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Potential of Rice Straw as a Carbon Source in Organic Rice Farming and its Effect on Global Warming Potential

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Abstract

The potential benefits of rice straw in organic farming in terms of rice productivity, soil organic carbon (SOC) stocks, carbon sequestration rate (CSR) and global warming potential (GWP) were studied for five years covering 10 wet (*kharif*) and dry (*rabi*) seasons with a wide seasonal temperature range (28-31 °C and 30-40 °C during wet and dry seasons, respectively). Field experiments were conducted at the ICAR-IIRR, Hyderabad, in a black clayey vertisol. The organic sources used were rice straw + green manure in *kharif* and rice straw + poultry manure in *rabi*. Organic system resulted in initial yield reduction by 15-20% than inorganic system and yields stabilized after two and five years in wet and dry seasons, respectively, with improved soil health parameters. The SOC stocks were higher with organics by 34-43% compared to inorganics after five years of study. The CSR was also positive with organics (0.97 and 0.57 t/ha/year during wet and dry seasons, respectively) compared to inorganics (-021 and -0.33 t/ha/year during wet and dry seasons, respectively) which recorded negative C sequestration rate. Organics recorded favourable C sequestration even under dry situations which is more desirable to mitigate the adverse effects of global warming to certain extent by reducing CO_2 emissions. The global warming potential under organic system was 20% higher than in conventional system with increased CO_2 and CH_4 and reduced N_2O emissions. Since GWP was higher with rice straw, mixing of straw with other potential organics in proper proportions reduce the GWP in addition to carbon sequestration in organic rice cultivation.

Key words: Organic farming, rice straw, greenhouse gases, carbon sequestration, global warming potential

Introduction

One of the major challenges faced by humankind is to cope up with the changing climate and managing it for the sustenance of healthy life. IPCC, (2014) report reaffirms that human influence on the climate system is clear and recent anthropogenic emissions of greenhouse gases (GHGs) are the highest in history. According to Intergovernmental Panel on Climate Change (IPCC) (2014) data, it shows that 0.15 °C increase in temperature per decade, which is causing a drastic change in different farming systems and their productivity, is expected to increase by 1.7-4.8 °C by the end of the century.

Climate change and agriculture, being interrelated, do influence each other and the relationship between them is of high importance as the imbalance between world population and world food production is increasing. Agriculture is considered both as a contributor to climate change and a victim as well. Soil health degradation has emerged as a major factor responsible for the stagnation in agricultural production. Continuous use of inorganic fertilizers has not only brought about loss of vital soil fauna and flora but also resulted in loss of secondary and micronutrients. Agriculture, responsible for 20-30% of global GHG emissions, contributes to climate change through practices such as excessive use of synthetic fertilizers, fossil fuel combustion during fertilizer production and intensive tillage operations. These practices release significant amounts of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), which contribute to global warming. Global warming potential (GWP) is a metric that measures how much heat a greenhouse gas (GHG) traps in the atmosphere compared to carbon dioxide (CO_2) over a specific period of time.

Rice (*Oryza sativa* L.) is the major staple food crop in India, occupying around 45 million hectares (mha) of land and contributing about 135 million tons (mt) to the total food grain production (Agricultural Statistics at a Glance, 2023). Although rice production will be affected by climate change, rice farming also has the capacity to amplify the problem of GHG emission mediated global warming, which is a common phenomenon in rice growing countries especially in South Asia. Rapid mineralization of SOC compounds may lead to higher CO_2 flux to the atmosphere (Reicosky *et al.,* 1995) thus leading to global warming. Soil C sequestration restores degraded soils, enhances biomass production and reduces the rate of enrichment of atmospheric CO_2 (Lal, 2004). Organic agriculture enables ecosystems to better adjust to the effects of climate change and improves carbon sequestration potential of the soil (Bhooshan and Prasad, 2011) and carbon sequestration is considered as a mitigation option to adverse effects of climate change. Keeping this in view, field experiments were conducted to study the influence of rice straw in organic farming on soil organic carbon, greenhouse gas emissions and global warming potential.

Materials and Methods

Field experiments were conducted over a spread of five years covering ten rice cropping seasons [five wet (WS) and five dry (DS)] on a deep black clayey vertisol (Typic pellustert) at the Indian Institute of Rice Research (IIRR) farm, Rajendranagar, Hyderabad. Organic and conventional farming systems were compared in terms of rice productivity, soil organic carbon (SOC) stocks, carbon sequestration rate (CSR) and global warming potential (GWP). The experimental soil characteristics were slightly alkaline (pH 8.2); non-saline (EC 0.71 dS/m); calcareous (free $CaCO_3$ 5.01%); with CEC 44.1 C mol (p+)/ kg soil and medium soil organic carbon (0.69%) content. Soil available N was low (228 kg/ha); available phosphorus was high (105 kg P_2O_5 /ha); available potassium was high (530 kg K_2O/ha) and available zinc was also high (12.5 ppm). The temperature variation among the two seasons (wet and dry) was shown in **Table 1**.

