INTEGRATED NUTRIENT MANAGEMENT SYSTEMS PROMOTE SOIL HEALTH AND INCREASE PADDY YIELD

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Abstract

Understanding the dynamics of carbon (C), nitrogen (N), and microbial activity under integrated nutrient management is essential for promoting soil health and sustainable agriculture, yet remains inadequately explored in paddy systems. This study aimed to assess the temporal changes in soil C and N pools, C stock, microbial biomass, and rice yields under the influence of organic and inorganic fertilizers. An experiment was conducted during transplanted Aman season at the research field of Gazipur Agricultural University, Bangladesh. The experiment followed a randomized complete block design with five treatments: Control (no organic input), cow dung (CD), vermicompost (VC), rice straw (RS), and poultry manure (PM), each applied at a C-equivalent rate of 2 t ha^{-1}. The results demonstrated significant improvements in soil organic carbon and nitrogen dynamics due to organic amendments. Soil C content increased notably by 30 days after transplanting (DAT), with CD treatment achieving the highest gain (29%), followed by RS, PM, and VC. However, soil C gradually declined thereafter, indicating temporal turnover of organic matter. Inorganic and organic nutrient additions significantly enhanced total N, ammonium, and nitrate levels 2-5 folds compared to initial values. Microbial biomass was positively influenced, reflecting enhanced biological activity and nutrient cycling. Notably, the PM treatment yielded the highest rice grain production (6.42 t ha^{-1}), followed by RS and VC. These findings underscore the critical role of integrated organic inputs in restoring soil C and N pools, stimulating microbial processes, and enhancing crop productivity. The study provides vital evidence that integrating organic amendments in nutrient management is a viable strategy to boost soil health and ensure long-term sustainability in rice-based agroecosystems.

Keywords: Carbon and nitrogen dynamics, Microbial biomass, Carbon stock, Rice yield

1. Introduction

Rice (*Oryza sativa* L.) is a critical staple food, meeting about one-fifth of the daily caloric needs for over half of the global population (Birla *et al.,* 2017; Al-Amin *et al.,* 2025). In Bangladesh, rice dominates the cropping system, occupying nearly 75% of the total cropped area and more than 80% of irrigated land (Islam *et al.,* 2024). However, the increasing pressure to meet rising food demands amidst shrinking cultivable land and a growing population have led to the intensive use of chemical fertilizers (Abdullah *et al.,* 2019; Rahman *et al.,* 2020a). While this practice has temporarily enhanced productivity, it has also accelerated the depletion of soil organic matter (SOM), degraded soil structure, reduced microbial activity, and ultimately undermined soil fertility and soil health (Rahman and Billah, 2024). SOM plays a central role in sustaining agricultural systems, acting as a reservoir for essential nutrients such as carbon (C), nitrogen (N), phosphorus (P), and sulfur (S) (Rahman, 2014). It also influences key soil properties including bulk density, water-holding capacity, and nutrient cycling (Roy *et al.,* 2019). In rice-based cropping systems, particularly under flooded conditions, the dynamics of SOM are complex due to continuous submergence, high temperatures, and rapid microbial decomposition. These conditions intensify C mineralization and result in significant CO_2 emissions, contributing to climate change (Rahman *et al.,* 2016; Hossain *et al.,* 2017; Arofi *et al.,* 2019).

