A STUDY OF THE FERTILITY AND CARBON SEQUESTRATION POTENTIAL OF RICE SOIL WITH RESPECT TO THE APPLICATION OF BIOCHAR AND SELECTED AMENDMENTS

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ABSTRACT

A study was carried out to assess the effect of biochar on the carbon dynamics of wetland rice soils and on the growth and grain yield of rice plants (*Oryza sativa L.*). Pot experiments were conducted with amendments of chemical and organic origins in addition to wood-derived biochar. Maximum soil carbon storage was observed with biochar compared to organic amendments such as composts and chemical fertilizer. Major soil carbon sequestration parameters like soil organic carbon (SOC), particulate organic carbon (POC) and microbial biomass carbon (MBC) were found to be greater with biochar. Aggregate formation was also significant under biochar trials. Considerable reduction in greenhouse gases (GHGs) emission, especially carbon dioxide (CO_2) and nitrous oxide (N_2O), was observed with biochar. Applications of biochar considerably influenced the growth profile and grain yield of the rice plants compared to other amendments. Hence, these results suggest that biochar of appropriate applied proportion can influence wetland rice soil carbon dynamics and has the potential to combat global warming without compromising productivity. The role of biochar as a green viable carbon negation option is supported by the study since the results showed a positive response towards soil and vegetation carbon sequestration and yield optimization even without the addition of any nitrogen fertilisers.

Keywords: Biochar, soil organic carbon, particulate organic carbon, microbial biomass carbon, greenhouse gas, global warming.

1. INTRODUCTION

Kuttanadu, the rice bowl of Kerala in India, is unique among the rice ecologies of the world: The largest wetlands of the country (53600 ha.) that accounts for 18% of the rice growing area and 25% of total production of Kerala. This is a unique agricultural area, lying 0.6 to 2.2 m below mean sea level [1]. The soils of the Kuttanad area are typical water-logged soils and fall under the acid sulfate group. However, the soil acidity, salinity intrusion and accumulation of toxic salts in the soils make this area less fertile for rice [2]. Excess application of chemical fertilisers and pesticides in the paddy fields of Kuttanadu to enhance the rice yield has been reported at least for the past three decades. Hence, intensive and extensive cultivation of high yielding varieties coupled with the application of geometrically increasing amounts of agrochemicals has resulted in the deterioration of the environmental quality of this wetland system.

Wetland characteristics lead to the accumulation of organic matter in the soil and sediment, serving as carbon (C) sinks and making them one of the most effective ecosystems for storing soil carbon [3]. It has been estimated that different kinds of wetlands contain 350-535 Gt C, corresponding to 20-25% of world's soil organic carbon [4]. However, long term storage is often limited by rapid decomposition processes and release of C to the atmosphere from paddy fields. Hence, wetlands are dynamic ecosystems where significant quantities of C may also be trapped and stored in sediments.

In the current scenario of climate change, wetland paddy fields similar to Kuttanadu are considered to be major sources of greenhouse gases, especially methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) as they experiences both dry and wet conditions depending on water availability. The total annual global emission of methane is estimated to be 500 Tg yr^{-1} and up to a quarter of this is attributed to wetland rice fields [5]. According to OECD [6], agricultural activity contributes 1% of the excess CO_2 to global emissions. The carbon dioxide from farming results from rice photosynthesis and respiration, soil microbes and the loss of soil organic carbon [7]. Apart from this,

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activities like conventional tillage and non-tillage in paddy fields also results in CO_2 fluxes [8]. Nitrous oxide is a trace gas that contributes to global warming and its concentration increases by 0.8±0.2 ppb/yr [9]. Nitrous oxide results from the general use of nitrogen fertilizers, which decompose into nitrous oxide through the denitrification process caused by flooding [10] as observed in wetland rice fields. The emission of greenhouse gases, especially methane and carbon dioxide, results in loss of stored carbon in soil and thus affects the process of soil carbon sequestration.

Soil organic carbon (SOC) storage has been widely considered as a measure for mitigating global climate change through C sequestration in soils [11]. The loss and gain of organic C in soils depends on soil type, temperature, erosion, and vegetation type and land management. The SOC stock also depends on cation exchange properties [12], soil texture and aggregation [13]. Some SOC fractions, such as particulate organic carbon (POC), microbial biomass carbon (MBC) and potential carbon mineralization (PCM) are considered as more sensitive indicators of soil management than total SOC [14-16].

In the present study, the possibilities of biochar application as a better soil amendment in order to increase soil fertility, carbon sequestration potential and to reduce the negative effects of rice-based wetland systems on global climate have been investigated. Biochar is a carbon-rich product obtained when biomass is heated in a closed container with little or no available air. It has been shown that biochar has multiple uses. When added to soil it can significantly improve soil fertility [17] and also reduce greenhouse gas emissions and increase carbon sequestration [18].

