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RESEARCH ARTICLE

Exploring the effect of fertilizer application on yield and decoding CO_2 flux under flooded paddy conditions towards sustainable agriculture

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Abstract

The impact of organic and inorganic nutrient management on the emission of carbon dioxide (CO_2), soil properties such as available nutrients, microbial population and soil organic carbon (SOC) were investigated in paddy (*Oryza sativa* L.) field (at 8° 46' N Latitude and 77° 42' E Longitude) under flooded condition during late pishanam season in 2023-2024. The treatments were designed to observe the effects of applying fertilizer based on the soil test crop response (100 % STCR-based NPK) that had been modified by organic amendments, which include absolute control (unfertilized), inorganic fertilizers, sole application of organic amendments (Farm yard manure, Green leaf manure, Vermicompost and Poultry manure) and combined these organic amendments with inorganic fertilizers. The main objective of this study is to understand the intricate relationship between fertilizers and carbon flux in paddy soils, which is crucial for developing sustainable agricultural practices that minimize environmental harm while ensuring food security. The observation of the experimental field study reported that the combined application of poultry manure at the rate of 5 tonnes per hectare with 100% STCR-based inorganic fertilizer recorded maximum yield and yield attributes. The treatment combination of poultry manure + inorganic fertilizer enhanced in sequestrating the soil organic carbon (0.67%) resulted in higher grain yield (5972 kg ha^{-1}) and also observed that this combination will limit the emission of CO_2 to the atmosphere. Therefore, it could be a better choice for carbon storage and higher productivity in a sustainable rice cropping system.

Keywords

carbon dioxide; carbon emission; production; rice; sustainable agriculture

Introduction

Rice *(Oryza sativa* L.) is essential for food security and has a rich cultural legacy that influences customs, cuisines and ways of life worldwide (1, 2). Estimated rice production during 2022-2023 is 1357.55 lakh tonnes, 62.84 lakh tonnes higher than the last year. The general concept for paddy cultivation was flooded condition (3). The method is well-known for its effectiveness in yielding large quantities of rice, which sustains the lifestyles of millions of people worldwide. Production of paddy will decline because global warming impacts the management of rice crop cultivation (4). Soil is the crucial factor for sinks and sources of greenhouse gases and contributes to climate change

(5). Approximately 20% of greenhouse gas emissions come from agriculture (6). GHG emission from rice cultivation alone is about 19% of the whole agriculture sector emission (7).

Carbon dioxide is a large contributor to greenhouse gas emissions from paddy fields despite methane having a more significant potential for global warming per molecule due to its sheer abundance (8). Carbon emissions from rice fields can happen both during the growing season and after harvesting, although they usually peak during times of elevated temperature (9). Furthermore, soil disturbance from management, such as drainage and land preparation operations, might result in carbon dioxide (CO_2) emissions during paddy cultivation. Fertilizers are frequently used in paddy fields to promote crop growth. When making nutrient management through general fertilizer recommendations, there might be a surplus or lack of nutrients, which could lower crop output (10). Using inorganic fertilizer in large amounts to achieve the target yield may cause harmful effects on the environment (11). Organic amendments enhance soil quality by increasing stability, water retention, nutrient availability, and biomass production (12). While maintaining the productivity and resilience of rice-based agro ecosystems, it is possible to reduce carbon emissions from paddy fields by implementing methods including appropriate application of synthetic fertilizer and organic fertilizer on a combined basis, which are vital to modern agriculture because they give crops the nutrients, they need to maximize yields and controls the emission of carbon dioxide from the paddy field to the environment (13). However, the usage of organic manure is also declining as the need for inorganic fertilizers rises (14). The present study lays the groundwork for a detailed examination of the dynamics, impacts, and potential mitigating actions connected to carbon emissions in rice farming. Through this research, we intend to get a deeper insight into the finer points of paddy production in flood-prone areas and highlight the significance of sustainable farming practices that combine agricultural output with environmental conservation.

Materials and Methods

Experimental site

This experimental study conducted a field trial at Agricultural College and Research Institute, Killikulam, Tuticorin district, Tamil Nadu. Geographically speaking, the experiment site was located at 8° 46' N Latitude and 77° 42' E Longitude, 40 meters above mean sea level (MSL) in the southern agro-climatic zone of Tamil Nadu. Soil texture was found to be sandy clay loam (Clay 28%, Silt 15%, Sand 25% and Fine sand 31%), Bulk density 1.22 Mg m^{-3}, Water holding capacity 55%, pH 7.65, EC 0.17 ds m^{-1}, Soil organic carbon (SOC) 0.51%, Available nitrogen 210.29 kg ha^{-1}, Available phosphorus 182.42 kg ha^{-1} and Available potassium 196 kg ha^{-1}.