Integrated nutrient management (INM), the strategic combination of organic and inorganic nutrient sources has emerged as a sustainable alternative to conventional fertilizer-based practices (Al-Amin *et al.,* 2024). Organic amendments such as poultry manure (PM), cow dung (CD), rice straw (RS), and vermicompost (VC) improve soil physical and chemical properties, promote microbial diversity, enhance nutrient retention, and contribute to long-term C sequestration (Rahman *et al.,* 2022). Their decomposition not only supports microbial biomass growth but also sustains nutrient release over time, improving crop nutrient use efficiency and resilience (Alam *et al.,* 2019). Microbial biomass is a sensitive and reliable indicator of soil biological activity and fertility (Alam *et al.,* 2023; Khanam *et al.,* 2024). It represents a labile pool of nutrients available for plant uptake and plays a crucial role in driving biogeochemical processes, especially C and N transformations (Jenkinson, 1990; Rahman *et al.,* 2020b). Although microbial biomass constitutes only a small fraction of total soil C (0.1–5%), its influence on nutrient cycling and soil function is significant (Singh and Gupta, 2018). The quantity and composition of soil microbes are closely influenced by management practices, particularly organic input types and tillage intensity (Wang *et al.,* 2017). For instance, tillage often reduces microbial abundance and SOM by disrupting soil aggregates and enhancing C oxidation (Weidhuner *et al.,* 2021). Despite the growing awareness of the benefits of INM, limited data exist on the temporal dynamics of soil C and N, microbial populations, and rice yields in soils amended with diverse organic materials in the subtropical conditions of Bangladesh. Particularly under paddy rice systems, the transformation patterns of applied organic materials and their contribution to C sequestration, microbial activity, and crop productivity remain underexplored. The effect of different organic amendments such as PM, CD, RS, and VC on microbial biomass C and N and their relationship with nutrient cycling processes during the rice-growing season is not well documented.

Soils in Bangladesh are becoming increasingly degraded due to continuous intensive cropping with high-yielding varieties and excessive dependence on synthetic fertilizers, with minimal or no addition of organic inputs (Ferdous *et al.,* 2021; Rahman *et al.,* 2024). This has led to nutrient imbalances, loss of SOM, poor soil structure, and reduced biological activity. These scenarios jeopardize sustainable crop production. Moreover, the country's climate characterized by high temperature and humidity accelerates SOM mineralization, leading to elevated CO_2 emissions and reduced C sequestration. Considering such circumstances, we hypothesized that the integration of organic amendments with inorganic fertilizers improves the temporal dynamics of soil C and N, enhances microbial biomass and activity, rice yields compared to sole inorganic fertilizer application. The study objectives were: to investigate the temporal dynamics of soil C, N, and C stock under different organic amendments in paddy soils, to assess changes in microbial biomass C and N during the rice-growing season, and rice grain yields as influenced by organic inputs. This study aimed to provide comprehensive insights into soil biological and nutrient processes under integrated nutrient management, contributing to improved soil health, enhanced productivity, and long-term sustainability of rice-based cropping systems in Bangladesh.

2. Materials and Methods

2.1 Experimental site and soil

The field experiment was carried out at the research field of Department of Soil Science, Gazipur Agricultural University (GAU), Gazipur 1706, Bangladesh during July 2022 to December 2022 in Aman season using variety BRRI Dhan49. The experimental site is located in 24.090 N latitude and 90.260 E longitudes at 8.5 m above the mean sea level. The study area was under the Madhupur Tract (AEZ 28). Nationally, the experimental field belongs to the Sanla series of shallow red brown terrace soil and according to the USDA it is classified under the order of Inceptisols. The soil is silty clay loam in texture and acidic in nature being characterized by poor fertility status and impeded internal drainage.

2.2 Treatments and design of the experiment

There were five treatments in the experiment viz., (i) Control (only inorganic fertilizers), (ii) Cow dung (CD), (iii) Vermicompost (VC), (iv) Rice straw (RS), and (v) Poultry manure (PM). The organic materials were applied considering carbon rate 2 t ha^{-1}. The treatments were laid out in a randomized completely block design with four replications. The whole experimental field was divided into four blocks and each block representing a replication. Each block was further subdivided into 5-unit plots. Total number of plots were 20, and the unit plot size was 4 m × 5 m, while the plots were separated by 0.5 m.

2.3 Land preparation, manuring and fertilization

The selected land was well ploughed with tractor drawn disc plough followed by harrowing and laddering up to a good tilth. All weeds and stubbles were removed. The plots were prepared with drains made around each plot. Ridges were compacted and raised around each plot to restrict the lateral run off irrigation water. Well decomposed cow dung (CD), vermicompost (VC), poultry manure (PM), rice straw (RS) was applied in the respective treatments one week before final land preparation. Different organic materials, their nutrient concentrations and amount of nutrient added in soils are provided in the Table 1.