Table 1 The conditions (amendments) used for the study

Sl no.	Code	Amendment	Amount applied
1	B_{15}	Biochar	15 gm
2	B_{25}	Biochar	25 gm
3	B_{35}	Biochar	35 gm
4	C_E	Compost –Eichhornia	25 gm
5	C_P	Compost- *Pueraria*	25 gm
6	C_F	Chemical Fertilizer-Superphosphate	5 gm
7	C	No soil amendment (Control)	-

Besides that, biochar can act as a soil conditioner, enhancing plant growth by supplying and, more importantly, retaining nutrients by providing other services such as improving the physical and biological properties of soils [19,20]. Application of biochar can significantly reduce greenhouse gases emission from flooded rice soils [21]. According to IPCC [22], the management of rice agriculture for positive climate impact must consider the combined effects of carbon storage and soil greenhouse gas emissions; hence the present study was carried out to examine the potential of biochar application as a sustainable management option in wetland rice-cultivating areas like Kuttanadu.

2. METHODOLOGY

2.1. Experimental Set Up

Pot trials were conducted for the comparative study of the effect of biochar and other selected amendments on rice growth and soil properties. Soil used for the study was collected from the experimental plot of Maniyaparambu (9°38’39.03” N, 76°28’58.64”E), a part of the Kuttanadu rice cultivating tract. Soil was collected from a depth of 0-30 cm, then dried, homogenised and sieved through a 2.0 mm sieve. 5 kg of ground soil was then put into earthen garden pots with an inside diameter of 30 cm.

Seven treatments were arranged in a fully randomised design with three replications. The amount of soil amendment applied was calculated based on the surface area of the pot. The amount of soil amendment applied was proportional to the field application and is depicted in Table 1. Amendments were mixed to a depth of 20 cm, after which they were incubated at water content close to field capacity for 5 days. Viable seeds of 12x55 cultivar rice variety *(Oryza sativa)* were collected from local farmers and the seeds were allowed to sprout in the traditional manner. After two days, the sprouted seeds were transferred to a soil-filled earthen pot as stock. On the tenth day, the saplings were replanted to each specific pot (with different amendments) and were subjected to lowland rice cultivating conditions. Amendments (composts of *Eichhornia* crassipes and *Pueraria* sp., biochar in different quantities and superphosphate fertilizer) were added during the 18th, 33rd and 54th day of the plant growth cycle as per the traditional rice cultivating practice of the area. During the growth cycle no additional nitrogen fertilizers were applied.

2.2. Production and Characterisation of Amendments

2.2.1. Biochar

Biochar was prepared from rubber tree (*Hevea brasiliensis*) in an earthern mound kiln (temperature < 500°C) [23]. Biochar thus prepared was ground to pass through a 0.05 mm sieve for further analysis [24]. The bulk density, pH, N, P, K, moisture content and cation exchange capacity (CEC) were determined [25]. An EDX system (JEOL-JSM, Japan) was used to quantify the elemental distribution and FTIR analysis was used to identify the C functional groups present in the biochar.

2.2.2. Organic Compost

Two major weeds, *Eichhornia* and *Pueraria* were used as substrates for the preparation of organic compost. *Eichhornia* (water hyacinth) is listed as one of the most productive plants on earth [26]. It is an aquatic weed that thrives in polluted waters. *Pueraria* is a terrestrial climber infesting the plantation and open scrub regions. The compost was prepared from finely chopped fresh plant biomass, common cow dung and soil in the ratio 5:1:1 and kept under anaerobic decomposition condition [27] in earthen garden pots for 30 days. The whole content was dried, homogenised and sieved to < 2 mm for amending purposes.

2.3. Soil Analysis

Soil bulk density was determined by the clod method [28]. Soil pH was measured in 1:2.5 ratio soil solutions (with de-ionized water) with a pH meter [29]. A TOC analyser (Hyper TOC-Thermo) was used to determine organic C content. POC was determined following the sodium hexa-metaphosphate dissolution method [30]. MBC was determined with a modified substrate induced respiration method [31]. Aggregate stability was measured with the routine wet-sieving method [32]. Total N content was measured by the Kjeldhal method [29]. The CEC was determined by the ammonium acetate method [33]. CO_2 and N_2O emissions from rice soils were measured in an incubation study [34] followed by gas analysis by GC (Perkin-Elmer). Total heterotrophic bacterial (THB) count was conducted with the spread plate method.