Treatments and crop establishment

The field experiment was lined up using a randomized block design (RBD). The crop variety and treatment details are presented in Table 1. Fertilizers based on soil test crop response (STCR) were applied to maximize rice grain output. The prescribed dose of N: P_2O_5:K_2O at the rate of 182:63:25 kg ha^{-1} of NPK in the form of inorganic fertilizer was provided as the basal treatment. In the relevant treatment plots, organic amendments such as FYM, vermicompost, poultry manure and GLM were applied at five tons per hectare. The field adopted for this study was well prepared by flooding two days before puddling, and the field was puddled twice with Adequate Water. Rice cultivation practices from sowing to harvest, including spacing, transplanting and plant protection activities, were all carried out as per the standard protocol prescribed by TNAU and released as the Crop Production Guide (CPG, 2020) by the Department of Agriculture, Government of Tamil Nadu.

Table 1. Crop and treatment details

Treatment	Detail
T1	Absolute control
T2	100 % STCR based NPK
T3	100 % STCR based NPK + FYM 5t ha^{-1}
T4	100 % STCR based NPK + Vermicompost 5t ha^{-1}
T5	100 % STCR based NPK + Poultry manure 5t ha^{-1}
T6	100 % STCR based NPK + GLM 5t ha^{-1}
T7	FYM 5t ha^{-1}
T8	Vermicompost 5t ha^{-1}
T9	Poultry manure 5t ha^{-1}
T10	GLM 5t ha^{-1}

Soil sampling and analysis

The soil samples were collected initially at different physiological stages of rice, such as active tillering, panicle initiation and postharvest stages. The processed samples were used to analyze the soil's physical, chemical and biological properties. Five hills were chosen randomly in every treatment plot and all the selected hills were tagged in respective plots to take the following biometric parameters. In each plot, plant heights, number of tillers per square meter, soil plant analysis development readings and productive tillers were explicitly measured in the selected hills and the measurements were taken at active tillering (AT), panicle initiation (PI), heading and harvest stage (HA) and expressed in their respective units. Plant samples were collected from each treatment plot in the experimental rice field. Collected samples were dried using a hot air oven and powdered the dried sample. Analyses were carried out using these powdered samples to determine nutrient content per the standard protocols.

Analysis of CO_2 flux

The incubation study was carried out for 56 days using an alkaline absorption method under anaerobic conditions involving 0.1 N sodium hydroxide solution introduced into a test tube, suspended inside the conical flask containing adopted treatment soil and sealed. The conical flask was sealed with non-absorbent cotton and covered with aluminium foil to maintain a controlled environment. To measure CO_2, the 0.1 N NaOH solutions were titrated with 1 N hydrochloric acid (HCl) using phenolphthalein as an indicator until the colour changed from pink to colourless.

The soil carbon dioxide fluxes were determined from a bare plot (5×6 cm) introduced at the mentioned site for crop growth and development using the closed chamber method (15). A transparent cylindrical chamber was made with the dimensions 120cm (height) x 45cm (diameter), one open end and the opposite end fixed with an exhaust fan (inside the chamber) with a sample collecting tube and current supplying battery connected (outside the chamber). The crop is covered through the open end of the cylindrical chamber and the moisture present in that field acts as a binder, which prevents the interaction between the inside area of the chamber and the outer environment. Air samples from the chamber were collected using a 20ml plastic syringe after 24 hours of closed period. Sample collection was carried out during the active tillering stage of rice and between 11.00 AM and 1.00 PM. The collected samples from the field were brought to the laboratory and the concentration of carbon dioxide was determined using GCMS- gas chromatography-mass spectrometry.