Soil test-based fertilizer rates for the control treatment were 75, 15, 55 kg ha^{-1} of N, P and K, respectively. Sulphur and zinc were applied @ 16 and 2 kg ha^{-1}, respectively in the previous boro season. Inorganic treatments, N, P and K were applied following integrated plant nutrient systems. Phosphorous (P) and potassium (K) were applied at the time of final land preparation in the form of triple super phosphate (TSP) and muriate of potash, respectively. Nitrogen (N) from urea was applied in three equal splits. One third of urea was applied at the time of final land preparation.

Table 1. Organic materials their amount and nutrient concentrations and nutrient applied

Treatments	C rate (2 t ha^{-1})	C content (%)	Nutrient conc. (%)			Nutrient applied (kg ha^{-1})		
			N	P	K	N	P	K
Control			-	-	-	-	-	-
CD	2000	22	0.5	0.15	0.23	45.45	13.64	20.91
VC	2000	25	0.65	0.35	0.5	52.00	28.00	40.00
RS	2000	41	0.2	0.05	0.45	9.76	2.44	21.95
PM	2000	20	0.6	0.35	0.45	60.00	35.00	45.00

2.4 Intercultural practices, crop harvesting and data collection

The experimental plots were infested with some common weeds. So weeding was done to keep the crop free from weeds at 14, 24 and 44 days after transplanting. Though, T. aman is a rainfed crop, however, supplementary irrigation was given in the field when needed to keep available moisture for plant growth. Precautionary measures were taken against different pests and diseases regularly and hence no severe infestation of pest and diseases in the field was observed. The crop was harvested on November 17, 2022. Grain yield was adjusted to 14% moisture content. Yield data of both rice grain and straw were recorded from 1 m^2 areas and then extrapolated to t ha^{-1}.

2.5 Soil sample collection

The soil samples were collected before final land preparation (initial), and at 30, 60, 90 and 130 days after transplanting from the plough depth layer (0-15 cm) to analyze soil pH, organic carbon, bulk density, total N, available N (NH_4^+-N and NO_3^--N), biomass C and N, microbial populations.

Calculation of C stock and C enrichment

Carbon stock and C sequestration were calculated using the following equation (Rahman *et al.,* 2016).

Carbon stock (t ha^{-1}) = Carbon concentration (%) x bulk density (g cm-3) x depth (cm)
Carbon enrichment (t ha^{-1}) =Final C in OM treated plot (t ha^{-1}) – Final C in fertilizer control plot (t ha^{-1})

2.6 Soil samples processing and analysis

Collected soil samples were processed, preserved and analyzed as per standard protocols. Soil pH was measured by a glass electrode pH meter using a soil water ratio of 1:2.5 (Black, 1965). Soil organic carbon was estimated by Walkley and Black's wet oxidation method as described by Jackson (1973). Total nitrogen was determined by micro-Kjeldahl method by (Page et al., 1989). Nitrate N (NO_3^--N) and ammonium N (NH_4+-N) of soil samples were estimated by a diffusion technique as described by Khan et al. (2000). The bulk density of soil was determined using the core sampling method. The chloroform fumigation extraction method provided by Anderson and Domsch (1978) was used to estimate the amount of microbial biomass C in soils. Biomass N was determined according to the method described by Brooks et al. (1985a and 1985b).

2.7 Statistical data analysis

The data collected on different parameters were subjected to statistical analysis using procedure described by Gomez and Gomez (1984). Microsoft EXCEL and Statistix 10 software program were used wherever appropriate to perform statistical analysis. Relationships among the parameters were established through correlation and regression analysis. Mean differences among the treatments were adjusted by using the least significance difference (LSD) test at 5% level of significance.

3. Results and Discussion

3.1 Soil pH and organic carbon as affected by different organic and inorganic fertilizers

Combined application of organic and inorganic fertilizers as integrated nutrient management showed significant effects on soil pH in each time of sample collection of rice growing season (Table 2). The initial soil pH was slightly acidic (6.11 - 6.33), while at final sampling of 130 days after transplanting (DAT) it again appeared as slightly acidic even though values under different treatments decreased with an exception in case of vermicompost (VC) where pH increased from 6.14 to 6.24. In each sampling day, treatments exhibited significant effects on soil pH, however, the highest increase of pH (6.60) was found in poultry manure (PM) treatment at 30 and 60 DAT, and in case of rice straw (RS) treatment the highest pH of 6.68 was observed at 60 DAT.