3. RESULTS

Some important characteristics of biochar and other amendments are presented in Table 2. The pH of the amendments ranged from 4.8 to 7.9 and CEC from 9.3 to 11.2 C mol kg^{-1}. Biochar showed slightly alkaline properties with a pH of 7.9, which is higher than all other amendments. A higher CEC of 11.2 C mol kg^{-1} was recorded for the biochar whereas the Eichhornia compost recorded the lowest (9.3 C mol kg^{-1}). Maximum conductivity and moisture content were recorded for the Eichhornia compost. N, P and K values showed remarkable variations between the amendments. The maximum N value for biochar was 0.42 ppm.

3.1. Characteristics of Amendments

Analysis of the FTIR spectra of the biochar, used to determine chemical functionality (Fig. 1), shows assignments of peaks of carbon functional groups.

Table 2 Characteristics of amendments

Properties	*Compost-Eichhornia* crassipes (C_E)	*Compost-Pueraria* (C_P)	Biochar (B)	Chemical Fertilizer Superphosphate (C_F)
pH	4.8	5.5	7.9	5.7
CEC (C mol kg^{-1})	9.3	10.7	11.2	10.1
BD	0.96	0.94	0.85	0.65
Conductivity (ms)	1.74	0.93	0.28	0.34
Moisture content (%)	15.1	7.3	6.57	8.2
N (%)	0.038	0.03	0.40	0.35
P (kg/ha)	19.3	14.3	25.6	30.3
K (ppm)	147	154	100	135

The spectrum exhibits features that correspond to recalcitrant aromatic carbon compounds and probably graphite (near 1581 cm^{-1}). The EDX spectrum (Fig. 2) of biochar also revealed the high carbon compound percentage (98.18%) in the sample. The elemental concentration (%) of potassium is 1.16, magnesium 0.15, phosphorus 0.22 and calcium 0.29 were recorded.

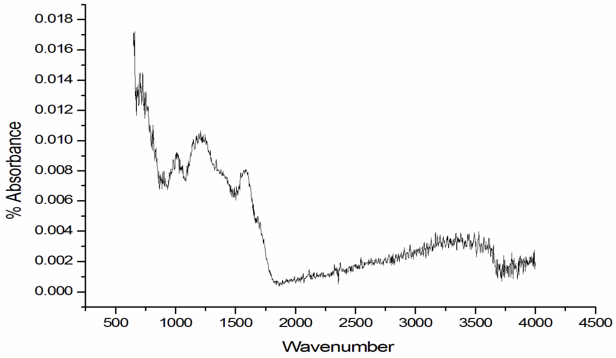

Figure 1 FTIR Spectrum of Biochar

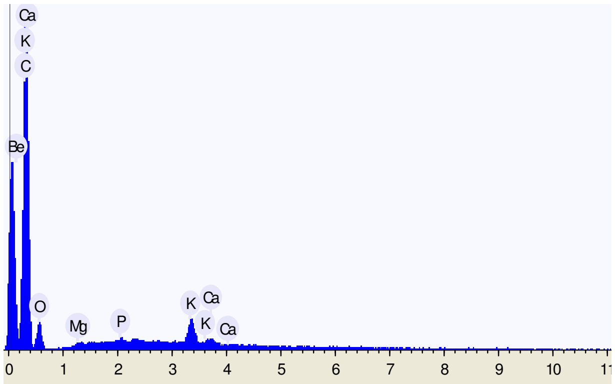

Figure 2 EDX Spectrum of Biochar

3.2. Soil Properties

The physical and chemical properties of soil prior to treatments revealed that the soil was highly acidic (pH 4.5), Table 3. The bulk density and CEC values were 0.66 gcm^{-3} and 9.1c mol kg^{-1}, respectively. The nutrient availability (N, P and K) was found to be 0.045%, 12.09 kg/ha and 54 ppm respectively. SOC content was 4.89%, where POC contributed nearly 68% of SOC. PCM and MBC were 3.39 and 4.4 mg CO_2-C/g^{-1}, respectively. Among the water stable aggregates (WSA), macroaggregate (>0.2 mm) constituted about 43.4% whereas micro-aggregates (<0.05 mm) were only 15.4%.

Table 3 Baseline properties of the soil prior to the treatments

pH	4.5
Conductivity (ms)	0.46
CEC (C mol kg^{-1})	9.1
Bulk density (g cm^3)	0.66
TN (%)	0.05
P (kg/ha)	12.09
K (ppm)	54
N (%)	0.05
SOC (%)	4.89
POC (%)	3.32
PCM (mg CO_2-C/g^{-1})	3.96
MBC (mgCO_2-C/g^{-1})	4.4
Micro aggregate (%)	15.50
Macro aggregate (%)	43.40

3.3. Soil Characteristics after the Growth Trial

Table 4 presents physical and chemical properties of the soil after completion of the growth cycle and harvesting of the rice plants. Application of soil amendments produced significant variations in the physical and chemical properties of the soil. The highest pH value was observed in the trial treated with maximum biochar, while the lowest values were recorded in the control.