Table 1: Mean Temperature (°C) range during crop growth period

Year	Wet season (August-December)		Dry season (February-May)	
	Range	**Mean**	**Range**	**Mean**
1st year	28.5-30	29.3	32.9-38.1	35.5
2nd year	28.6-30.9	29.7	31.4-31.2	36.0
3rd year	29.5-30.6	30.0	30.5-39	34.8
4th year	29.3-31.4	30.0	33.9-40.3	37.3
5th year	28.5-31.4	30.3	33.0-40.3	37.5
Overall range	**28.5-31.4**	**-**	**30.5-40.3**	**-**

The four treatments consisted of: control (T1); 100% inorganic fertilisers (T2); 100% organics (T3) and 50% inorganics + 50% organics (T4, INM) with five replications. The organic sources used were green manure, dhaincha (*Sesbania aculeata*) + paddy straw during wet seasons (WS) and poultry manure + paddy straw during dry seasons (DS). Super fine rice varieties, BPT 5204 and Vasumati were tested in wet and dry seasons, respectively. The local recommended dose of inorganic fertilizers were given to conventional system @ 100-60-40 kg N, P_2O_5, K_2O/ha during both seasons through urea, single super phosphate, muriate of potash and 25 kg of Zinc sulphate, respectively. Nitrogen was applied in three equal splits at basal, maximum tillering and panicle initiation stages while P, K and Zn were applied as basal doses only. Through organics, N dose was adjusted to recommended level based on their moisture content and 'N' concentration on dry weight basis. Organic fertilizers were incorporated one day before transplanting rice. Grain yield was recorded at the end of each season. At the end of 5 years, soil samples were collected from 15 cm depth and analysed for various parameters. Carbon stocks and C sequestration rate were computed using the following formulae (Lal *et al*., 1998).

1) SOC storage (C stock t/ha) = [%C x bulk density x soil depth (m) x 10000] / 100
2) SOC sequestered (t C/ha) = SOC (current) - SOC (initial)

Integrated evaluation of GHG emissions expressed as GWP was computed for the current experiment by using the IPCC factors for calculating the combined GWPs for 100 years [GWP = 24.5 $*CH_4 + CO_2 + 320 *N_2O$ kg CO_2-e ha^{-1}] from CH_4, N_2O and CO_2 efflux values under different treatment conditions (IPCC, 2007). The GHG emissions and GWP for inorganic fertilizers and organics sources used were calculated based on the studies of Snyder *et al.,* (2009); Bhattacharyya *et al.,* (2012); Wang *et al.,* (2019) and Fauzan *et al.,* (2021).

Results and Discussions

Grain yield trends

Grain yield trends showed that, during the wet season, yields in plots with fertilizer application and integrated nutrient management (INM) remained stable, ranging from 5.2-5.5 t/ha and 4.7-5.2 t/ha, respectively. These yields were 15-20% higher than those in organic plots in the first two years, but organic yields improved over time, reaching comparable levels with inorganic treatments (4.8-5.2 t/ha) in later years. In the dry season, however, inorganics and INM consistently outperformed organics for four consecutive years, with organic yields matching those of inorganics and INM only in the fifth year **(Table 2)**. Unfertilized control treatment recorded the lowest grain yields throughout the experiment. It was evident that all treatments with fertilization resulted in high yield increases, but yields were generally less in the DS.

Initially, organic farming led to a yield reduction of around 24% for rice, as reported by Mader *et al*., (2002), but a gradual yield increase with organic methods over time was noted by Surekha *et al*., (2010) and Urkurkar *et al*., (2010). This may be due to a mismatch between the nutrient release from organic sources and crop demand, influenced by seasonal conditions in the initial years. Once soil fertility reached an adequate level, the organic system produced yields comparable to the conventional system. The slow, gradual release of nutrients from organic sources during the early years of conversion to organic farming did not immediately lead to higher yields. However, repeated applications of organic inputs over time built up sufficient soil fertility by enhancing soil biological activity (Surekha and Satishkumar, 2014).