Results and Discussion

Growth measures

The application of fertilizer based on soil test results is growing in popularity worldwide. Soil testing determines the soil's nutrient level and fertilizer recommendations based on test results aid in maintaining nutrient balance and crop production sustainability (16). The height of the plant increased significantly after applying organic supplements (17). In the present study, the treatments significantly influenced the plant height (cm) (Table 2). Among the treatments, maximum plant growth and development were observed under the treatment applied with 100 % STCR-based NPK combined with poultry manure 5t ha^{-1} overall. The plant height (cm) ranged from 44.8 to 63.08 cm, 75.18 to 97.90 cm and 87.93 to 115.66 cm at AT, PI and heading, respectively. The lowest plant growth and growth attributes were recorded by the treatment T1 (Absolute control). Most of the nutrients that plants require for their development and growth are found in organic manures along with inorganic fertilizers, which aid in the formation of new shoots, which eventually increase the plant's overall height and leaf area index. The relationship between nitrogen fertilizers and photosynthesis and cell division, in particular, may have aided the plants in producing more leaves (18). In the current study, it was evident that the treatments had a considerable impact on the leaf area index (LAI) (Table 2). Leaf area index ranged from 0.82 to 4.24, 1.19 to 5.38 and 1.25 to 5.48 at active tillering, panicle initiation and heading, respectively. The treatment T5 (100% STCR + Poultry manure 5 t ha^{-1}) recorded the highest leaf area index (LAI) overall.

Yield measures

The nutrient status and yield were highly enhanced by the integrated application of organic and synthetic fertilizer based on STCR recommended dose, followed by inorganic STCR-based fertilizer application alone (19). Various treatments impact the number of productive tillers, panicle length and 1000 seed grain weight (Table 3). The application of 100 % STCR along with poultry manure 5t ha^{-1}was recorded to be greater in all yield parameters (20). Rapid decomposition of poultry manure and higher organic matter content improve soil fertility and physical properties faster than other organic amendments (21). Enhanced soil structure improves root penetration and water retention, improving plant growth and height. Fertilizers that include inorganic and organic substances have desirable advantages for soil health and using organic amendments reduces the need for inorganic fertilizers (22). Using fertilizers with the STCR suggestion resulted in higher intakes of both phosphorus and nitrogen and surpassed alternative application of fertilizer techniques concerning

Table 2. Effect on plant height and leaf area index were influenced by various treatments and their levels at different physiologica l stages in paddy.

Treatment details	Plant height (cm)			Leaf area index		
	AT[1]	PI[2]	Heading	AT[1]	PI[2]	Heading
T1 (Absolute control)	44.80	75.18	87.93	0.83	1.19	1.25
T2 (100% STCR)	55.64	89.51	103.82	2.19	3.27	4.37
T3 (100% STCR + FYM 5 t ha^{-1})	57.63	91.00	106.95	3.19	3.28	4.39
T4	60.49	95.33	110.21	4.21	4.31	4.44
T5 (100% STCR + Poultry manure 5 t ha^{-1})	63.08	97.90	115.66	4.24	5.38	5.48
T6 (100% STCR + GLM 5 t ha^{-1})	59.00	93.11	108.68	3.21	3.30	3.43
T7 (FYM 5 t ha^{-1})	47.64	79.32	92.92	1.15	2.21	2.29
T8 (Vermicompost 5 t ha^{-1})	52.01	84.74	98.64	2.17	2.24	2.32
T9 (Poultry manure 5 t ha^{-1})	53.69	86.27	100.73	2.18	2.26	2.34
T10 (GLM 5 t ha $^{-1}$)	50.23	82.62	95.80	1.16	2.23	2.30
SEd	**0.37**	**0.44**	**0.70**	**0.004**	**0.005**	**0.006**
CD (0.05)	**0.77**	**0.91**	**1.46**	**0.008**	**0.009**	**0.014**

[1.]active tillering, [2]panicle initiation production, gross profits and BCR (23). The results from the current investigation (Table 3) demonstrated that the higher yield was obtained under the combination of 100 % STCR along with poultry manure 5t ha^{-1} recorded the grain yield of 5972 kg ha^{-1} and straw yield of 8389 kg ha^{-1}. The lowest grain yield (2250 $kgha^{-1}$) and straw yield (3361 kg ha^{-1}) was recorded under absolute control. The soil's overall yield and fertility status were enhanced dramatically by STCR-based inorganic fertilizer combined with organic compared to the farmer's regular practices (24, 25).

Nutrients status

In the present study, available nutrients, SOC and soil micronutrients were superior under poultry manure combined treatment. From the experiment, all the available nutrients (Table 4) were higher under the application of 100 % STCR + Poultry manure 5t ha^{-1}. The treatment T1 (absolute control) recorded the lowest nutrient availability overall. This may be due to combining inorganic fertilizers with poultry manure, which leverages the high nutrient availability of the manure while ensuring that the overall soil fertility and nutrient balance meet the crop needs (26-28).

Table 3. Various treatments influenced yield measures in paddy.

