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Effect of organic and inorganic fertilizers and rice straw on carbon sequestration and soil fertility under a rice–rice cropping pattern

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ABSTRACT

Rice–fallow–rice, the dominant cropping system in Bangladesh, has received little attention regarding soil organic carbon (SOC) changes through organic amendments. Understanding the contributions of organic amendments in C sequestration is important for carbon budgeting. This study determined the effect of organic amendments on CO_2 emission to the atmosphere and C sequestration in soil. A series of field experiments in five consecutive rice seasons were conducted during 2010–2012 at the research farm of Bangabandhu Sheikh Mujibur Rahman Agricultural University, Bangladesh, using five treatments – control, cow dung (CD), poultry manure (PM), rice straw (RS) and soil test-based fertilizer (STB). The carbon application rate from CD, PM and RS was 2 t C ha^{-1} $season^{-1}$. Carbon dioxide production from rice fields was measured through NaOH absorption followed by HCl titration. The difference in the amount of cumulative CO_2 evolution and SOC accretion between the control and organic treatments gave apparent C balance and C sequestration. CD, PM and RS contributed to the positive soil nutrient balance. Application of CD, PM and RS resulted in 36, 28 and 37% loss of applied C through emission, respectively. The application of organic C through RS, CD and PM accounted for 10, 30 and 49% sequestration, respectively. There were 34, 23 and 53% unaccounted amounts of applied C from CD, PM and RS, respectively, which may be attributed to anaerobic decomposition where CO_2 was not produced, or escaping of the produced CO_2 through aerenchyma channels to the leaf surface. Poultry manure was found to be efficient in increasing carbon and other nutrients in soils, and contributed to a higher grain yield of rice compared to RS and CD. Due to STB fertilization, microbial activities might be enhanced and favored better growth of root biomass, which contributed to slight sequestration of SOC in the rice–rice cropping system.

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organic manures; CO_2 emission; C sequestration; rice–rice cropping pattern

Introduction

Carbon (C) sequestration is a process of capturing atmospheric C through production of biomass and storing it in soil. Soil may serve either as a source of atmospheric CO_2 or a sink of C depending on different crop and land management practices. It is well known that vegetation and soils are major storage sinks of atmospheric CO_2 [1]. In Bangladesh, there is a low reserve of C and plant nutrients in soils. Adoption of best management practices may sequester C in soils, which can significantly improve soil quality [2,3]. During the past two centuries, land-use practices such as deforestation and tillage have resulted in a net loss of soil C to the atmosphere [4]. The addition of C-enriched materials like crop residues, cow dung, poultry manure, farmyard manure, compost, etc. improves soil physical, chemical and biological characteristics. The improvement of soil properties favors the development of the crop root system, elongating it both at the surface level and in deep soil, which ultimately helps to accumulate more C in soil. It was also found that combined application of organic and inorganic sources of nutrient to soils increased the use efficiencies of production inputs and also increased crop yields [5,6]. This implies that by integrating organic matter in the fertilization program, a substantial saving on the yearly cost of inorganic fertilizers could be made. Cow dung is the most ancient organic matter source, as compared to *Sesbania* and straw, to increase organic C content in soils. The utilization of poultry manure to supply nutrients for plants is a recently debated issue because of its heavy metal contents. However, poultry manure is a potential source of soil C and plant nutrients. Application of rice straw was assumed to promote synchrony and reduce gaseous N losses from basally applied mineral N fertilizer. Continuous application of straw builds up the soil C content and ensures an adequate N supply. The soil organic C pool in agriculture land uses is capable of

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enhancing agricultural sustainability and serving as a potential sink of atmospheric CO_2 [7]. Agriculture, forestry and other land-use change showed an increase of CO_2 emission to the atmosphere from 1970 to 2010. In the Fifth Assessment Report of the IPCC it was reported that between 1750 and 2010, cumulative anthropogenic CO_2 emissions to the atmosphere were 2040 $\pm$ 310 $GtCO_2$. Cumulative CO_2 emissions from forestry and other land use increased from 490 $GtCO_2$ in 1970 to 680 $GtCO_2$ in 2010 [8].

To offset climate change, the emissions of CO_2 and other greenhouse gases need to be reduced. The rate of soil C emission is strongly regulated by the amount and types of organic materials added to soil. Both the quantity and the quality of soil C inputs, tillage intensity and crop rotation influence C storage and the potential for C sequestration [9]. Rice−fallow−rice is the dominant cropping pattern in Bangladesh and releases C as CO_2 and/or CH_4 depending on rice cultivation systems. Alternate wetting and drying conditions release more CO_2 compared to a continuously flooded or lowland rice culture system, which releases a significant amount of CH_4 to the atmosphere [10,11]. Methane emission from rice fields to the atmosphere occurred by three pathways: molecular diffusion, ebullition as gas bubbles, and rice-mediated transport, where the last one is the major pathway accounting for more than 90% of the total CH_4 emission from soils over the growing season [12]. It is uncertain whether rice fields accumulate C and how organic carbon (OC) level changes with different management practices [13], which need to be investigated. Up-to-date information on the dynamics of soil C under different soil and crop management practices is necessary to help maintain a good level of carbon for soil health and its productivity, and restraining from global warming [14]. The present study is aimed to compensate for the lack of such studies on C sequestration and CO_2 emission under different organic and inorganic fertilizer management options in rice cultivation. The objective of the research was to determine the rates of CO_2 emission and C sequestration from the addition of cow dung, poultry manure, rice straw and soil test-based inorganic fertilizers in soils.

Materials and methods

A series of field experiments in five consecutive rice-growing seasons of transplanted aman (July to November) and boro (December to May) during August 2010−November 2012 were conducted in a natural environment at the research farm of the Department of Soil Science of Bangabandhu Sheikh Mujibur Rahman Agricultural University, Bangladesh. The aman rice is grown in the monsoon as a rainfed crop (sometimes supplemental irrigation is needed if there is not enough rainfall) when maximum rainfall (269 to 370 mm) occurs, while the boro rice is grown after harvesting of T. aman under fully irrigated conditions in the dry season (0 to 55 mm rainfall). The study site is located at 24.09°N latitude and 90.25°E longitude with an elevation of 8.2 m above sea level, which is under the agro-ecological zone (AEZ) Madhupur Tract (AEZ 28). The soil of the study site belongs to the Salna series and has been classified as Shallow Red Brown Terrace soil in the Bangladesh soil classification system and Inceptisol in the United States Department of Agriculture (USDA) classification system, which is characterized by clay within 50 cm of the surface and is acidic in nature. The climate of the area is sub-tropical, wet and humid. The soil of the experimental field was silty clay loam in texture, having pH 5.95, organic carbon 11.3 g kg^{-1}, total nitrogen 0.9 g kg^{-1}, available phosphorus 22 mg kg^{-1}, exchangeable potassium 0.14 c-mol (+) kg^{-1}, available sulfur 15 mg kg^{-1} and available zinc 4 mg kg^{-1}.