Soil pH displays the soil capability to make nutrients available for plant uptake. A slightly acidic to slightly alkaline soil i.e., pH ranges from 6.5 to 7.5 might be suitable for making almost all essential nutrients available for crops. Soil pH in the present study even though lower compared to the suitable range, it may not be a problem especially for wetland paddy fields.

Upon submergence pH of acidic soil moves towards neutrality. There are different factors which are responsible for soil acidity. Application of urea fertilizer, crop removal and leaching of basic cations (Ca^{2+}, Mg^{2+}, and K^{+}), decomposition of organic materials and H^{+} ions released by Al^{3+} might be the causes pH declination in soils. It is recognized that soil pH controls solubility and availability of essential plant nutrients and manages all bio-physico-chemical reactions in soils (Rahman *et al.,* 2020a; Deveautour *et al.,* 2022).

Table 2. Changes of soil pH with time from organic and inorganic fertilizers application

Treatments	Soil pH at different days of rice growing				
	Initial	30	60	90	130
Control (no OM)	6.15	6.26bc	6.48ab	6.40a	5.97b
Cow dung	6.11	6.22bc	6.30b	6.05b	5.94b
Vermicompost	6.14	6.07c	6.55ab	6.41a	6.24a
Rice straw	6.22	6.46ab	6.68a	6.29a	6.18ab
Poultry manure	6.33	6.60a	6.60ab	6.44a	6.25a
S.E. (±)	-	0.135	0.143	0.106	0.113
CV (%)	-	3.02	3.10	2.38	2.63

Different lowercase letters within a single column indicate the statistically significant differences at 5% level

The treatments displayed significant effects on OC content in soils collected at different DAT (Table 3). Initial soil OC content was ranged from 0.87% to 0.95%, which is as per fertility ranking rated as low. At 30 DAT, organic amendments plus inorganic fertilizer as per INM approach showed the significantly highest OC content over the control treatment where no organic materials were applied but inorganic fertilizers were applied. From the initial level, OC increased considerably at 30 DAT under all the treatments, but from 30 DAT to onwards until 130 DAT OC decreased following almost a similar fashion. It is a good sign that at 130 DAT OC content in soils rated as medium. The highest amount of OC content was attributed in the CD treatment (1.28%) followed by RS (1.16%), VC (1.09%), PM (1.08), and the control (1.02%). The control treatment always exhibited the significantly lowest OC as the treatment received inorganic fertilizers and more especially N fertilizer enhances the mineralization processes and thereby contributed to lower OC.

Table 3. Variations in soil organic C with time under organic and inorganic treatments

Treatments	Soil OC (%) at different days of rice growing				
	Initial	30	60	90	130
Control (no OM)	0.91	1.04b	1.15b	1.11	1.02b
Cow dung	0.95	1.37a	1.39a	1.30	1.28a
Vermicompost	0.92	1.36a	1.21ab	1.12	1.09ab
Rice straw	0.89	1.33a	1.26ab	1.19	1.16ab
Poultry manure	0.87	1.31a	1.19ab	1.14	1.08b
S.E. (±)	-	0.071	0.103	0.106	0.088
CV (%)	-	11.20	11.77	12.80	11.12

Different lowercase letters within a single column indicate the statistically significant differences at 5% level

It is generally known that a productive soil should contain at least 1.45% OC soil (FRG, 2024). But, in Bangladesh, OC content of most soils is less than 0.57%, and in some soils. The low OC content adversely affects soil tilth, soil water retention, soil erosion, infiltration of air and water, and the fate of pesticides applied in soils, thus affecting environmental health and crop production. Low OC content results from the intensive cultivation solely depending on inorganic fertilizers and removal of crop stubble from the fields to use as a form of fuel in Bangladesh. Furthermore, climatic conditions of the country are also conducive for faster mineralization organic matter in soils, and thereby attributed to lower C in soils. However, as OM is a life of soils which governs all bio-physico-chemical properties of soils. It is the therefore, necessary to increase OM level in soil adopting best management practices (Rahman *et al.*, 2020b). World Soil Day 2020 also emphasized to retain soil healthy for sustainable agriculture as the theme of the day was 'Keep Soil Alive, Protect Soil Biodiversity'.