Soil Organic Carbon (SOC) stocks and C sequestration rate (CSR)

The carbon stock and sequestration rate for each treatment were shown in **Table 3**. After five years, SOC stocks were significantly higher in organic

Table 2: Grain yield (t/ha) as influenced by nutrient sources

Sl. No	Year	Wet season				Dry season			
		Control	Inorganics	Organics	INM	Control	Inorganics	Organics	INM
1	1st year	3.59^{c}	5.52^{a}	4.92^{b}	5.17^{ab}	1.92^{c}	3.82^{a}	3.62^{b}	4.36^{a}
2	2nd year	3.55^{c}	5.63^{a}	4.92^{b}	5.56^{a}	2.33^{c}	3.81^{a}	3.11^{b}	3.81^{a}
3	3rd year	3.32^{b}	5.50^{a}	5.22^{a}	5.31^{a}	2.77^{c}	4.22^{a}	3.37^{b}	4.04^{a}
4	4th year	3.43^{b}	5.52^{a}	5.60^{a}	5.48^{a}	1.98^{c}	3.74^{a}	3.14^{b}	3.82^{a}
5	5th year	3.34^{b}	5.29^{a}	5.27^{a}	5.02^{a}	2.13^{b}	4.21^{a}	3.98^{a}	4.22^{a}

Numbers followed by the same letter in each row are not statistically significantly treatments, with values of 19.54 t/ha in the wet season and 17.55 t/ha in the dry season, compared to inorganic treatments, which recorded 13.63 t/ha and 13.05 t/ha, respectively. CSR were also positive for organic treatments, at 0.97 t/ha/year in the wet season and 0.57 t/ha/year in the dry season. In contrast, inorganic treatments showed negative CSRs of -0.21 t/ha/year and -0.33 t/ha/year for the wet and the dry seasons, respectively. The INM treatment showed intermediate values, while the lowest SOC stock levels were recorded in the control treatment.

Carbon sequestration rate was nearly half during dry season which recorded higher temperatures than that of CSR during wet season that favoured the loss of SOC stocks due to faster decomposition and mineralization. The treatment, 100% organics recorded 43% and 34% higher SOC stocks followed by INM treatment that recorded 34% and 20% higher SOC stocks over 100% chemical fertilisers during wet and dry seasons, respectively. Thus, it was evident that organic rice farming can lead to better carbon accumulation under varied climatic conditions and increasing organic carbon in agricultural systems has been reported as an important mitigation option by IPCC (Muller, 2009). Bhattacharyya *et al.,* (2012) also noticed that carbon storage rate was also found to be significantly higher (0.35 Mg C ha^{-1} y^{-1}) in the application of rice straw. An increase in soil carbon by 15-28% in organic systems was also reported by Paul (2003). Similarly, higher values of SOC by 0.18 ± 0.06%, for C stocks by 3.50 ± 1.08 Mg C ha^{-1} and for sequestration rates by 0.45 ± 0.21 Mg C ha^{-1} y^{-1} in organically farmed soils over non-organic management was reported by Gattinger *et al*., (2012).

Table 3: Soil Organic carbon (SOC) stocks and C sequestration rate after five years

Treatments	Soil organic Carbon (%)	Bulk density (g/cc)	Carbon stock (t/ha)	SOC sequestered (t/ha)	C seq. rate (t/ha/yr)
Wet season					
Control	0.59	1.36	12.04	-2.66	-0.53
Inorganics	0.64	1.42	13.63	-1.07	-0.21
Organics	1.01	1.29	19.54	4.84	0.97
INM	0.91	1.34	18.29	3.59	0.71
Dry season					
Control	0.54	1.38	11.18	-3.52	-0.70
Inorganics	0.60	1.45	13.05	-1.65	-0.33
Organics	0.90	1.30	17.55	2.85	0.57
INM	0.79	1.32	15.64	0.94	0.19
Initial value	**0.69**	**1.42**	**14.7**	**-**	**-**

Global warming potential (GWP)

The global warming potential along with the emission of greenhouse gasses such as CO_2, CH_4 and N_2O with usage of inorganic fertilizers and organic fertilizers were presented in **Table 4.** For inorganic fertilizers, urea contributed the most to emissions, particularly during application, where N_2O emissions were high compared to organics. Combined across both seasons, inorganic sources emitted a total GWP of 13,157 kg CO_2-e/ha. Organic applications resulted in higher CO_2 and CH_4 emissions but lower N_2O emissions compared to inorganics. The total emissions from organic sources across both seasons were with a GWP of 15,909.6 kg CO_2-e/ha. Greenhouse gas emissions and GWP from organics were higher in *rabi* season than in *kharif* season. The application of organic fertilizers increased the CO_2 and CH_4 emissions by 15.5% and 33.2% and reduced N_2O emissions by 27.4% over inorganics though there was an increase of 20.9% in GWP with the application of organics. The data suggests that using organic fertilizers, such as rice straw and poultry manure, increased total greenhouse gas emissions compared to inorganic fertilizers. However, it also reduced N_2O emissions, a particularly potent greenhouse gas, by 27.4%