The experiment consisted of five treatments − control, cow dung (CD), poultry manure (PM), rice straw (RS) and soil test-based fertilizer dose (STB), laid out in a randomized complete block design (RCBD) with four replications in both aman and boro rice. In the field, the study was replicated 5 times (three T. aman seasons and two boro seasons). The unit plot size was 4 m $\times$ 3 m. The rate of C application from CD, PM and RS was 2 t C ha^{-1} $season^{-1}$ and, according to the integrated plant nutrition system, CD and PM treatments received no inorganic fertilizer, but in RS treatment 132 and 60 kg N with 2 and 0 kg P per ha from urea and triple superphosphate in boro and T. aman seasons, respectively, was applied for the first year and then fertilizer rates were adjusted based on soil test values. The tested rice varieties were BRRI dhan29 and BRRI dhan49 in boro and T. aman, respectively.

The nutrient contents of organic materials and rice straw were analyzed (Table 1). Although the C concentrations in CD, PM and RS differed significantly, the C application rates were the same as 2 t C ha^{-1} $season^{-1}$, where the application rates of CD, PM and RS as organic materials were 10, 16.67 and 5 t ha^{-1} $season^{-1}$, respectively. Thus, the total C input from each of CD, PM and RS in five consecutive rice growing seasons

Table 1. Carbon and nutrient status of the organic materials applied in the experimental field.

Organic materials	Moisture (%)	OC	N	P (g kg^{-1})	K	S	Zn (mg kg^{-1})	C:N ratio
CD	69.6 $\pm$ 0.16	200 $\pm$ 9.2	9.92 $\pm$ 0.4	9.04 $\pm$ 1.2	9.33 $\pm$ 0.6	4.42 $\pm$ 0.8	124 $\pm$ 18	20.20
PM	33.6 $\pm$ 4.77	120 $\pm$ 11.3	17.12 $\pm$ 1.0	23.43 $\pm$ 1.3	12.71 $\pm$ 1.5	8.01 $\pm$ 1.2	205 $\pm$ 19	7.02
RS	26.2 $\pm$ 0.03	400 $\pm$ 15.7	4.93 $\pm$ 0.2	1.04 $\pm$ 0.2	16.02 $\pm$ 1.0	0.84 $\pm$ 0.2	36 $\pm$ 10	81.63

CD: Cow dung; OC: Organic carbon; PM: Poultry manure; RS: Rice straw.

was 10 t C ha^{-1}. The transplanting aman (T. aman) rice 2010 was transplanted on August 5, 2010. On the other hand, the boro rice 2011 seedlings were transplanted on January 25, 2011. The T. aman rice 2011 was transplanted on August 12, 2011, the boro 2012 on January 23, 2012, and the T. aman 2012 on August 14, 2012. Thirty-day-old seedlings were transplanted at 20 cm × 20 cm spacing. Soil test-based fertilizer doses were calculated for each rice crop. These were N-P-K-S at 162-10-71-15 kg ha^{-1} in boro and 90-2-37-10 kg ha^{-1} in T. aman for the first year of experimentation. Organic materials were applied in the field before 7 days of transplanting. Post-harvest soils were also collected (up to 15 cm depth) for bulk density, organic carbon and nutrient study following the standard procedure [15].

Carbon dioxide production in all of the treatments was measured using trap-through NaOH absorption followed by HCl titration [16] from the first day of transplanting. Carbon dioxide traps were prepared using 80 mL of 2 N NaOH in plastic bottles and placed in the plots under each treatment. Traps were covered with plastic buckets, which were inserted into soft mud to protect the entrance of air CO_2. An empty bucket was used as a control without soil but of alkali of same strength in the field. After 7 days of exposure, traps were collected from plots at 10:00 am covered with screw caps and replaced with another set of new traps. A fixed time of 10:00 am was considered to make the CO_2 absorption time exactly 1 week, while variation in trap setting and removal time might influence the amount of trapped CO_2 because of diurnal changes in soil and air temperature and also CO_2 absorption time. From 80 mL of alkali solution exactly 2 mL was titrated, adding a few drops of phenolphthalein indicator against 2 N HCl. Sodium hydroxide absorbed the evolved CO_2 as Na_2CO_3. Before titration, $BaCl_2$ was added for precipitation of the trapped CO_3^{2-} as $BaCO_3$. Residual NaOH was titrated with HCl to determine the CO_2 concentration. The buckets covered the soil for 7 days, which perhaps caused the change in soil temperature and oxygen content and affected soil respiration. This was of course a limitation of the method. Carbon dioxide emission measurement was continued until 14 weeks of both T. aman and boro rice-growing seasons. Beyond the rice-growing season, CO_2 emission during the fallow period of 336 days (between three T. aman and two boro rice crops) was also measured. The amount of CO_2 evolved from soil was calculated using Equation (1).

$$\text{Milligrams of C or } CO_2 = (B - V)\, N\, E \qquad (1)$$

where B and V are the volume (mL) of acid needed to titrate NaOH of traps in control and treatments, respectively; N = normality of the acid; and E (equivalent weight) is either 6 or 12 to express data in terms of C or CO_2, respectively. Data were expressed as kg CO_2 ha^{-1} week^{-1}. During the fallow period, root respiration was not considered in measuring CO_2 emission as there was no crop in the field. Because of the method used in the present study, it was not possible to partition total CO_2 emission into microbial emission and root respiration. However, using the knowledge gathered from the available published literature, we set a limit of root respiration to find a reasonable amount of CO_2 emission from organic matter decomposition. The source of root respiration is photosynthates and their translocation to the root, while application of manures and organic residues, litter fall and addition of dead roots to soil expedite microbial respiration. In general, root respiration contributes about 50% of the total soil respiration, while in a wheat field it ranged from 12 to 15% and in a soybean field from 35 to 40% [17,18]. Xu *et al.* [19] reported that root respiration of 5−6-week-old rice seedlings contributed 85−92% to bulk soil respiration. Young roots respire more compared to old roots [20]. We harvested rice at grain maturity where the contribution of root respiration will be much lower because of older roots. Furthermore, the instrumental set-up in the rice fields in the present study for trapping CO_2 might not be efficient enough to trap CO_2 emission from root respiration. This is because traps for measuring released CO_2 in our experiment were set up in the middle of four hills, where rice roots were obviously few, and we assumed that root respiration may contribute 30% to total CO_2 emission. Thus, 30% emission was deducted from total CO_2 emission to obtain heterotrophic emission.

The concentration of labile carbon in post-harvest soils was determined by $KMnO_4$ oxidation followed by absorbance reading on a double-beam spectrophotometer [21]. Carbon stock, C sequestration and loss of C through emission were calculated using Equations (2), (3) and (4), respectively.

$$\begin{aligned}\text{Carbon stock } (\text{t ha}^{-1}) &= \text{Carbon concentration } (\%) \times \text{bulk density } (\text{g cm}^{-3}) \\ &\quad \times \text{depth (cm)}\end{aligned} \qquad (2)$$

$$\text{Carbon sequestration } (\text{t ha}^{-1}) = \text{Final C stock } (\text{t ha}^{-1}) - \text{Initial C stock } (\text{t ha}^{-1}) \qquad (3)$$

$$\begin{aligned}\text{Emission loss of C } (\%) &= (\text{Emission from treatment} - \text{Emission from control}) / \\ &\quad \text{C input} \times 100\end{aligned} \qquad (4)$$

Data of collected parameters were statistically analyzed using IRRISTAT software version 4. Means were separated by least significant difference (LSD).