3.2 Soil bulk density and carbon stock

Soil bulk density did not respond to a significant change because of addition of organic and inorganic fertilizers in paddy fields (Table 4). Bulk density varied from 1.33 to 1.38 g.cc, which is the common range in silty clay loam soil of Bangladesh. Soil C stock at crop harvest was determined where treatments' influence was observed insignificant. However, a positive response of organic amendments was attained in soil C increment. Compared to the control, C increment in soil was the highest in CD (28.52%), followed by RS (14.51%), PM (7.23%) and VC (4.94%). Though organic materials were applied in soils considering 2 t C ha^{-1}, differences in C accumulation in soils under different organic amendments were occurred because of their quality, C: N ratio and mineralization potentials. The materials which are almost decomposed during application, the rate of C accumulation will be higher and mineralization will be slower. Several research findings suggest that when mineralization increases C storage in soil decreases (Rahman, 2014; Rahman *et al.*, 2016). Cowdung may contain more humified and recalcitrant C as compared to other organic materials. Therefore, CD was found more effective in building SOC than straw. As soil is a highly heterogeneous in nature even in a closer distance, therefore, such variation in C enrichment in soils even from the same organic source may occur (Rahman *et al.*, 2016; Hossain *et al.*, 2017; Alam et al., 2019). Yang *et al.* (2004) demonstrated that the C in paddy soil was 40–60% higher when nutrients were applied using organic and inorganic sources against the sole inorganic fertilizers.

Effect of organic and inorganic fertilizers on soil nitrogen Integrated nutrient management did not show significant effects on soil total N (Table 5) and ammonium N (Table 6) in either of the sampling time during rice growing season. The initial soil total N varied from 0.087 to 0.095%, while at final sampling of 130 days after transplanting (DAT) all the values under different treatments increased some extent ranged from 0.103 to 0.128% (Table 5). It was observed that in all other sampling dates i.e., at 30, 60 and 90 DAT as total N in soils followed almost similar patterns. The initial status of soil N was mainly very low, while in case of CD (0.095%) and VC (0.092%) treatments rated as low. According to FRG (2024) N contents in soil rated very low when it contains <0.090% N, while low belongs to the range of 0.090 % to 0.180%.

Table 4. Soil bulk density, C stock and C increment as affected by different treatments

Treatment	Soil bulk density (g c.c.$^{-1}$)	C stock (t ha^{-1})	C increment compared to the control (%)
Control	1.35	20.64	-
Cow dung	1.37	26.52	28.52
Vermicompost	1.33	21.65	4.94
Rice straw	1.37	23.63	14.51
Poultry manure	1.38	22.13	7.23
S.E. (±)	0.067	2.17	-
CV (%)	6.97	13.45	-

Table 5. Changes in soil total N with time from organic and inorganic fertilizers application

Treatments	Soil total N (%) at different days of rice growing				
	Initial	30	60	90	130
Control (no OM)	0.090	0.103	0.115	0.111	0.106
Cow dung	0.095	0.125	0.139	0.130	0.128
Vermicompost	0.092	0.122	0.121	0.110	0.103
Rice straw	0.089	0.119	0.126	0.119	0.116
Poultry manure	0.087	0.121	0.119	0.114	0.108
S.E. (±)	-	0.007	0.010	0.011	0.009
CV (%)	-	11.20	11.63	13.24	11.95

3.3 Soil ammonium and nitrate N

There was no significant change in ammonium N contents in soils under different treatments (Table 6). However, from the initial values (7.34 to 8.12 mg kg^{-1}) a large increment in ammonium N contents in soil was observed in case of all treatments and all sampling dates. At 30 and 130 DAT, the increments were almost double than that of the initial ammonium N, while at 60 DAT the rates of increments were almost three times higher over the initial levels. At 30 DAT ammonium N contents in soils under different treatments ranged from 13.16 to 15.82 mg kg^{-1}, while at 60 DAT it varied from 17.92 to 23.10 mg kg^{-1}.