Application of biochar in acidic soils helps to increase pH [17,25]. It can be seen that application of biochar showed a neutralizing effect on the acidic soil [35,36]. Similarly, CEC values also increased linearly with the level of biochar addition [25,37]. An increase in soil CEC with the application of biochar has also been shown [38]. The increase in CEC of the soil with organic soil amendments is probably due to the negative charge arising from the carboxyl groups of the organic matter. A significant positive correlation was observed (r = 0.89) between pH and CEC values. The increase in CEC and soil pH with the addition of organic matter has been shown elsewhere [37].

Biochar, an organic amendment, was slightly alkaline pH (7.9); therefore it is reasonable that the soil treated with biochar in high concentration can reduce acidity. Such ability is related to the liming value of the biochar. This result indicates that biochar could be used as a substitute for lime materials to increase the pH of acidic soils.

Table 4 Effect of biochar and other amendments on soil characteristics

Treatments	pH	Conductivity (ms)	CEC (C mol kg^{-1})	N (%)	P (kg/ha)	K (ppm)	TN (%)	Bulk density (g/cm^3)
Control	4.4±0.17	0.56±0.02	9.5±0.13	0.06±0.02	13.88±0.66	48.5±0.57	0.26±0.01	0.68±0.01
C_E	4.4±0.12	0.68±0.04	9.4±0.17	0.12±0.01	31.36±0.86	34±0.86	0.32±0.02	0.66±0.02
C_P	4.4±0.07	0.64±0.02	9.9±0.13	0.09±0.02	27.78±0.94	36.5±0.68	0.36±0.03	0.63±0.02
C_F	5.2±0.17	0.64±0.03	10.0±0.11	0.12±0.02	33.60±0.79	54.5±1.18	0.35±0.04	0.65±0.02
B_{15}	4.8±0.11	0.72±0.05	10.1±0.06	0.08±0.01	32.20±0.28	58±0.69	0.39±0.03	0.64±0.01
B_{25}	5.4±0.28	0.49±0.05	10.5±0.11	0.09±0.02	33.74±0.47	62±0.46	0.39±0.05	0.62±0.02
B_{35}	5.5±0.07	0.43±0.04	10.6±0.17	0.17±0.03	37.77±0.79	69±1.02	0.42±0.02	0.60±0.01

Bulk density (BD) decreased from 0.678 g cm^{-3} in the control experiment to 0.60 g cm^{-3} in the biochar treated soil and this may be due to the formation of soil aggregates [25,39] as BD and macroaggregate bears a negative correlation where r = -0.78. The aggregation status of the soil between the treatments showed that organic amendments increased the process of aggregation (macroaggregates) and was represented as water-stable aggregate proportions (Fig. 3). With respect to this observation, formation of the macroaggregate category of WSA recorded the maximum in biochar trials whereas the microaggregate proportion narrowed as the amount of biochar application increased (r = -0.11) (Fig. 3). The formation of macroaggregates in the rice soils as a result of biochar amendment will increase total porosity and at the same time will increase soil water retention [40].

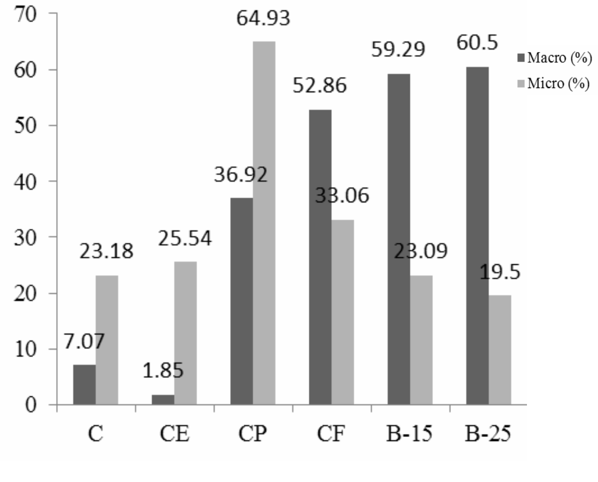

Figure 3 Proportion of WSA

The application of amendments significantly influenced the nutrient status of the soil. Maximum variation was found in the B_{35} trial, as maximum biochar application improved the chemical properties of the experimental soil. Under B_{35} trial, about a 60% increase was observed in the available N content of the soil compared to control. Application of C_E (Eichornia compost) and superphosphate also increased the available N. Likewise, a remarkable increases of about 63, 29 and 38% were recorded for P, K and TN respectively in the B_{35} trial in comparison to the control. The increase in nutrient status is in accordance with the amount of biochar applied. Application of other amendments also showed variations in the soil nutrient status.