Results and discussion

Weekly CO_2 emission from soils

It was found that emission of CO_2 from the T. aman rice field significantly increased and reached a peak value within 4 to 7 weeks, while from 7 weeks onward it decreased gradually and then became almost steady from 12 weeks and beyond (Figure 1). In T. aman 2010, rice was transplanted during the first week of August and the air temperature as well as soil temperature was high at that time, which favored rapid microbial decomposition of added organic manures and released more CO_2. Initially, PM released more CO_2 compared to other organic materials and inorganic fertilizer. The CO_2 emission from PM was the highest in the fourth to fifth weeks after transplanting (529 kg CO_2 ha^{-1} wk^{-1}). In the case of CD, the highest emission was recorded at the sixth week (524 kg CO_2 ha^{-1} wk^{-1}), and from RS it was at the seventh week (544 kg CO_2 ha^{-1} wk^{-1}) after transplanting of rice. After the seventh week, CO_2 emission from different treatments decreased gradually and finally, at the end of the crop growing period, it reached below the initial level.

Carbon dioxide emission from the inorganic fertilizer-treated plot was much lower than from organic matter (OM)-treated plots throughout the crop-growing season. However, the inorganic fertilizer treatment released more CO_2 than did the control treatment (Figure 1a). Carbon input was not applied to the inorganic fertilizer and control treatments; therefore, emission of CO_2 from soils under these two treatments was found to be low. The total CO_2 emission was higher in the RS treatment followed by CD, PM and soil test-based fertilizer treatments, and the lowest amount was observed in the control treatment. In T. aman 2011 and T. aman 2012, more or less similar trends of CO_2 emission were observed in different organic manure and inorganic fertilizer management practices. Emission of CO_2 from different manures and rice straw-treated plots were higher in the fourth to seventh weeks after transplanting; then it decreased up to the eleventh week of transplanting and remained almost stable within 323−377 kg CO_2 kg^{-1} wk^{-1} in T. aman 2011 (Figure 1b), and 235−294 kg CO_2 kg^{-1} wk^{-1} in T. aman 2012 (Figure 1c).

It was also found that emission of CO_2 from the boro rice field significantly increased and approached the maximum in the vegetative stage during the sixth week after transplanting. After that, CO_2 emission decreased gradually and continued to the end of the rice-growing period (Figure 2). In boro 2011, rice was transplanted in the last week of January when the air and soil temperature were low, which decreased the microbial decomposition of added organic manures thus resulting in low emission of CO_2 at the beginning. After the fourth week following transplanting the rate of CO_2 emission decreased slightly, then increased again sharply in the sixth week after transplanting and

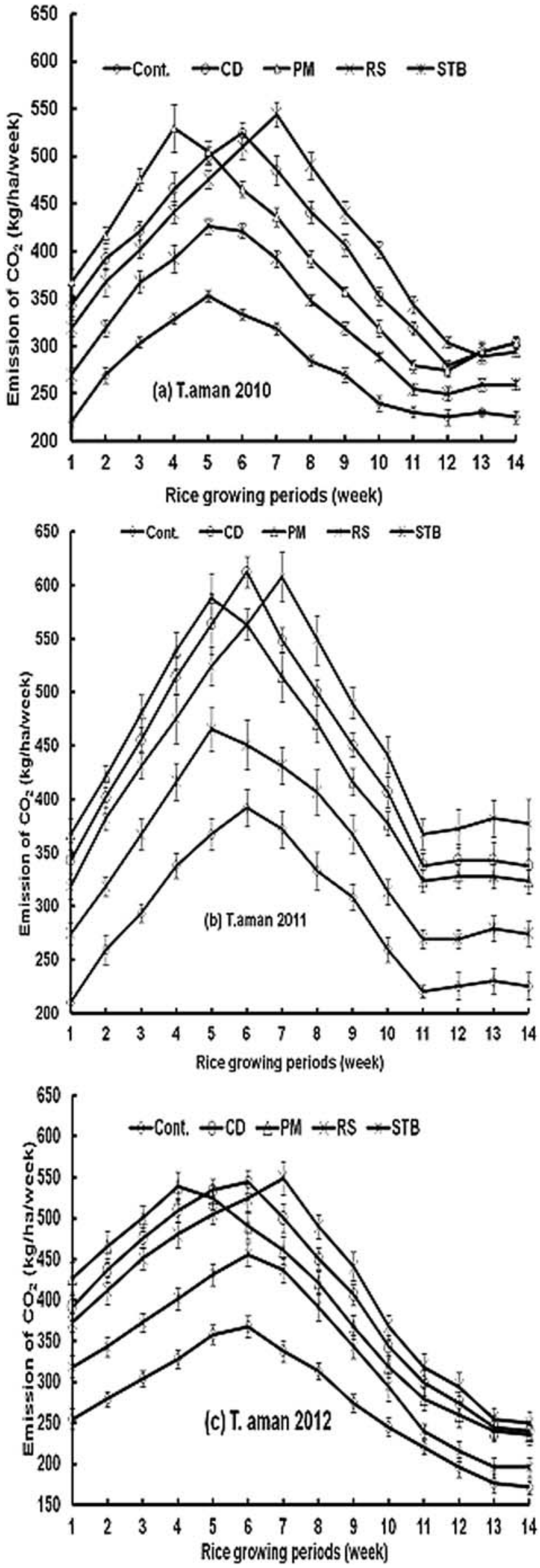

Figure 1. Effect of organic manures, rice straw and inorganic fertilizer management practices on CO_2 emission (kg CO_2 ha^{-1} wk^{-1}) during T. aman rice in different years: (a) 2010, (b) 2011 and (c) 2012. CD = cow dung, PM = poultry manure, RS = rice straw, STB = soil test-based fertilizer.