On the other hand, the treatments exhibited significant contribution to increase nitrate N in soils at different DAT except 90 DAT (Table 7). The initial nitrate N in soils varied from 4.33 to 7.32 mg kg^{-1} soils, which increased by 3 to 5 times at different DAT. At 30 DAT, the significantly highest amount of nitrate N (26.74 mg kg^{-1}) was attributed in the CD treatments which was found statistically similar with RS treatment (20.44 mg kg^{-1}). The significantly lowest amount of nitrate N contents in soils was found in the VC treatment (14.56 mg kg^{-1}), which was insignificantly varied with the control and PM treatments. under different treatments ranged from 13.16 to 15.82 mg kg^{-1}, while at 60 DAT it varied from 17.92 to 23.10 mg kg^{-1}. At 60 (33.04 mg kg^{-1}) and 130 (25.06 mg kg^{-1}) DAT, the significantly highest amount of nitrate N contents were also found in the CD treatment compared to all other treatments (Table 7).

It was appeared that ammonium and nitrate N contents in the INM treatments were comparatively higher than that of the control i.e., where only inorganic fertilizers were applied. The increment of ammonium and nitrate N with the advancement of time i.e., at different DAT reveled that more N was mineralized through ammonification and nitrification process from both organic and inorganic fertilizers. The mineralization of different organic materials has augmented both ammonium and nitrate Nin soils. Substantial differences in released patterns of NH_4^+-N and NO_3^--N in different organic materials and N fertilizer treatments were related with variations in mineralization of different inputs. Mineralization of different organic materials inconsistently varies under different soil and crop management practices because of C types and their comparative resistance to microbial breakdown process. Among the factors that control mineralization of OM are composition or quality of residues added, soil temperature and water content, drying and rewetting events, soil biota and soil characteristics (Alam *et al.* 2019). It was reported that organic materials having higher C: N ratios exhibited the slower rates of mineralization (Ostrowska and Porębska, 2015; Rahman *et al.,* 2016). Different organic materials under various levels of N fertilizer showed inconsistent trends in the release of soil NH_4^+-N and NO_3^--N under different rice growing periods.

Table 6. Changes in soil ammonium N with time from organic and inorganic fertilizers

Treatments	Soil ammonium N (mg kg^{-1}) at different days of rice growing				
	Initial	30	60	90	130
Control (no OM)	7.87	14.84	19.74b	17.08a	13.44bc
Cow dung	7.34	15.40	21.28ab	17.50a	14.56b
Vermicompost	8.12	15.82	23.10a	18.76a	16.38a
Rice straw	7.50	13.16	17.92b	13.16b	12.30c
Poultry manure	7.92	14.98	22.26a	18.48a	14.84b
S.E. (±)	-	2.97	3.76	3.72	3.36

Different lowercase letters within a single column indicate the statistically significant differences at 5% level

Table 7. Changes in soil nitrate N with time from organic and inorganic fertilizers application

Treatments	Soil nitrate N (mg kg^{-1}) at different days of rice growing				
	Initial	30	60	90	130
Control (no OM)	4.55	17.60b	19.74b	16.20	15.77b
Cowdung	5.34	26.74a	33.04a	28.28	25.06a
Vermicompost	4.33	14.56b	19.88b	16.66	14.42b
Rice straw	5.56	20.44ab	14.78b	19.35	17.38b
Poultry manure	7.32	19.14b	22.96b	19.32	16.09b
S.E. (±)	-	3.44	3.92	4.21	2.50
CV (%)	-	24.75	25.13	29.83	19.91

Different lowercase letters within a single column indicate the statistically significant differences at 5% level

3.4 Influence of organic and inorganic fertilizers on soil biomass C and N

The treatments comprising different organic residues and chemical fertilizers significantly influenced the microbial biomass C content in soil at different days after transplanting of rice