The microbial populations in terms of total heterotrophic bacterial (THB) count were influenced by amendments. Maximum THB count was noticed in B_{35} and the minimum values were recorded in control trials (Table 5). These observations support the fact that organic amendments can increase the soil microbial community by providing suitable substrates. Thus, applications of organic amendments improve some of the physical, chemical and biological properties of soils under trials.

Table 5 Soil microbial population

Treatments	THB (cfu)
Control	$14x10^6$
C_E	$20x10^6$
C_P	$37x10^6$
C_F	$35x10^6$
B_{15}	$36x10^6$
B_{25}	$38x10^6$
B_{35}	$39x10^6$

3.4. Soil Carbon Fractions

3.4.1 Soil Organic Carbon (SOC)

SOC concentration was found to be high (4.66%) in B_{35} treatment, which is about 11.1 % more than the control (Fig. 4). The SOC concentration (%) ranged in the order: B_{35} (4.66) > B_{25} (4.4) > C_E and Control (4.14), > C_P (4.08) > B_{15} (3.9) > C_F (3.78). It was interesting to note that the trial with a chemical fertilizer (superphosphate) showed the lowest SOC concentration. Maximum SOC gain was observed in B_{35}. This hence shows the highest soil carbon sequestration potential.

Measurement of SOC alone does not adequately reflect changes in soil quality and nutrient status [41,42]. This is because SOC has a large pool size and inherent spatial variability. Measurement of biologically active fractions of SOC such as MBC and POC that change rapidly with time could better reflect changes in soil quality and productivity that alter nutrient dynamics due to immobilisation-mineralisation [43,44]. These fractions can provide an assessment of soil organic matter changes induced by management practices [45,46]. Important counterparts of soil carbon cycling are soil organic carbon (SOC), microbial biomass carbon (MBC), and particulate organic carbon (POC).

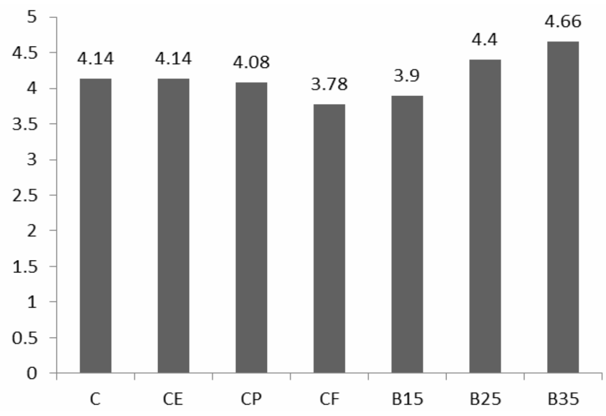

Figure 4 soil organic carbon percentage

3.4.2. Particulate Organic Carbon (POC)

POC is considered as an intermediate fraction of SOC between active and slow fractions that change rapidly over time due to changes in management practices [30,38,47]. The POC also provides substrate for microorganisms and influences soil aggregation. The POC concentrations (%) varied as shown in Table 6. The POC concentration decreased in the order B_{35}> B_{25}> C_E> B_{15}> Control> C_F> C_P. The % contribution of POC to SOC was found to be more significant under biochar trial. POC concentrations bear a significant direct correlation with SOC (r = 0.88). The biochar trials had a linear effect on the SOC, POC and aggregate stability.

Table 6 Percentage contribution of POC to SOC

Treatments	SOC (%)	POC (%)	POC/SOC (%)
Control	4.14 ± 0.02	3.14 ± 0.02	75.9
C_E	4.14 ± 0.01	3.38 ± 0.02	81.6
C_P	4.08 ± 0.03	3.00 ± 0.07	73.5
C_F	3.78 ± 0.02	3.10 ± 0.07	82.0
B_{15}	3.90 ± 0.05	3.26 ± 0.05	83.6
B_{25}	4.60 ± 0.03	3.74 ± 0.2	81.3
B_{35}	4.66 ± 0.03	3.98 ± 0.01	85.4

3.4.3. Microbial Biomass Carbon (MBC)

MBC values fluctuated between 0.1 to 1.98 mg CO_2-C ha^{-1} during the study. The maximum value recorded was 1.98 mg CO_2-C ha^{-1} (Table 7) in C_P and B_{35} as a result of an enhanced microbial community build-up. This has been well documented, with soil conditions for microbial activity being improved by organic amendments [48, 49]. The finding was in accordance with the reports of refs. [50,51] that fungal-dominated microbial commun-ities slow SOC turnover, with increased carbon input and this favors soil carbon sequestration.