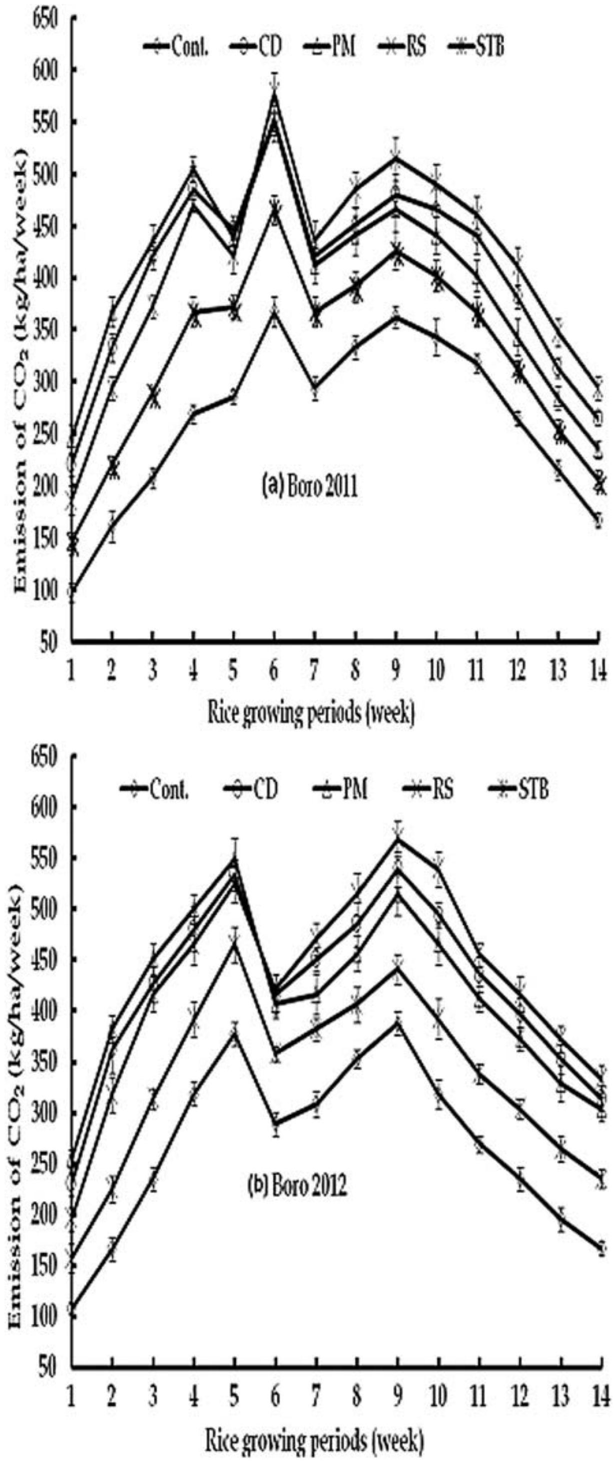

Figure 2. Effect of organic manures, rice straw and inorganic fertilizer management practices on CO_2 emission (kg CO_2 ha^{-1} wk^{-1}) during boro rice in different years: (a) 2011 and (b) 2012. Cont. = control, CD = cow dung, PM = poultry manure, RS = rice straw, STB = soil test-based fertilizer.

reached a peak of 578 kg CO_2 ha^{-1} wk^{-1} in the RS treatment, due to raising the soil and air temperature which favored the microbial decomposition of straw. The CO_2 emission after the ninth week decreased gradually with the increase in the crop growth period and continued until the end of 14 weeks, because of a reduction in the readily decomposable part of carbon. All treatments followed more or less the same trend in CO_2 emission throughout the rice-growing season. Among the organic materials, PM showed higher CO_2 emission at an earlier stage but it came down after 1 month following rice transplanting. In the case of RS, the rate of CO_2 emission was slower in the earlier stage of crop growth, but after the fifth week the rate increased and remained higher throughout the period, because of its high C:N ratio as mentioned earlier. The STB inorganic fertilizer showed comparatively much lower CO_2 emission than did organic manure and RS, while the lowest emission was observed in the control treatment where no organic manure or inorganic fertilizer was applied (Figure 2a). A more or less similar trend in CO_2 emission was observed in the boro 2012 season (Figure 2b). The rate of CO_2 emission was increased up to the fifth week after transplanting, and then it came down in the sixth week, started increasing further to the ninth week and, after that, gradually decreased to the end of the fourteenth week. The RS treatment released more CO_2, followed by CD and PM. At the beginning of the fifth week, the PM treatment released the highest CO_2 (549 kg CO_2 ha^{-1} wk^{-1}), while RS released the most at the ninth week of crop growth. After that, the emission decreased gradually throughout the crop-growing season. The findings of other researchers are in agreement with the findings of this study. It was reported that the loss of CO_2 from soil is related to the abundance and activity of soil microorganisms. The usual range of CO_2 loss under submerged conditions is 70−700 kg CO_2 ha^{-1} wk^{-1} [22,23]. It is generally assumed that after incorporation of crop residues and other organic matter to soils, it takes about 1 month for maximum microbial activities, depending on the C:N ratios of the provided organic materials. The higher the C content, the more time is needed to decompose the materials. Carbon dioxide is released from the soil through microbial decomposition, where microflora contributes about 99% of the CO_2 arising as a result of decomposition of OM under aerobic conditions [24]. Chemical oxidation of organic residues also contributes to CO_2 emission from soils, which is normally pronounced at higher temperatures. Large quantities of organic carbon (OC) added to soils through different manures and wastes to supply plant nutrients may significantly contribute to CO_2 emission. However, proper management of organic manures and wastes, conservation tillage, improving soil biodiversity, microaggregation and mulching can play an important role in reducing CO_2 emission and thus increasing C sequestration in soil [2].

The variation in time of peak emission of CO_2 among different manures and rice straw was due to the differences in the C:N ratio of these organic materials (Table 1). Because of a low C:N ratio, microbial decomposition might be faster in PM and thus it released more CO_2 at the beginning, while high C:N

Table 2. Effect of organic manures, rice straw and inorganic fertilizer on cumulative CO_2 emission, C loss and accumulation.

Treat.	Cumulative CO_2 emission in crop seasons (kg/ha/14 weeks of each T. aman & boro) and fallow period of 336 days								Total C input (kg)	C emission loss (%)	C seq. (%)	C unaccounted (%)
	Aman 10	Aman 11	Aman 12	Boro 11	Boro 12	Fallow	Total CO_2	Total C emission				
Control	3832	4038	3827	3688	3729	5760	24874	6784	–	–	–	–
CD	5527	6159	5650	5679	5919	9000	37935	10346	10000	36	30	34
PM	5415	6042	5527	5563	5811	6840	35198	9599	10000	28	49	23
RS	5620	6282	5709	5762	6012	9000	38385	10469	10000	37	10	53
STB	4567	4905	4635	4591	4675	6120	29493	8044	–	–	–	–
CV (%)	*9.0*	*8.3*	*5.8*	*6.7*	*8.5*	*10.3*						
LSD $_{(0.05)}$	*275*	*421*	*410*	*341*	*437*	*492*						

CD: Cow dung; PM: Poultry manure; RS: Rice straw; STB: Soil test-based fertilizer; Treat.: Treatment; CV: Coefficient of variation; LSD: Least significant difference.

ratio of RS extended its decomposition time and released more CO_2 at the latter stage. The rice straw- and organic matter-containing treatments released more CO_2 compared to the inorganic fertilizer treatment. The application of organic materials increases carbon input in soil from enhanced biomass production returned to soil, which ultimately increases CO_2 emission [25].

Cumulative amount of CO_2 emission from soils

The cumulative amount of CO_2 emitted among different treatments in T. aman seasons varied significantly (Table 2). The maximum cumulative CO_2 emission for 14 weeks in T. aman 2010 was found in the RS treatment (5620 kg CO_2 ha^{-1}) followed by the CD (5527 kg CO_2 ha^{-1}) and PM (5415 kg CO_2 ha^{-1}) treatments, while the minimum amount was from the control treatment (3832 kg CO_2 ha^{-1}). The soil test-based inorganic fertilizer treatment emitted the least amount of CO_2 compared to rice straw and organic manure treatments. A more or less similar trend was also found in the case of total CO_2 emission from different treatments in T. aman 2011 and 2012 (Table 2). The similar pattern of cumulative emission of CO_2 was also observed among different treatments in boro seasons (Table 2). The emission of CO_2 from RS-, CD- and PM-treated plots did not vary significantly; however, these treatments released significantly higher amounts of CO_2 compared to the STB and control treatments. The maximum cumulative emission of CO_2 was found in the RS treatment in boro 2012 season, which was 6012 kg CO_2 ha^{-1}. Rahman [23] conducted an incubation study on CO_2 emission from different organic residues using a carbon rate of 0.25 g 100 g^{-1} soil and found that RS and CD released 313 and 283 mg CO_2, respectively, during 118 days of study, which is almost equivalent to 6270 and 5660 kg CO_2 ha^{-1} for the period mentioned here and thus endorses the findings of the present study. Bhattacharyya *et al.* [26], in a long-term experiment of rice-rice cropping, found that application of farmyard manure at the rate of 5 t ha^{-1} released 5159 kg CO_2 ha^{-1} yr^{-1}. These variations in carbon rate and time periods might bring changes in the rate of CO_2 emission from soil.