(Table 8). Biomass C in soil under different treatments even at zero days was found significant. The experiment was started in 2 010 following the same treatments and therefore even at zero days of transplanting of rice biomass C in soil showed significant differences among the treatments. In the zero day the biomass carbon was found significantly higher in the poultry manure treated plot compared to other treatments. This was because of higher amount of nitrogen present in the poultry manure resulting lower or optimum C: N ratio, which favored rapid and faster microbial colonization in the poultry manure treated plot compared to rice straw, vermicompost and cowdung. This was observed not only at zero day, but also found in 30, 60. 90 and 120 days after transplanting (Table 8). Irrespective of residues or treatments biomass C contents in soils were increased with the advancement of rice growing periods i. e the maximum biomass C was found at crop harvest and followed the order 0<30<60<90<120 days after transplanting. Biomass C contents in soils under different organic residues were significantly higher over the control treatment ($p<0.005$). The biomass C enriched in soils in the order of poultry manure >cowdung >vermicompost> rice straw. The maximum biomass carbon was found in the poultry applied plot at harvest, which was 208 mg kg^{-1}, while the lowest was found in the control treatment at zero day after transplanting of rice (36 mg kg^{-1}).

Table 8. Microbial Biomass C in soil as affected by organic and inorganic fertilizer

Treatments	Biomass C (mg kg^{-1}) at different days of rice growing			
	30	60	90	130
Control	35.86e	36.17e	36.47e	36.77e
Cow dung	71.34b	80.14b	88.94 b	99.79b
Vermicompost	51.09 c	64.17c	68.44c	76.74c
Rice straw	47.49d	48.29 d	49.09d	49.64d
Poultry manure	117.92a	153.71a	182.51a	208.31a
S.E. (±)	1.34	2.73	3.19	5.31
CV (%)	2.94	5.05	5.30	7.97

Different lowercase letters within a single column indicate the statistically significant differences at 5% level

Soil microbial biomass, a living part of SOM, is an agent of transformation of added and native organic matter and as a labile reservoir for plant available N, P and S. The activity of the microbial biomass is commonly used to characterize the microbiological status of soil and to determine the effects of cultivation and soil and crop management on soil microorganisms (de Silva *et al.,* 2014; Smith and Paul, 2017). The microbial biomass C fluctuations occurred due to temperature, moisture condition, growth stages of plant, supply of nutrients and lack of substrate. The treatments significantly influenced the microbial biomass N content in soil at different days after transplanting of rice (Table 9). Biomass N in soil under different treatments even at zero days was found significant. Irrespective of days after transplanting i. e. 0, 30, 60, 90 and 120 days after transplanting biomass N in soils were found significantly higher in the poultry manure treated plots compared to other treatments. This was because of higher amount of N present in the poultry manure resulting lower or optimum C: N ratio, which favored rapid and faster microbial colonization in the poultry manure treated plot compared to RS and CD (Table 9). The maximum biomass N was found at crop harvest and followed the order 0<30<60<90<120 days after transplanting. Biomass N contents in soils under different organic residues were significantly higher over the control treatment ($p<0.05$). As observed in the biomass carbon, the biomass N also enriched in soils in the order of PM>CD >VC> RS. Like biomass C the maximum biomass N was also found in the PM applied plot at harvest, which was 33.22 mg kg^{-1}, while the lowest was found in the control treatment at 30 days after transplanting of rice (3.45 mg kg^{-1}).

Table 9. Biomass N in soil as affected by organic and inorganic fertilizer application

Treatments	Biomass N (mg kg^{-1}) at different days of rice growing			
	30	60	90	130
Control	3.45d	4.23 d	4.78e	4.83 d
Cow dung	7.02 c	13.05 b	20.10 b	24.90 b
Vermicompost	7.47b	11.75 b	14.80 c	18.35 c
Rice straw	6.73c	7.26c	7.81 d	8.61 d
Poultry manure	13.59 a	20.87 a	26.17 a	33.22 a
S.E. (±)	0.132	1.26	1.31	1.81
CV (%)	2.45	15.68	12.60	14.25

Different lowercase letters within a single column indicate the statistically significant differences at 5% level

From the study it was found that the microbial biomass N ranged from 3.25 mg kg^{-1} in the control treatment at zero day after transplanting to 31.6 mg kg^{-1} in soil under PM treated plot at 120 days after transplanting. The fluctuations of microbial biomass N occurred in organic residues and chemical fertilizer amended soil. The higher amount of biomass N was found in the STB treatment over the RS and CD treatments due to the presence of higher amount of available nutrients especially N in the fertilizer treatment, which favored rapid microbial activity i.e., mineralization in soils. The higher microbial biomass attributed due to the higher available C substrates and nutrients contents in soils (Smith and Paul, 2017; Khanam *et al.,* 2024).

