the required time and stage of the crop. Addition of SPMC with *Gd* proved equally effective to RDF as N, P and K uptake collectively by the sugarcane plant and ratoon crops of the system under the treatment was similar for N (1747 kg/ha against 1748.4 kg/ha with RDF) and higher for P (247.9 against 217.5 kg/ha) and K (1736.5 against 1732.2 kg/ha). The other bio-manures too registered similar uptake of these nutrients in the system. Balance of these nutrients in soil was positive under all the treatments, except control that recorded a loss of 33 kg N/ha at the end of the system. Further, a higher final balance of N, P and K in soil under different bio-manures over that with RDF suggests that bio-amendment based nutrient supply in sugarcane long term plant-ratoon system adds to soil quality by enhancing the fertility status.

Sugarcane yield, gross carbon input and soil carbon sequestration

Use of bio-manures effected conspicuous enhancement of cane yield in plant and subsequent ratoon crops (Table 5) as that with RDF over control. After a marginal increase in cane yield of first ratoon over the plant crop it gradually declined up to the ninth ratoon crop being steeper in control as compared to the bio-manures and the RDF. Phenomenon of ratoon yield decline has been well investigated and build-up of ratoon stunting pathogen, comparatively less radiation use efficiency, gaps in crop stand and perpetuation of weeds have been reported to be majorly responsible for this (Ramburan *et al*. 2013, Srivastava *et al*. 2002). However, these adversities can be addressed to some extent with better management (Ramburan *et al.* 2013) is evident from the findings that addition of bio-manures, by positively influencing the soil quality, arrested the yield decline in subsequent ratoon crops.The highest cane yield in plant crop (78.6 t/ha) was produced with vermi-compost and *Gd* followed by SPMC and *Gd* (77.5 t/ha) as compared to 76.1 t/ha with RDF and 53 t/ha in control. The mean cane yield for the system was lowest (31.07 t/ha) in control and the highest with addition of SPMC and *Gd* (65.87 t/ha). Application of RDF recorded 61.15 t/ha mean cane yield while it ranged with different bio-manures from 60.2 to 65.87 t/ha.

The mean annual gross carbon input (GCI) under

Table 5 Sugarcane yield in plant and nine subsequent ratoon crops with bio-manures

Treatment	Sugarcane plant and ratoon yield (t/ha)										Mean cane yield
	Plant	R1	R2	R3	R4	R5	R6	R7	R8	R9	
Control	53.0	46.3	41.8	37.6	35.0	24.8	18.5	18.7	19.0	16.0	31.07
RDF (NPK: 150, 60, 60 kg/ha)	76.1	78.1	71.6	66.5	64.3	53.8	51.0	51.0	49.8	49.3	61.15
Vermi-compost (10 t/ha)	76.7	77.7	70.4	64.6	64.3	54.5	54.0	53.9	51.0	50.7	61.78
Farmyard manure (10 t/ha)	70.9	70.7	68.3	63.3	63.0	55.0	54.9	53.5	51.5	51.0	60.21
Biogas slurry (10 t/ha)	71.9	70.4	68.8	63.5	63.2	54.8	54.4	53.2	51.0	50.8	60.20
SPMC (10 t/ha)	75.3	77.9	72.5	67.4	67.3	57.9	57.5	54.8	53.6	53.2	63.74
Vermi-compost (10 t/ha) + *Gd*	78.6	79.0	71.6	65.8	65.6	54.6	54.2	53.2	51.0	50.8	60.20
Farmyard manure (10 t/ha) + *Gd*	74.0	72.1	69.6	64.4	64.3	55.2	55.0	54.3	51.6	51.3	61.18
Biogas slurry (10 t/ha) + *Gd*	75.0	72.6	69.7	64.7	64.0	54.5	54.5	54.1	51.0	51.0	61.11
SPMC (10 t/ha) + *Gd*	77.5	80.8	74.8	70.0	69.5	60.5	60.0	57.4	54.2	54.0	65.87
CD (*P*=0.05)	6.5	9.7	5.7	5.8	4.6	4.2	4.3	5.1	4.3	3.6	