Table 7 Concentration of Microbial Biomass carbon

Treatments	MBC(mg CO_2-C/g^{-1})
Control	0.10 ± 0.02
C_E	0.44 ± 0.03
C_P	1.98 ± 0.02
C_F	1.32 ± 0.02
B_{15}	1.54 ± 0.02
B_{25}	1.64 ± 0.04
B_{35}	1.98 ± 0.02

3.5. GHG Production and the Global Warming Potential (GWP)

3.5.1. Production Potential of GHGs - CO_2 and N_2O

As products of carbon and nitrogen mineralization, considerable amounts of CO_2 and N_2O were produced during the incubation. Total CO_2 production, however, varied in a much wider range from 220 µg g^{-1} in soil under C_P and control to 1760 µg g^{-1} in soil under C_E as shown in Table 8. Apparently, CO_2 production predominated over N_2O in the majority of cases. Fertilization affects CO_2 production differently compared to N_2O, although both were significantly influenced by the different amendments.

Significantly higher C_{min} values were observed in C_E and C_F, which were about 8 and 5 times as much as that under control, respectively. Biochar amendments produced significantly lower CO_2: B_{15} and B_{35} produced about 440 µg g^{-1} followed by 660 µg g^{-1} from B_{25}. A relative dominance of CO_2 was observed in most of the cases. The capacity of CO_2 production was likely to depend on available carbon resources for microbes. It has been well addressed that application of different amendments could enhance the bio available pool of organic carbon [52,53]. N_2O production capacity was maximum for C_F, which was about 200 times higher than Control. Low N_2O emissions were recorded from biochar-amended trials.

3.5.2. Global Warming Potential (GWP)

The effect of different fertilizer treatments was standardized by determining the GWP from the production potential of N_2O and CO_2 released during the incubation. GWP for each of these gases was calculated on the basis of CO_2 as the reference gas. According to IPCC [54], 1 mmol CO_2 is assumed as 1, and 1 mmol N_2O is 275 for a 20-year duration. GWP is then calculated as described by Cai [55]. Total GWP for CO_2 and N_2O is computed as: GWP (CO_2) + GWP (N_2O). The calculated total GWP (CO_2 + N_2O) as per IPCC [54], under different treatments ranged in decreasing order $C_F > B_{15} > C_E > B_{25} > B_{35} > C_P$, respectively (Table 8). High CO_2 and N_2O production potential in the soil can be attributed to increased soil carbon and nitrogen mineralization through enhanced microbial activity.

3.6. Growth Profile of the Cultivar

The growth profile of the rice cultivar under various treatments was assessed based on visual observation and measuring the plant height, tiller number, number of productive tillers, number of leaves, total biomass and grain yield (Table 9). Maximum height was attained in B_{35} treatment (72.6 cm) whereas the minimum was recorded in C_F (55.8 cm). Cultivars in general attained maximum height under biochar-treated trials. The maximum tiller number was observed in B_{35} followed by B_{25}. Highest total biomass and grain yield were recorded under B_{35} trial. In the entire experiments, the overall yield was recorded low since no type of N fertiliser was applied. However, the application of biochar significantly increased the yield when compared to control.

From the growth assessment it could be seen that the cultivar under B_{35} was highly vigorous with maximum biomass allocation and produced healthy tillers. Initiations of spikelets were noticed at an earlier stage under biochar amended cultivar. Hence, there is a possibility of early maturing of grains so that the chance of reducing the duration of total growth cycle of the cultivar cannot be ruled out. In short, cultivars under biochar treatments produced a preferable growth profile even in the absence of any additional nitrogen fertiliser application.

Table 8 Production potential of GHGs and the corresponding GWP

Treatments	GHG production (µg g^{-1} soil)		GWP		Total GWP
	CO_2	N_2O	CO_2	N_2O	
Control	220 ± 4.5	0.05 ± 0.03	5	0.33	5.33
C_E	1760 ± 8.0	0.02 ± 0.01	40	0.11	40.1
C_P	220 ± 3.5	0.03 ± 0.01	5	0.16	5.2
CF	1100 ± 0.7	10.22 ±0.01	25	63.9	88.9
B_{15}	440 ± 4.1	6.27 ± 0.02	10	39.2	49.2
B_{25}	660 ± 6.9	3.46 ± 0.02	15	21.7	36.7
B_{35}	440 ± 4.5	0.04 ± 0.01	10	0.30	10.3