The application of CD, PM and RS resulted in 36, 28 and 37% loss of applied C as CO_2 through microbial decomposition (Table 2). The application of organic C through CD and PM accounted for 30 and 49% sequestration, while the sequestration of C from RS accounted for only 10%. There was an unaccounted amount of applied C in all three sources, with variable magnitude. The unaccounted portion of C in soil from CD and RS represented 34 and 53%, respectively, but in the case of PM it was only 23% (Table 2). The unaccounted portion of the added C may be attributed to the anaerobic decomposition where CO_2 was not produced or escaping of the produced CO_2 through aerenchyma channels to the leaf surface.

There are some uncertainties associated with emission determination. Carbon dioxide emission in rice field soils mainly depends on soil respiration and organic matter decomposition amplified by soil temperature and moisture regimes [8,27,28]. Temperature from plot to plot may vary, and water depth in all plots could not be maintained at equal depths as flood irrigation was provided to rice fields. The instrumental set-up in rice fields for trapping CO_2 might be another uncertainty. The traps were covered with buckets for 7 days which perhaps caused changes in soil temperature and oxygen content and affected soil respiration. This was of course a limitation of the method. Carbon concentrations and degradation rates of CD, PM and RS are different, which might bring variation in CO_2 emission as well as C sequestration under different treatments used in the experiment. The diurnal variation also may cause uncertainty in measuring CO_2. In the present study, CO_2 was measured from fields at 10:00 am. Liu *et al.* [29] found that peak emission of CO_2 occurred in the late afternoon. Therefore, uncertainties remain in the current experiment and need to be addressed in future study.

Soil carbon content, stock and sequestration in post-harvest soil

The organic carbon of post-harvest soil (0–15 cm depth) increased significantly in rice straw- and organic manure-treated plots compared to the control and inorganic fertilizer treatments (Table 3). Among the

Table 3. Effect of organic manures, rice straw and inorganic fertilizers on bulk density, carbon stock and carbon accumulation in soil after harvesting of five rice crops (0−15 cm soil depth).

Treatment	Initial soil				Post-harvest soil			Carbon accumulation ($t\ ha^{-1}$)
	OC ($g\ kg^{-1}$)	BD ($g\ cm^{-3}$)	C Stock ($t\ ha^{-1}$)	Labile C ($g\ kg^{-1}$)	OC ($g\ kg^{-1}$)	BD ($g\ cm^{-3}$)	C Stock ($t\ ha^{-1}$)	
Control	11.30	1.38	23.39	2.92	10.82	1.36	22.03	− 1.36
CD	11.30	1.38	23.39	5.70	13.93	1.27	26.42	3.03
PM	11.30	1.38	23.39	4.88	14.54	1.30	28.30	4.90
RS	11.30	1.38	23.39	6.98	13.22	1.24	24.43	1.04
STB	11.30	1.38	23.39	3.78	11.83	1.32	23.43	0.04
CV (%)	–	–	–	–	*3.3*	*1.9*	*4.8*	*80.1*
LSD (0.05)	–	–	–	–	*0.81*	*0.046*	*2.78*	*2.31*

BD: Bulk density; CD: Cow dung; OC: Organic carbon; PM: Poultry manure; RS: Rice straw; STB: Soil test-based fertilizer; CV: Coefficient of variation; LSD: Least significant difference.

treatments, the highest amount of SOC accumulated in PM-treated plots (14.54 g kg^{-1}) followed by CD (13.93 g kg^{-1}), RS (13.22 g kg^{-1}) and STB (11.83 g kg^{-1}). Soil organic carbon slightly increased (9.26%) in STB inorganic fertilizer-treated plots and significantly increased (34%) in PM-treated plots compared to the control treatment (10.82 g kg^{-1}) in post-harvest soil after 2.5 years of rice cultivation. Bhattaacharyya *et al.* [25] found that application of rice straw and green manure at the rate of 7.12 t ha^{-1} yr^{-1} during 10 years of rice cropping increased organic carbon content in soil by 34%. Bhattaacharyya *et al.* [26] also reported similar findings in carbon increment in soils in rice fields. Brar *et al.* [30] observed an increment of 69.8% organic carbon in 100% NPK treatments after 9 years of rice−wheat cropping, which was explained in such a way that balanced fertilization attributed to increased plant biomass addition to soil. Animal manure is more effective in building soil C than straw is, possibly due to the presence of more humified and recalcitrant C forms in animal manure as compared to the straw [31]. Besides, manure is more resistant to microbial decomposition than plant residues are; consequently, for the same C input, C storage is higher with manure application than with plant residues [32]. On the other hand, the lowest organic carbon in soils was found in the RS treatment among the organic materials, which attributed to the highest emission of CO_2 in this treatment. This might be due to the use of additional inorganic N fertilizer in the RS treatment over the PM and CD treatments. Fertilizers were applied using the integrated plant nutrition system (IPNS) concept, where nitrogen contents in PM and CD were 17.12 and 9.92 g kg^{-1}, respectively, and the amount of nitrogen added to soil in the first crop (T. aman 2010) from the applied 16.67 t ha^{-1} PM and 10 t ha^{-1} CD exceeded the amount recommended for the crop. P, K and S were also high in all PM, CD and RS treatments, which fulfilled the requirements of these three nutrients for rice crops. Therefore, additional inorganic fertilizers of these nutrients were not needed. But in the case of RS, N content was low (4.93 g kg^{-1}) compared to PM and CD, and could not supply the amount required for the crop. Therefore, additional inorganic N fertilizer was applied in the RS treatment, which might have stimulated soil microbial activity, therefore increasing CO_2 emission. Thus, treatments with inorganic nitrogen fertilizers favor degradation of SOC, which ultimately resulted in low C content in soil. This is an agreement with Halvorson *et al.* [33].

The OC, bulk density, C stock and sequestration in soils were significantly influenced by different rice straw, organic manure and inorganic fertilizers (Table 3). The initial SOC, bulk density and C stock in soils were 11.3 g kg^{-1}, 1.38 g cm^{-3} and 23.39 t ha^{-1}, respectively. After harvesting of the fifth rice crop, the SOC increased significantly where the OM was applied. There was a significant influence of organic materials on soil bulk density compared to the control treatment. Bulk density values were slightly lowered by the organic materials. Although the change in soil bulk density was not much, it gave a positive sign of importance or influence of organic materials on soil bulk density. A significantly lower bulk density of soil was observed in the RS (1.24 g cm^{-3}) treatment, followed by CD (1.27 g cm^{-3}) and PM (1.30 g cm^{-3}) treatments. Many researchers [30,34,35] have reported the lowering of soil bulk density with the application of different organic fertilizer in soils. Continuous application of rice straw compost has some positive effects on soil physical properties, as stated by Watanabe *et al.* [36]. Therefore, the application of different organic wastes containing greater levels of OM causes a relatively loose structure in the surface layer of the field soil and thus decreases the bulk density of the soil to favorable levels. In contrast, researchers also mentioned that the application of organic fertilizers in rice fields did not change soil bulk density even after 4 to 10 years of cropping (Bhattaacharyya *et al.* [25,37].