over inorganics. This trade-off highlights that while organic fertilizers may contribute more to CO_2 and CH_4 emissions in rice, they offer environmental benefits by lowering N_2O emissions, which could be advantageous for climate mitigation strategies focused on this gas. Wang *et al.,* (2018) also reported that rice straw increased CO_2 and CH_4 emissions but reduced N_2O emissions. According to He *et al.,* (2024) the straw return might facilitate soil respiration and oxygen depletion, leading to oxygen limitation and eventually spurring the reduction of N_2O to N_2 during denitrification, especially in oxygen-depleted paddy fields. Thus, it leads to a reduction in N_2O emissions.

GHG emissions when rice straw along with green manure (7764 kg CO_2-e/ha) applied were less compared to the rice straw and poultry manure (8145 kg CO_2-e/ha). The high C/N ratio in rice straw also contributes to increased GHG emissions from organic sources. Poultry manure and green manure have lower C/N ratios than rice straw, which contains abundant cellulose and hemicellulose (Li *et al.,* 2023). Gao *et al*., (2023) reported that green manure increases soil fertility and rice yields without increasing CH_4 emissions in green manure-rice system than fallow-rice practice. Bayer *et al.,* 2014 reported that the high C/N ratio of rice straw increased the metabolic C substrate available to methanogenic bacteria, thus promoting the production of CH_4 and lead to carbon loss by accelerating soil organic matter mineralization through the priming effect. Khosa *et al*., (2010) reported that rice straw compost reduced the GHG emissions compared to sole application of straw/ green manure, as direct straw use leads to increased GHGs. He *et al.,* (2024) reported that GHG and GWP were influenced by a combination of straw size, straw return method and straw amount and recommended straw incorporation > 7.5t/ha with size ≥ 5 cm for reducing GHG emissions and GWP from straw return in paddy fields. Though rice straw has high potential as carbon source in organic farming, due to its contribution to global warming, its positive effects may not be visible. Hence, it is essential to find out suitable organic sources and their proportions to mix with straw so that GWP from straw can be reduced.

Table 4 : GHG emissions and GWP from inorganic and organic sources (kg CO_2-e ha^{-1} yr^{-1})

	GHG Emissions			**GWP**
Inorganics	**CO_2**	**CH_4**	**N_2O**	
Kharif	**(kg CO_2-e ha^{-1})**	**(kg CO_2-e ha^{-1})**	**(kg CO_2-e ha^{-1})**	**(kg CO_2-e ha^{-1})**
During Manufacture				
Urea 100 kg	310	7.77	0.93	320
Phosphate (SSP) 60 kg	60	2.268	0.372	60
Potash (KCl) 40 kg	28	0.084	0.124	28
During Application				
Urea-N 100 kg N/ ha	2412.83	3241.00	516.67	6170.50
Rabi				
During Manufacture				
Urea 100 kg	310	7.77	0.93	320
Phosphate (SSP) 60 kg	60	2.268	0.372	60
Potash (KCl) 40 kg	28	0.084	0.124	28
During Application				
Urea-N 100 kg N/ ha	2412.83	3241.00	516.67	6170.50
TOTAL (*Kharif* + *Rabi*)	**5621.67**	**6502.24**	**1036.19**	**13157.00**
ORGANICS				
Kharif				
During Application				
Rice straw + Green Manure @100 kg N	3097.50	4294.50	372.00	7764.00
Rabi				
During Application				
Rice Straw + Poultry Manure @100 kg N	3397.50	4368.00	380.14	8145.64
TOTAL (*Kharif* + *Rabi*)	**6495.00**	**8662.50**	**752.14**	**15909.64**
% Increase/decrease with organics	**15.5%**	**33.2%**	**-27.4%**	**20.9%**

Conclusion

Organic farming in rice production, though initially yields less, can match conventional yields over time by enhancing soil fertility through sustained nutrient release. Organic practices significantly improved soil organic carbon stocks and sequestration rates, supporting soil resilience and adaptation for climate change. However, organic treatments increased CO_2 and CH_4 emissions but reduced N_2O emissions by 27.4%, indicating potential climate change mitigation benefits. Overall, organic farming enhances soil health and carbon storage supporting long-term sustainable productivity amidst climate change. Alternative ways of effective straw utilization like composting must be explored to reduce the GHG emissions and also to obtain fullest benefits from rice straw utilization in organic farming.

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