Treatments	Parameters			Yield	
	Productive tillers (No/m²)	Panicle length (cm)	Test weight (g)	Grain yield (Kg ha^{-1})	Straw yield (Kg ha^{-1})
T1 (Absolute control)	115	17.50	23.70	2250	3361
T2 (100% STCR)	243	21.00	24.30	4056	6333
T3 (100% STCR + FYM 5 t ha^{-1})	269	22.93	24.50	4528	6889
T4 (100% STCR + Vermicompost 5 t ha^{-1})	319	24.73	24.67	5528	7806
T5 (100% STCR + Poultry manure 5 t ha^{-1})	345	26.17	24.70	5972	8389
T6 (100% STCR + GLM 5 t ha^{-1})	295	23.90	24.67	5194	7306
T7 (FYM 5 t ha^{-1})	143	18.43	24.10	2583	3806
T8 (Vermicompost 5 t ha^{-1})	194	19.77	24.23	3333	5139
T9 (Poultry manure 5 t ha^{-1})	218	20.43	24.27	3694	5417
T10 (GLM 5 t ha^{-1})	169	19.00	24.20	3000	4583
SEd	**11.79**	**0.32**	**0.44**	**132.74**	**130.77**
CD (0.05)	**24.58**	**0.67**	**NS**	**276.90**	**272.79**

Table 4. Available nutrients were influenced by various treatments and their levels at different physiological stages in paddy.

Treatments	Available Nitrogen (Kg ha^{-1})			Available Phosphorus (Kg ha^{-1})			Available Potassium (Kg ha^{-1})		
	AT(1)	PI(2)	PH(3)	AT(1)	PI(2)	PH(3)	AT(1)	PI(2)	PH(3)
T1 (Absolute control)	184	166	158	18.74	16.54	15.46	181	170	163
T2 (100% STCR)	265	256	235	22.96	21.44	19.92	264	239	231
T3 (100% STCR + FYM 5 t ha^{-1})	282	271	249	23.74	22.50	20.75	279	253	245
T4 (100% STCR + Vermicompost 5 t ha^{-1})	315	302	277	25.91	24.39	22.54	311	282	273
T5 (100% STCR + Poultry manure 5 t ha^{-1})	332	319	293	26.74	25.31	23.37	326	297	289
T6 (100% STCR + GLM 5 t ha^{-1})	299	287	263	24.82	23.48	21.66	295	266	258
T7 (FYM 5 t ha^{-1})	201	190	173	19.82	17.55	16.35	197	183	178
T8 (Vermicompost 5 t ha^{-1})	235	223	207	21.78	19.61	18.19	230	212	205
T9 (Poultry manure 5 t ha^{-1})	245	239	221	22.76	20.48	19.02	248	225	218
T10 (GLM 5 t ha^{-1})	216	207	188	20.80	18.59	17.28	214	197	191
SEd	**7.09**	**7.53**	**6.38**	**0.47**	**0.41**	**0.38**	**6.43**	**5.74**	**5.13**
CD (0.05)	**14.79**	**15.72**	**13.18**	**0.98**	**0.87**	**0.79**	**14.14**	**12.63**	**12.33**

[1] active tillering [2] panicle initiation [3] postharvest

Carbon dioxide (CO_2) emission

Outline of the carbon emission (CO_2-C) rates in milligrams per gram per day, measured over different days of incubation for various treatments. Across all treatments, CO_2 emissions initially increase, peaking around the 42nd day and then decrease towards the 56th day (Fig. 1). This pattern suggests a typical microbial respiration curve, where microbial activity (and thus CO_2 emission) was initially low, accelerates as microbial populations and enzymatic activities increase and eventually declines as substrates become depleted and microbial activity diminishes (29). In the early days (1st to 7th), CO_2 emissions were relatively low across all treatments, with T1 showing the lowest emission rate (0.7 mg CO_2-C g^{-1} day^{-1} on the 1st day) and T2 the highest (2.1 mg CO_2-C g^{-1} day^{-1} on the 1st day). This variability can be attributed to differences in initial substrate availability. Higher early CO_2 emissions in T2 suggest more readily available substrates in this treatment. By the 14th day, there was a noticeable increase in CO2 emissions, with T1 still at the lower end of the spectrum and T2 maintaining higher values, followed by the combined treatments with organic amendments. The trend continues, with significant CO_2 production peaking around the 35th day. This phase likely reflects peak microbial activity and substrate utilization. The CO_2 emissions begin to decline from the 42nd day onward. The decline is observed across all treatments, with T2 consistently showing the highest emission rates while T1 shows the lowest. From the observation, it is clear that organic amendments control CO_2 emission by comparing the sole application of inorganic fertilizers. Specifically, the T5 emission rate was lower than all other combined treatments.