The SOC stock increased significantly from 22 t ha^{-1} in the control to 28 t ha^{-1} in the PM treatment (Table 3). The SOC stocks of all the fertilizer treatments were greater than that of the control treatment. Among the organic materials the highest C stock was found in the PM treatment (28 t ha^{-1}), which was statistically higher than that of the other organic materials and STB treatments. Compared to the control treatment, SOC storage of the PM, CD, RS and STB treatments within the 0−15 cm soil depth was increased by 28.5, 20.0, 11.0 and 5.0%, respectively. The treatments that combined inorganic fertilizers and organic amendments had greater SOC stock compared to those that received only inorganic fertilizers. This was consistent with the results of other studies [38–41].

The C sequestration in the post-harvest soil increased significantly with the application of organic fertilizers (Table 3). Among the treatments, PM sequestered the maximum amount of OC in the post-harvest soil, followed by CD. In the control treatment, C sequestration was negative – that is, as there were no external organic inputs, microbial degradation of the inherent C exhausted the C stock and thus the final stock was less than the initial stock. There was a slight C sequestration in STB treatment, which was because of balanced fertilization that stimulated vigorous plant growth and higher root biomass which contributed to slight sequestration of SOC in the rice–rice cropping system. The sequestration of OC in the PM treatment was 4.9 t ha^{-1}, while it was 3.0 and 1.04 t ha^{-1} in the CD and RS treatments, respectively (Table 3). Bhattaacharyya *et al.* [25] was found that application of rice straw and green manure at the rate of 7.12 t ha^{-1} yr^{-1} during 10 years of rice cropping sequestered 1.23 t C ha^{-1} while rice straw applied at the rate of 4.8 t ha^{-1} along with inorganic fertilizers contributed 1.39 t C ha^{-1}. In the present study, the sequestration efficiencies of the applied C through RS, CD and PM accounted for 10, 30 and 49%, respectively (Table 2). The addition of different manures and rice straw improved the transformation of organic carbon and labile carbon contents in soils (Table 3). The highest amount of labile carbon in soils after harvesting of five rice crops was found in the RS treatment, followed by CD and PM, which indicated the potential for further emission of CO_2 from rice straw. Results of the study revealed that the SOC buildup in the rice–rice cropping system were 40, 60 and 58 kg t^{-1} in the RS, CD and PM applications, respectively, during the five rice growing seasons. This small increment in the soil organic carbon (SOC) stock may create great impacts in reducing the atmospheric C concentration. Many researchers have mentioned that application of animal manure to land promotes SOC sequestration in soil due to its relatively high C content. It was also reported that poultry litter application to croplands led to significant soil organic C sequestration [42]. Application of rice straw and different composted manures resulted in a significant amount of C sequestration in the soil, which increased agronomic, physiological and recovery efficiencies of N, P and K [6,40,43].

Rice grain yields under different treatments

Grain yields were significantly influenced by applying different organic materials and chemical fertilizer in both T. aman and boro rice (Table 4). The PM treatment was found to be superior in producing rice grain over the other treatments in all five seasons of T. aman and boro. The observed yields of different treatments were in the order of PM > CD > STB > RS > control. The highest grain yields in the PM treatment of T. aman 2010, boro 2011, T. aman 2011, boro 2012 and T. aman 2012 were 5.43, 6.70, 5.53, 6.83 and 5.61 t ha^{-1}, respectively. All nutrients in PM were high compared to other organic material treatments. As the C:N ratio of PM was low to optimum, the mineralization might be faster compared to other organic materials including RS. Thus, nutrient release from PM was faster, which favored nutrient uptake and thereby higher yield. Integrated application of PM with inorganic nutrients improved the soil physical, chemical and biological environment, which encouraged the proliferation of roots resulting in more absorption of water and nutrients from a larger area and depth, resulting in a higher grain yield. It is well documented in other research findings that combined application of organic and inorganic fertilizers in balanced doses increases crop yields [5,6]. In the initial stage, microbes utilized inherent nitrogen from rice fields with high C:N ratio containing RS which restricted the growth and development of shoot and root and ultimately contributed to lower grain yield.

Seasonal and year-to-year variations in grain yields of T. aman and boro rice were also observed. Better management of soil, water and crops contributed to increase grain yields of rice positively from the year 2010 to 2012, which is applicable for both aman and boro rice. The yield of boro rice was higher than that of aman rice because of the higher yield potential of boro rice varieties and more photosynthetically active radiation in the boro season. Hossain *et al.* [44] stated that the average yield of modern rice varieties was 1.0 to

Table 4. Effect of different organic manures, rice straw and inorganic fertilizers on grain yields of T. aman and boro rice.

	Yield of rice grain at harvesting (t ha^{-1})				
Treatments	T. aman 2010	Boro 2011	T. aman 2011	Boro 2012	T. aman 2012
Control	3.81	3.97	3.64	3.86	3.46
Cow dung	5.29	6.59	5.40	6.72	5.45
Poultry manure	5.43	6.70	5.53	6.83	5.61
Rice straw	4.68	5.93	5.01	6.09	5.12
STB	5.00	6.48	5.23	6.54	5.26
% CV	*2.3*	*3.0*	*2.1*	*1.8*	*2.7*
LSD (0.05)	*0.17*	*0.27*	*0.16*	*0.20*	*0.25*

STB: Soil test-based inorganic fertilizers; CV: Coefficient of Variation; LSD: Least significant difference.

1.5 t ha^{-1} higher in the boro season compared to the aman season due to a favorable growing environment such as high sunshine hours and low pest pressure.

Fertility status of post-harvest soil after harvesting five rice crops

The soil fertility in terms of soil nutrient status (0–15 cm depth) increased significantly over the control treatment from the application of rice straw and different organic materials in soil during the five consecutive rice seasons of T. aman and boro (Table 5). The contribution of PM, CD and RS in increasing soil fertility was found to be positive in trend. A significant increment in soil pH was observed from the application of PM and CD in the experimental plots over the control and STB dose of fertilizer (Table 5). The soil pH in post-harvest soils among the treatments of PM, CD and RS did not vary significantly. The maximum increment in soil pH was found under the PM treatment, which was 6.91, while it was 5.85 in the initial soil and 5.83 in the control treatment. The increment of soil pH in the PM treatment was due to the addition of calcium from the poultry manure. Therefore, PM was found to increase soil pH, which was reported by many researchers [6,10,45]. The increase of pH from cow dung application has been attributed to its buffering effect and the organic acid released [46]. The organic matter from the crop residue improved the soil pH status by increasing the soil buffering capacity [47]. Organic fertilizers increase the cation exchange capacity, which contributes to a high base saturation of the soil. As the base saturation increases, the relative amount of acid cations neutralizes. Our findings are supported by those of many other researchers [48-50], who explained that plants can alter soil pH by releasing root exudates, such as organic acid anions, to enhance mineral nutrient solubility, as well as by the liberation of H^+ and OH^- (or HCO_3^- resulting from OH^- carbonation) in order to counterbalance cations or anions entering the roots. Decomposition of organic acid anions can also increase soil pH due to proton consumption in the decarboxylation process. Such incremental changes in soil pH might help with the availability of macronutrients, especially phosphorus, calcium and magnesium in acid soil.