Table 9 Plant growth profile

Treatments	Plant height(cm)	Tiller no	No of productive tillers	No of leaves	Total Dry biomass (gm)	Grain yield (gm)
Control	56.0	5	3	13	64.3	12.4
C_E	56.8	7	4	16	72.1	15.0
C_P	60.9	8	5	20	76.2	15.7
C_F	55.8	8	5	26	76.0	13.4
B_{15}	61.5	9	6	16	75.4	12.5
B_{25}	67.6	12	8	19	76.9	17.2
B_{35}	72.6	15	10	30	79.5	20.0

4. DISCUSSION

The preferable characteristics of biochar used in this study depend on the chemical composition of the starting organic material, i.e, rubber wood and also on the carbonization pyrolysis systems of a traditional mound kiln by which it is made. According to Collison et al. [56], distinct growing environmental conditions and the time of harvest also contribute to the characteristic features of feedstock biomass. The most important factor controlling the properties of the resulting biochar are the pyrolysis conditions [57]. Higher pyrolysis temperatures generally cause greater condensation of aromatic structures and even the formation of graphitic cores [58]. High temperature biochars are also more resistant to chemical oxidation and microbial degradation and hence have a longer half-life in the soil environment than SOC; however, the recalcitrant characteristics of high temperature biochar would be a desirable property if the primary goal was to remove atmospheric CO_2 and sequester carbon in soil for millennia [59]. Baseline soil properties reveal the characteristic nature of Kuttanad wetland rice soil, which forms a unique lowland rice cultivating system. These wetland soils are acidic in nature with low to medium nutrient availability and high carbon content.

The application of amendments, especially biochar, significantly altered the soil characteristics during the growth trial. Additions of biochar to soil have shown increases in cation exchange capacity (CEC) and pH [60, 61]. Such ability is related to the liming value of biochar, which is preferable for the soils like that of Kuttanad. The preferable variation in the pH and CEC due to the application of biochar was generally attributed to the presence of ash residues that contain carbonates of alkali and alkaline earth metals, amounts of silica, heavy metals, sesquioxides, phosphates and small amounts of organic and inorganic N [62]. The high surface area and porous nature of biochar could increase the cation exchange capacity (CEC) of the soil. Thus, there could be a chance for Al and Fe to bind with the exchange site of the soil [63] and this might also be a possible explanation for high soil pH in biochar amended soils. Biochar has a high CEC and with its high recalcitrance [64] it is reasonable that soil amended with biochar had the highest CEC.

We found that the availability of soil nutrients remained higher in the treatments with biochar despite greater nutrient removal due to plant growth and higher grain yields and these results are in agreement with ref. [65]. Biochar application can reduce nutrient leaching from soil with resulting increase in fertiliser use efficiency [64-69]. Increased retention of N with biochar addition is also observed [66-68,70], as is increased P and K availability due to biochar addition [71]. The availability of nutrients in the biochar-added soil may be related to the great surface area of biochar material providing adsorption sites. Moreover, the increase in the water holding capacity of biochar-added soils may improve nutrient retention in the topsoil. Attachment of organic matter or minerals with sorbed nutrients (aggregation) to biochar may further increase nutrient retention [72]. Several studies demonstrate that pro-cessing temperatures <500°C favor nutrient retention in biochar [73] while being equally advantageous in respect to yield [74]. The present findings are in accord with the above cited studies.

Application of biochar has also been shown to change soil biological community composition and abundance [75-81]. Biochar acts as a habitat for soil microorganisms involved in N, P or S transformations [75]. The porous structure of biochar, its high internal surface area and its ability to adsorb soluble inorganic matter, gases and inorganic nutrients are likely to provide a highly suitable habitat for microbes to colonize, grow and reproduce, particularly for bacteria [82]. Biochar addition provides increased levels of refugia for soil microorganisms [83,84], and these may be the explanation for the high load of THB in the biochar trials. Increased microbial activity due to application of biochar could also be another reason for the highest nutrient uptake in biochar treated soils. Biochar has also the capacity to support the presence of adsorbed bacteria from which the organisms may influence soil processes.

The positive effect of biochar on SOC levels was expected due to its high carbon content (98.2%) and literature supports the fact that upon biochar addition the soil carbon level will be increased [85]. The ancient *terra preta* has higher organic C and total N compared with adjacent soils [86,87]. The highest values of organic carbon in biochar treated soils indicate the recalcitrant C-organic in biochar [88]. Application of biochar significantly increases the SOC content [89], and will probably add to the decadal soil carbon pool [90].