3.5 Effect of organic and inorganic fertilizers on rice grain and straw yields

Different organic amendments and inorganic fertilizers significantly increased grain and straw yields of rice (Fig. 1). The PM treatment significantly increased rice grain (6.42 t ha^{-1}) which was insignificantly different than that of RS treatment (6.23 t ha^{-1}). The control treatment i.e., only inorganic fertilizers (without organic fertilizers) produced the significantly lowest amount of grain yield of 5.31 t ha^{-1}. The straw yields in all organic treatments found statistically similar, and were revealed significantly higher than that of the control. The observed grain yields under different treatments followed the order of

PM>RS>VC>CD>Control. The application of organic and inorganic fertilizers attributed significant positive effect on rice grain yields.

Grain yields of BRRI dhan49 in the current study were found somewhat higher than its national average yield of 5 ± 0.5 t ha^{-1}. This was might be because of best management practices ensured in soil management and crop production. The PM was more potential in improving rice yields because it contained high amounts of most of the essential plant nutrients compared to other organic materials used (Sarkar *et al.,* 2016; Rahman *et al.,* 2016; Alam *et al.,* 2019). As the C:N ratio of PM was low to optimum, the mineralization was faster compared to other organic materials including RS. Thus, nutrient released from PM favored nutrient uptake and thereby provide higher grain yield of rice.

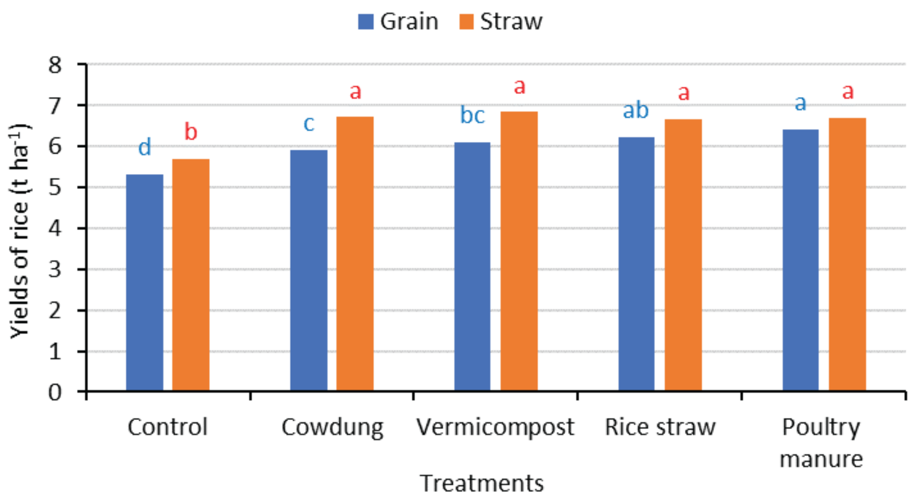

Fig. 1. Grain and straw yields of rice under different treatments (Different letters on grain and straw yields represent statistically significant differences among different treatments)

3. Conclusions

The application of organic amendments significantly improved soil carbon status, raising it from low to medium levels during the rice-growing season. Cow dung application was found to be the most efficient in increasing soil C (29%), followed by rice straw, poultry manure, and vermicompost. All organic treatments enhanced total, ammonium, and nitrate nitrogen many folds compared to initial levels. Poultry manure contributed the highest microbial biomass carbon and nitrogen. Integrated nutrient management increased rice yields. Poultry manure yielded the highest grain output which was about 21% higher over the control. Overall, integrating organic amendments into fertilizer regimes enhanced soil organic matter, microbial activity, and rice yield. These findings underscore the vital role of organic-inorganic nutrient strategies in restoring soil health and achieving long-term agricultural sustainability in rice-based systems.

Acknowledgements

The authors sincerely acknowledge the support of the Department of Soil Science, Gazipur Agricultural University in conducting research and providing laboratory facilities for analysis. The authors gratefully admit Prof. Dr. Md. Mizanur Rahman for editing the manuscript to make it suitable for publication.

Conflicts of Interest

The authors declare no conflicts of interest regarding publication of this paper.

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