Table 5. Effect of different organic manures, rice straw and chemical fertilizer management on nutrient status of post-harvest soil after completion of five rice crops (0–15 cm soil depth).

Treatment	pH	Total N (g kg^{-1})	Available P (mg kg^{-1} soil)	Exchangeable K (c-mol kg^{-1} soil)
Initial soil	5.85	0.90	22.0	0.13
Control	5.83	1.0	16.6	0.10
CD	6.20	2.0	35.3	0.24
PM	6.91	2.2	43.2	0.26
RS	6.00	1.6	26.0	0.28
STB	5.95	1.2	22.5	0.13
CV (%)	*1.0*	*12.7*	*13.4*	*10.3*
LSD (0.05)	*0.12*	*0.03*	*7.23*	*0.13*

Cont.: Control (no organic manure and chemical fertilizer); CD: Cow dung; PM: Poultry manure; RS: Rice straw; STB: Soil test-based fertilizers; organic matter was used at 2 ton carbon per hectare with IPNS-based chemical fertilizer; CV: Coefficient of variation; LSD: Least significant difference.

The soil nitrogen was significantly higher in organic fertilizer-applied plots over the control and inorganic fertilizer treatments (Table 5). Among the organic materials, PM showed the highest amount of total N followed by CD and RS. The nitrogen concentration between PM (2.2 g kg^{-1}) and CD (2.0 g kg^{-1}) did not vary significantly; however, they were significantly higher over the RS treatment (1.6 g kg^{-1}). There was no statistically significant difference in N contents in soils between the control and STB treatment, though the total N increment was higher in the STB treatment. As per the soil fertility ranking given by Bangladesh Agricultural Research Council (BARC) [51], the status of nitrogen concentrations in soils under the control treatment was very low, while it was medium in the PM and CD treatments, and low in the RS treatment. Though the organic materials were applied in soils at 2t C ha^{-1} in all PM, CD and RS treatments, differences exist in the quality of organic materials, mainly the C:N ratio. Because of the low to optimum C:N ratio or high concentration of N of the poultry manure, it mineralized fast and supplied N to soil. The total N increase in organic manure-treated soils was also reported by many researchers [52–54].

The soil-available P content in post-harvest soil increased significantly in the PM- and CD-treated plots compared to RS- and STB chemical fertilizer-treated plots (Table 5). The phosphorus contents in soil were 16.6, 35.3, 43.2, 26.0 and 22.5 mg kg^{-1} soil in the control, CD, PM, RS and STB fertilizer treatments, respectively. The PM treatment showed 92% higher P sequestration in soils compared to the STB treatment, while it was 160% higher over the control treatment. The phosphorus status in soil as per BARC fertility ranking [51] was medium in the control/initial soil, while it reached a very high level with the application of PM in soils and a high level in the CD-treated soils. The increment in soil P in the Salna silty clay acid soil is really a good achievement in terms of sustainable management of the most limiting plant nutrient, P, in the study soil. Soil pH is important in controlling different available forms of P, as well as precipitation–dissolution and adsorption–desorption reactions, and thus P solubility and availability to plants [49]. It was observed that soil pH under the PM treatment increased significantly in a favorable range for nutrient availability in soil; it might have a significant positive impact on nutrients, especially P. In post-harvest soil the pH value was around 7.0 in the PM treatment, which was optimum for P availability. Improvement of soil pH led to the solubilzation of inorganic P [46]. The enhanced biological activities in the manure-treated soil are evidenced by relatively high phosphatase activities, microbial biomass content and dehydrogenase activity. As suggested by Jenkinson *et al.* [55], microbial biomass not only contains a labile pool of nutrients but also drives the cycling of OM and nutrients in soil. Earlier, scientists also determined the availability of phosphorus in soil using various organic materials, and their findings support the above results [56–59].

The exchangeable K content in post-harvest soil under rice straw and organic manure treatments increased significantly. Among the treatments, RS showed a remarkable increase in soil K compared to other organic and inorganic fertilizer treatments (Table 4). In terms of K concentrations in soils, the STB treatment (0.13 c-mol kg^{-1}) appeared superior to the control treatment (0.10 c-mol kg^{-1}), while the organic treatments were better than the STB treatment. The maximum K concentration in soil was found under the RS treatment, which was 0.28 c-mol kg^{-1} followed by PM (0.26 c-mol kg^{-1}) and CD (0.24 c-mol kg^{-1}). Rice straw contains a high amount of potassium; therefore, the K concentration was higher in the RS treatment.

Variation of soil carbon and nutrients with soil depth

Soil carbon, total nitrogen (TN), available phosphorus (P) and exchangeable potassium (K) were found to be maximum in 0–5 cm topsoils under different treatments (Figure 3). A general declining trend of all soil