From this study, carbon dioxide emission during the crop growth period showed (Fig. 2) that the highest emission of CO_2 was recorded by the treatment T2, 100% STCR-based inorganic fertilizer alone. The emission rate was observed less under the sole application of organic amendments, but it took a risk on yield loss. Inorganic fertilizers do not directly contribute to carbon sequestration. Their impact on carbon dynamics is indirect, through changes in soil health and plant growth (30). Vermicompost, FYM, Poultry manure and GLM enhance soil carbon storage but may not achieve the same level of carbon sequestration as the combined treatment. The STCR approach combined with poultry manure enhances carbon sequestration by increasing soil organic matter. Poultry manure adds organic carbon, while STCR ensures that the crop receives balanced nutrients, improving soil health and promoting adequate carbon storage. In the context of climate change mitigation, managing soil carbon dynamics is critical. The focus was on evaluating the combined effect of 100% Soil Test Crop Response-Based Nutrient Supply (STCR) with poultry manure at 5 tons per hectare, compared to the sole applications of organic amendments (Farmyard Manure (FYM), Vermicompost, Green Leaf Manure (GLM)) and only inorganic fertilizers. The combined treatment of STCR and poultry manure is superior in mitigating CO_2 emissions due to its multifaceted approach to improving soil health (31). By increasing soil organic matter, enhancing soil structure, and fostering microbial activity, this treatment promotes efficient carbon sequestration (32). The study demonstrates that this approach leads to lower net CO_2 emissions than other treatments, making it a valuable strategy for enhancing agricultural productivity and contributing to climate change mitigation.

Conclusion

The treatment combining 100% Soil Test Crop Response-Based Nutrient Supply (STCR) with 5 tons per hectare (t/ha) of poultry manure emerges as the most effective strategy compared to sole applications of organic amendments (Farm yard manure, Vermicompost, Green leaf manure) or inorganic fertilizers alone. Poultry manure and inorganic fertilizer treatment optimizes nutrient management and supports soil health and carbon storage. This results in significant reductions in CO_2 emissions observed under both the experimental field and incubation period, which also contributes to broader efforts in carbon dioxide mitigation, showcasing its effectiveness as a sustainable agricultural practice.

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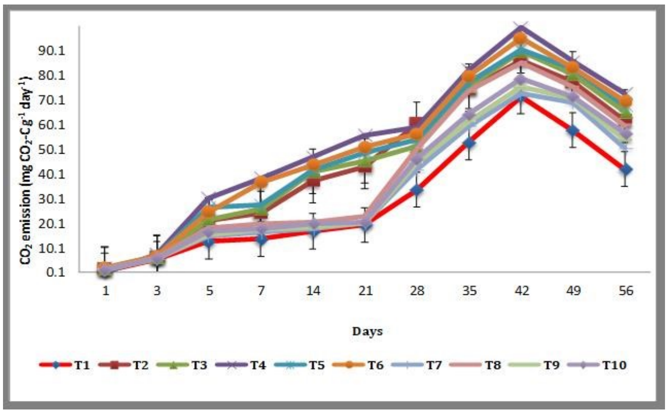

Fig. 1. Influence of various treatments on carbon dioxide emission under a controlled environment (mg m^{-2} hr^{-1})

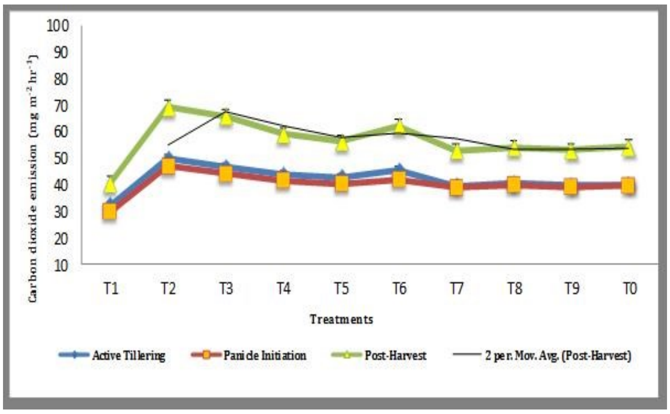

Fig. 2. Influence of various treatments on carbon dioxide emission (mg m^{-2} hr^{-1}).

would like to recognize my efforts in the research process.

Authors' contributions

All the authors have contributed equally to data collection, analysis, writing the original manuscript draft, editing and reviewing.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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