RDF, Recommended dose of fertilizers; N, nitrogen; P, phosphorus; K, potassium; FYM, farmyard manure; SPMC, sulphitation press mud cake; *Gd*, *Gluconacetobacter diazotrophicus*; R, ratoon

different treatments varied from 4.11 t/ha/yr in control to 11.73 t/ha/yr with the regular addition of FYM (Table 6). Application of RDF resulted in 7.34 t/ha/yr GCI, whereas the same with different bio-manures varied from 10.84 to 11.73 t/ha/yr. Carbon input in soil through manures ranged between 3.51 and 4.55 t/ha/yr, being the lowest with vermi-compost alone or with *Gd* and the highest with FYM alone or with *Gd*. Carbon input through root deposition was the highest (3.46 t/ha/yr) with SPMC + *Gd* and the lowest in control (1.78 t/ha/yr). RDF on the other hand accrued 3.24 t/ha/yr root carbon. Rhizo deposition was found highest (3.86 t/ha/yr) under SPMC with *Gd* followed by SPMC alone (3.77 t/ha/yr). In control rhizo deposition contributed 2.06 t/ha/yr whereas it was 3.64 t/ha/yr with RDF. Carbon input through fallen leaves was found lowest (0.27 t/ha/yr) in control and the highest (0.46 t/ha/yr) in SPMC and RDF. It was evident that carbon input through roots, fallen leaves and rhizo deposition under various bio-manures either matched those accrued under RDF or surpassed the same. GCI exhibited significant influence over the cane yield and the final SOC content as the correlation between cane yield and GCI (Fig 1a) was positive linear (r= 0.714) similar to the positive linear correlation (r= 0.907) between GCI and SOC content at the harvest of ninth ratoon crop (Fig 1b).

Finally the soil carbon sequestration over the years in the cropping system was worked out to range from 4.92 t/ha to 19.75 t/ha. SPMC alone or with *Gd* helped sequester higher quantity of carbon in soil than other bio-manures. RDF could accrue 9.51 t/ha carbon in soil against 4.92 t/ha recorded in control plots. Among bio-manures each of vermi-compost, FYM and biogas slurry made the soil richer in carbon by 10.59 t/ha over the initial, however the same under SPMC was 18.64 t/ha. Inclusion of *Gd* in nutrient supply schedule with bio-manures brought about

Table 6 Carbon sequestration rates and gross carbon input, through bio manure addition in sugarcane plant and nine subsequent ratoon crops

Treatment	Carbon input through different sources				Gross carbon input (t/ha)	SOC (t/ha)	SOC change (t/ha)	C-sequestration (t/ha/yr)
	Manure	Roots	Fallen leaves	Rhizo deposition				
Control	-	1.78	0.27	2.06	4.11	20.1	-	-
RDF (NPK: 150, 60, 60 kg/ha)	-	3.24	0.46	3.64	7.34	25.02	4.92	0.49
Vermi-compost (10 t/ha)	3.51	3.24	0.45	3.64	10.84	29.61	9.51	0.95
Farmyard manure (10 t/ha)	4.55	3.20	0.43	3.55	11.73	30.69	10.59	1.05
Biogas slurry (10 t/ha)	4.55	3.15	0.44	3.54	11.68	30.69	10.59	1.05
SPMC (10 t/ha)	3.65	3.36	0.46	3.77	11.24	30.69	10.59	1.05
Vermi-compost (10 t/ha) + *Gd*	3.51	3.24	0.40	3.69	10.84	38.74	18.64	1.86
Farmyard manure (10 t/ha) + *Gd*	4.55	3.18	0.40	3.61	11.74	28.45	8.35	0.83
Biogas slurry (10 t/ha) + *Gd*	4.55	3.22	0.39	3.58	11.74	31.24	11.14	1.11
SPMC (10 t/ha) + *Gd*	3.65	3.46	0.42	3.86	11.39	31.80	11.70	1.17

RDF, Recommended dose of fertilizers; N, nitrogen; P, phosphorus; K, potassium; FYM, farmyard manure; SPMC, sulphitation press mud cake; *Gd*, *Gluconacetobacter diazotrophicus*; SOC, soil organic carbon.