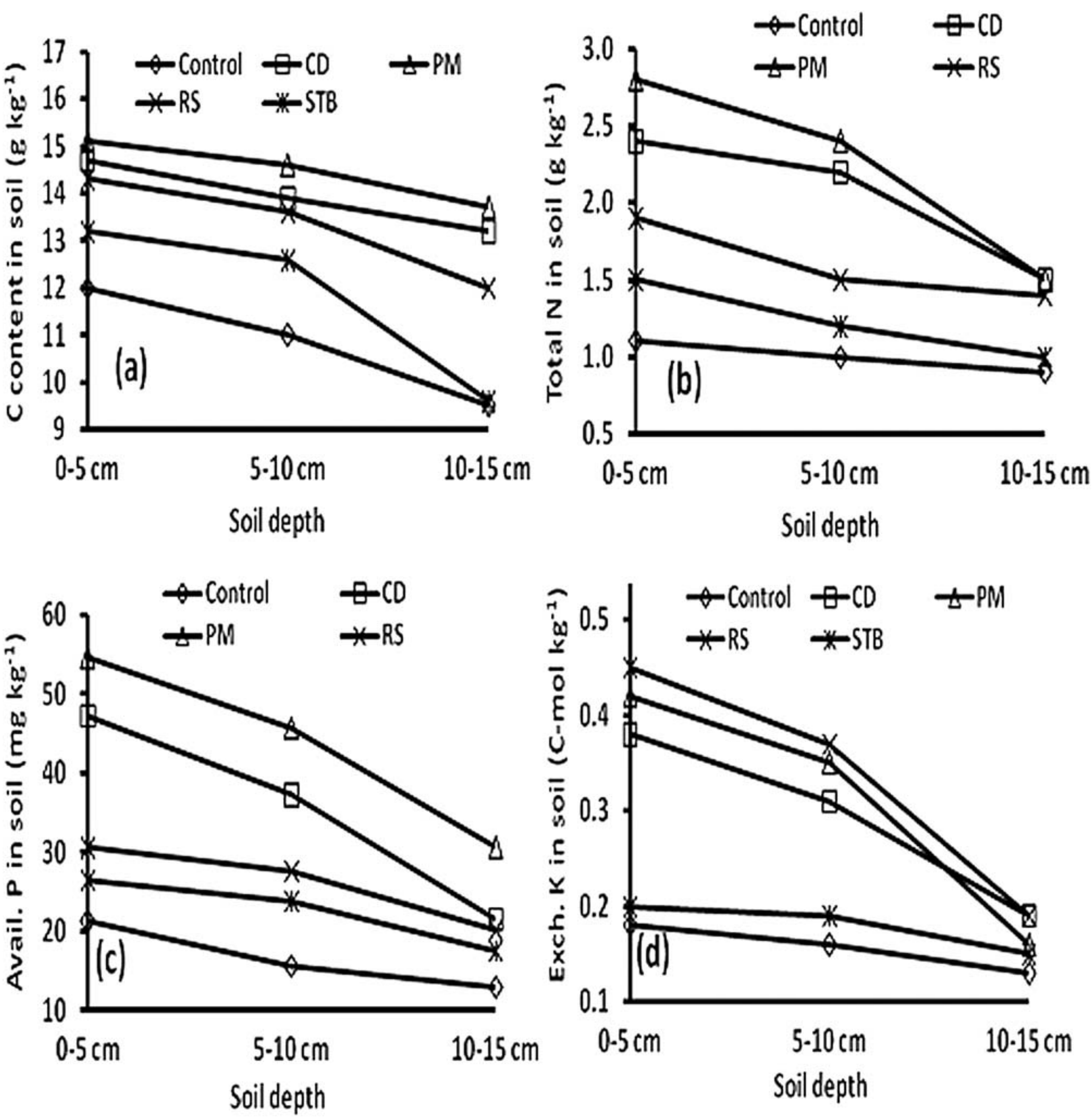

Figure 3. Variations of chemical properties under different treatments and soil depths of post harvest soil after completion of five rice crops: (a) soil organic carbon, (b) total nitrogen, (c) available phosphorus and (d) exchangeable potassium.

parameters, as mentioned, was observed with the increment of soil depths. Carbon contents in the topsoil are usually found to be the maximum. This is because of organic residues that are applied in the surface soil. The higher availability of OM in the topsoils has a profound influence on soil microbial population, which, on other hand, also contributes to the increased carbon level in soils. Through microbial decomposition of OM application in the topsoils, different nutrients were released, which might contribute to the higher availability of N, P and K in the topsoils. Inorganic fertilizers were also applied in the topsoil, which might have a residual effect in augmenting nutrient contents in the topsoils. Among three different manures and residues, PM contributed to more C, N and P in soils, followed by CD and RS (Figure 3a–c). In the top 5 cm soils, carbon contents were 15.1, 14.7, 14.1, 13.2 and 12.0 g kg^{-1} in the PM, CD, RS, STB and control treatments, respectively, while in the 10–15 cm soil depths these values were 13.7, 13.2, 12.0, 9.6 and 9.5 g kg^{-1}, respectively (Figure 3a). Poultry manure was found to be more effective in building soil C than RS and CD, as explained earlier [31]. Soil microbes broke down PM where easily decomposed portions of organic material disappeared relatively quickly, while the more resistant part known as humus was left behind.

In the top 5 cm of soils, total nitrogen contents were 2.8, 2.4 and 1.9, 1.5 and 1.1 g kg^{-1} in the PM, CD, RS, STB and control treatments, respectively, while the average values in 10–15 cm soil depths were 1.5, 1.5, 1.4, 1.0 and 0.9 g kg^{-1}, respectively (Figure 3b). Poultry manure was found to be more efficient to improve soil fertility as it contains more nutrients, compared to cow dung and rice straw. As per fertility ranking, nitrogen status in the topsoils under PM and CD treatments were medium to optimum [51]. Nitrogen added to the soil is subject to several changes (transformations) that ensure the availability of N to plants. The available forms of nitrogen in soils for plant uptake are ammonium (NH_4^+) and nitrate (NO_3^-). These transformations and dynamics of nitrogen in soils depend on the aeration and submergence of soils. Bacteria decompose organic material and release ammonium nitrogen to soils, which is predominant in anaerobic conditions. Ammonium nitrogen has properties that are of practical importance for nitrogen management in soils, especially in wetland rice crops. The ammonium nitrogen contains a positive charge (NH_4^+) and, therefore, is attracted to negatively charged soil and soil organic matter which protects its downward movement from soil systems.

Phosphorus contents in the top 0–5 cm soil depths under all treatments, even in the control, were found to be very high, with values of 54.57, 47.21, 30.56, 26.44 and 21.24 mg kg^{-1} in the PM, CD, RS, STB and control treatments, respectively, while the average values in 10–15 cm soil depths were 30.54, 21.55, 20.21, 17.50 and 12.98 mg kg^{-1}, respectively (Figure 3c). These data reveal that deliberate management of soil and crops could harness the potential of soil P for better crop productivity and environmental sustainability. Potassium contents were found to be the maximum in the RS treatment, followed by PM and CD (Figure 3d). In the top 5 cm soils, potassium contents were 0.40, 0.37 and 0.33, 0.15 and 0.13 c-mol kg^{-1} soil in the RS, PM, CD, STB and control treatments, respectively (Figure 3d). The data indicate that incorporation of RS is a major source of soil potassium. But removal of RS from fields is widespread in India, Nepal and Bangladesh to use as fuel for cooking, fodder and beds for animals and also for industrial raw materials, and causes K deficiency in soils. Dobermann and Fairhurst [60] reported that about 40% of N, 30 to 35% of P, 80 to 85% of K, and 40 to 50% of S taken up by rice remains in vegetative plant parts at crop maturity. Therefore, incorporation of RS in soil could substantially increase soil nutrients, and especially K contents could increase greatly.

Conclusion

The sequestration of organic carbon in the poultry manure treatment was 4.9 t ha^{-1}, while it was 3.0 and 1.04 t ha^{-1} in the cow dung and rice straw treatments, respectively. The results show that the application of CD, PM and RS resulted in 36, 28 and 37% loss of applied C through CO_2 emission. The application of organic C through CD and PM accounted for 30 and 49% sequestration, while the sequestration of C from RS accounted for only 10%. There was an unaccounted amount of applied C in all three sources, with variable magnitude. The unaccounted portion of C in soil from CD and RS represented 34 and 53%, respectively, but in the case of PM it was only 23%. The unaccounted portion of the added C may be attributed to the anaerobic decomposition where CO_2 was not produced, or the escape of the produced CO_2 through aerenchyma channels to the leaf surface. There was a slight C sequestration in the STB treatment. CD, PM and RS contributed to a positive soil nutrient balance, which indicates the improvement of soil fertility as well. Results of the study indicate that the buildup of organic carbon in soils under a rice–rice cropping system from residue application were 40, 60 and 58 kg t^{-1} of RS, CD and PM, respectively, during five rice-growing seasons, which might vary according to the initial carbon contents of residues applied to soil. Poultry manure was found to be efficient at increasing carbon and other nutrients in soils, and contributed to a higher grain yield of rice compared to RS and CD. Soil carbon and other nutrients decreased with increased soil depths irrespective of organic manures and rice straw. Though it is very difficult to increase carbon content in soils under tropical and subtropical climatic conditions, the regular replenishment of carbon through the application of different organic residues may maintain and increase carbon levels in soils to some extent. This small increment in soil organic carbon may create great impacts in reducing the atmospheric C concentration.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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