The higher concentrations of SOC in biochar applied soil may be due to the potential of biochar to increase the recalcitrant pool of soil carbon and will persist in the soil environment much longer than carbon added in the form of residues or biogenic soil organic matter [91]. The presence of aromatic species (probably graphite) detected in the FTIR analysis of biochar substantiates this finding. Biochar provides only a lower proportion of mineralizable carbon and hence the major part will remain recalcitrant, thereby resulting in net soil carbon gain or maximum soil carbon sequestration potential. Studies suggest that biochar sequesters approximately 50% of the carbon available within the biomass feedstock being pyrolyzed, depending upon the feedstock type [92].

High POC content in the biochar trials represented the accumulation of the dominant form of organic carbon normally noted under more conservative management practices of organic farming. The major contribution of POC to SOC detected in the biochar trial shows the ability of biochar-amended soil to stabilize and retain C in lower fractions of clay and silt. Contrary to the finding of Daniel [93], the microbial biomass carbon increased with added biochar. The previous studies of Kolb et al. [84] also support the present observation that MBC is significantly increased upon biochar addition.

The effect of biochar on the soil CO_2 emissions obviously depends on the soil environment and the microbial community present, as well as the physic-chemical characteristics of the biochar [94]. Chemisorptions of respired CO_2 to biochar surfaces accounts for the low CO_2 emission potential from biochar trials [95].

Emissions of nitrous oxide have been shown to decrease due to the influence of biochars on soil hydrology and nitrification-denitrification processes [96-98]. Organic amendments that result in more rapid immobilization of mineral N [99] explain the low N_2O emissions from biochar, which could be a result of inhibition of either stage of nitrification or promotion of the reduction of N_2O, and these impacts could occur simultaneously in soil [100]. Biochar-amended soil showed reduced GHG emission and hence low GWP and this can be attributed to the biological stabilization of carbon and nitrogen in soil [51].

Beneficial effects on crop yields have been documented in a number of pot and field trials [38,70,101-103]. Improved crop yields after biochar application have been ascribed to a number of mechanisms. The liming effect of biochar has been suggested in literature as one of the likely reasons for improved crop yields on acidic soils [104,105]. Improved crop yields have also been attributed to a ‘fertilizer effect’ of added biochar, supplying important plant nutrients such as K, N, Ca, and P [70]. Increased nutrient retention by biochar may be the most important factor for increased crop yields [65,101,102].

5. CONCLUSIONS

This study demonstrates the positive effects of biochar derived from local resources as an organic soil amendment from a climate change perspective. Biochar increased the chemical, physical and biological properties of rice soil, thereby improving soil fertility. Our study also shows that biochar can be employed as a lime substitute for the acidic soils of Kuttanadu, which will increase the yield of acid-sensitive crops. The improvement of soil properties with organic soil amendment applications resulted in an improvement of rice growth as shown by the increase in plant height, number of tillers, dry biomass and grain yield.

Carbon sequestration in soils and vegetation can remove carbon from the atmosphere, which in turn will reduce the atmospheric carbon dioxide concentration.

The application of biochar influences the C sink capacity of wetland rice soils, as maximum SOC and POC is recoded under biochar trials. Higher macro-aggregate formation was observed under the maximum biochar-applied soil, which favors the storage of substantial amounts of SOC and POC in the soil. Importantly, a positive relationship between SOC, POC and aggregate stability was noted. The study indicates that application of biochar increased the maximum allocation of carbon both in the soil and biomass, thus portraying its C sink capacity.

Application of biochar to soils may be a substantial solution to reducing the negative impact of wetland rice cultivation on global warming. If used instead of lime in the acid soils of Kuttanadu, biochar is an added advantage of CO_2 emission reduction. The study shows that biochar amendments can significantly reduce total direct N_2O emissions and indirect CO_2 emissions by saving N fertilizer use in accordance with an increase in agronomic N-use efficiency in rice agriculture.

Thus, the total global warming potential of rice soil can be curtailed to a considerable level with biochar and hence can be suggested as a potential tool against global warming without compromising productivity and food security. The ability of biochar to retain applied fertilizer against leaching with resulting increase of fertiliser use efficiency is highly desirable for the soils of Kuttanadu since nutrient leaching and contamination of soil and water systems of this rice cultivating tract is a major managerial issue. Since biochar application enhances the overall sorption capacity of soils towards anthropogenic organic contaminants, its incorporation into wetland rice soils may help to mitigate the toxicity and transport of common agro-based pollutants.

Even though organic composts and chemical fertilizer produced favorable results in certain respects, they were incapable of producing an overall impact on the rice soil from climate change and yield optimisation perspectives. Our results indicate the importance and need of a shift in high input agriculture practices to a cost effective sustainable system. Conversion to organic agriculture practices with biochar application can help in restoring the system resilience without comprising food productivity. Hence it is imperative to prefer sustainable agricultural practices in wetland rice cultivating tracts like Kuttanad towards attaining maximum yield without affecting our climate system.

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