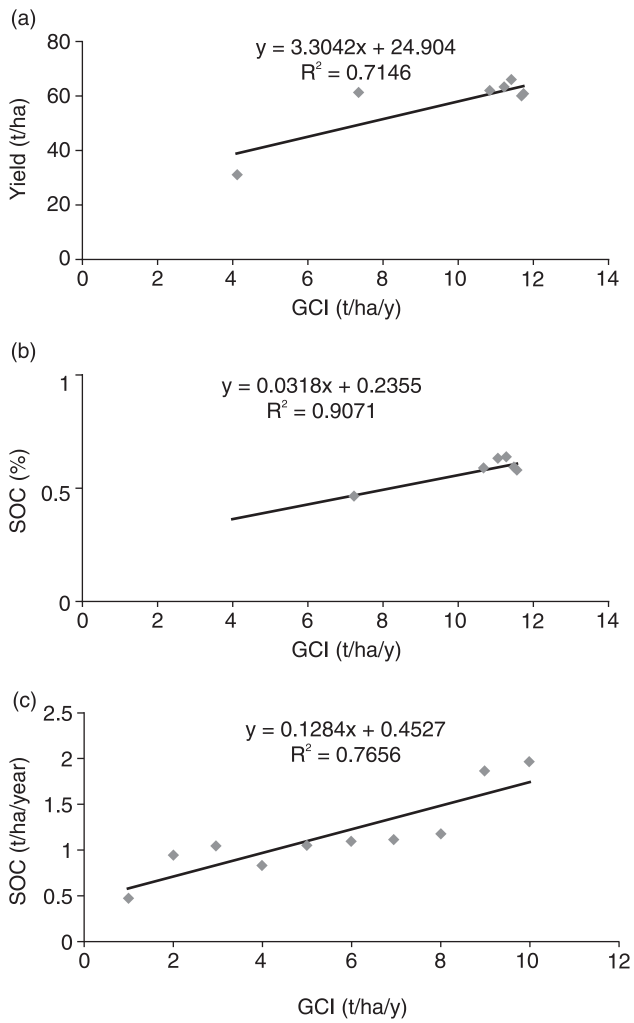

Fig 1 Correlation of gross cabron input (GCI) with (a) sugarcane yield, (b) soil organic carbon content and (c) soil carbon sequestration rate

improvement in soil carbon sequestration than that effected due to these manures alone, except vermi-compost. The annual soil carbon sequestration was the highest with addition of SPMC + *Gd* (1.97 t/ha/yr) and the lowest in control (0.49 t/ha/Yr), whereas application of RDF resulted in annual carbon sequestration of 0.95 t/ha/yr (Table 6). A linear positive correlation (r = 0.765) was observed between GCI and the annual sequestration of carbon in soil (Fig 1c). It is noteworthy that all the bio-manures effected higher sequestration of carbon in soil than the RDF in a long term sugarcane plant-ratoon system. Higher soil carbon sequestration under bio-manures happened possibly owing to higher gross carbon input as significantly positive correlation (r=0.765) existed between the two (Fig 1c). It is interesting to note that annual carbon sequestration up to the harvest of fourth ratoon crop in the study (Archna *et al.* 2009) was higher under RDF (1.59 t/ha/yr) as well as bio-manures (2.93-3.43 t/ha/yr) than at harvest of the ninth ratoon crop. These findings are in conformity with the report that under intensive agricultural practices, as in RDF and control in our case, the rate of organic carbon sequestration ranges from 0.3 to 0.5 t/ha/yr (Lal 2007). However, relatively less stabilization of organic carbon in arable soils receiving high quantity of organic materials occur in the long run (Sleutel *et al*. 2006). Higher soil carbon sequestration due to regular SPMC addition over a long period may be attributed to low decay rate constants for organic matter supplied through this bio-manure. Findings from the same experiment conducted on C loss due to soil respiration during fourth ratoon crop under the same plant-ratoon system revealed a linear relationship between C input and respiratory loss of C (R^2=0.935). Residual respiratory carbon loss of approximately 2.5 t/ha/yr was worked out even under no C input based on humification rate constant of 0.38 leading to a loss of carbon at the rate of 1.0 t/ha/yr from native soil organic matter and the addition of bio-manures was found to reduce the decay rate constant of soil organic matter (Archna *et al*. 2009). However, decay rate constant calculated based on Jenkinson (1988) equation showed that continuous long-term addition of FYM, biogas slurry and vermi-compost caused higher (0.111, 0.110 and 0.100, respectively) decay rate over the RDF (0.062) and control (0.081). Addition of SPMC alone (0.062) or with Gd (0.059) recorded a lower decay rate than the control that might have caused the highest sequestration of carbon under this.

Sugarcane production system composed of plant and subsequent ratoon crops itself adds substantial quantity of organic matter into the soil as stubbles, dried leaves and root deposition. However, it is unable to sustain the soil quality and system productivity on its own. Supply of plant nutrients through fertilizers and other sources is therefore required to sustain the soil quality and crop productivity. Bio manure addition led to reduction in bulk density, increase in infiltration rate, soil aggregates, SOC, soil microbial biomass carbon and microbial biomass nitrogen. Along with, it more than doubled the annual rate of soil carbon sequestration that enriched soil organic carbon pools and left a positive nutrient balance (N, P and K) after harvest of ninth ratoon crop. SPMC alone or in combination with *Gluconacetobacter diazotrophicus* proved to be most effective in improving soil quality and soil carbon sequestration in sugarcane multi-ratooning system surpassing RDF. This ensured highest mean biomass accumulation and evinced lowest decay rate constant for applied soil organic matter.

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